by Wong Nyuk Hien and Marcel Ignatius

Urban Heat Island in Singapore

Contributing Factors and Mitigation Solutions

What is Urban Heat Island?

The world has experienced unprecedented urban growth in the last and current centuries. In 1800, only 3% of the world's population lived in urban areas. It increased to 14% and 47% in 1900 and 2000 respectively. Since 2008, for the first time in history, more than half of the world population lives in the urban areas. In year 2003, United Nations estimated that by year 2030, up to 5 billion people will be living in urban areas accounting for 61% of the world's population.

The on-going migration to urban areas has massive environmental consequences. This condition of unprecedented shift from the countryside to cities has been influencing climate change, where urban areas account for up to 70% of the world greenhouse gas emissions. Since half of the world population lives in the tropics, including Singapore, significant attention should be paid to urban context within the tropics.

Cities are growing towards megacities with higher density urban planning, narrower urban corridors and more high-rise urban structures. Increasing urbanization causes deterioration of the urban environment, as the size of housing plots decreases, thus increasing densities and crowding out greeneries. Within the built environment at micro-scale, buildings and vegetation influence the incident solar radiation received by urban surface.

Cities tend to record higher temperatures than their non-urbanized surroundings, a phenomenon known as Urban Heat Island (UHI). Earlier studies show strong relation between urban morphology and increasing air temperature within city centers. Urban structures absorb solar heat during the day and release it during the night. Densely built areas tend to trap heat which is released from urban structures into the urban environment, increasing urban air temperature compared to surrounding rural areas and causes UHI effect.

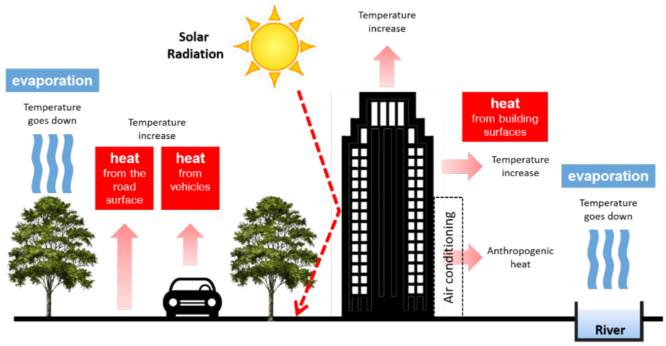


Fig. 1. Urban factors that may cause temperature increase and decrease.

UHI is the condition where an increase in building density results in cities recording higher temperatures in comparison to their non-urbanized surroundings. Several factors, such as diminishing of green area, low wind velocity due to high building density and change of street surface coating materials contribute to UHI. These may lead to overheating by human energy release and the absorption of solar radiation on dark surfaces and buildings. This problem will be further aggravated by increasing demand on air conditioning, which will again lead to further heating and CO_2 release.

UHI is a result of dense built infrastructures of cities that absorb and trap solar and traffic-generated heat, retaining it for periods longer than natural surfaces. UHI affects street level thermal comfort, health and environment quality and may increase energy demand. As cities add roads, buildings, and people, temperatures in city rise relative to their rural surroundings, creating a heat island.

UHI Mitigation Solutions

Many studies have provided solutions on reducing the UHI impact by several means:

- **Trees and vegetation**
  A vast study on greenery has shown that trees and vegetation cover lower surface and air temperatures by providing shade and a cool environment through evapotranspiration. Furthermore, the recent trend of growing a vegetative layer (plants, shrubs, grasses, and/or trees on the roof (green roofs) and building façade (vertical greenery) reduces the temperatures of the building envelope and the surrounding air.

- **'Cool' roofs and pavement**
  By installing a 'cool' roof using materials or coatings that significantly reflect sunlight and heat away from a building can help to reduce roof temperatures, increase the comfort of occupants, and lower energy demand. Moreover, using 'cool' paving materials (for sidewalks, parking lots, and streets) not only cools the pavement surface but also the surrounding air, reducing overall outdoor temperature.

- **Urban planning with UHI consideration**
  Proper city planning that implements UHI mitigation strategies is required, either by strategically designing open spaces with greenery or regulating the construction of building materials that meets the standard derived from the UHI studies. Furthermore, it is important for the planners and architects to acknowledge the importance of microclimate aspect in design.

However, in spite of the above mentioned strategies, finding optimal solutions to mitigate UHI impact comes with a big challenge since microclimate comprises a complex relationship between many elements (e.g. weather, urban texture, natural landscapes, etc.) which overlap with each other. Hence, mitigation strategies to be developed should not just focus on a certain aspect but more coherent and integrated solutions need to be established by looking into every aspect. In order to pursue this strategy, one needs to deconstruct different UHI aspects by firstly looking into the problem causes.

As briefly mentioned, UHI problems are mostly derived from man-built structures, hence urban planning plays a vital role. In order to oversee the impact of UHI on cities, our research group has been exploring several analysis methods for better urban planning related to microclimate or building energy performance:

1. Urban Climatic Map (UCMap): analysis method to investigate microclimate impact on urban planning
2. Urban Texture Analysis (UTA) and its relation to building energy consumption
3. Physically based Urban Climatic Modeling

Furthermore, based on UHI analysis on various factors, the group has identified mitigation strategies that focus on several urban components:

4. Landscape optimization through strategic plant selection and placement
5. Anthropogenic heat in the dense urban environment
6. Building facade reflectivity on the visual and thermal environment

The following sub-topics will discuss more details about the analysis method, factors that have been causing UHI phenomenon in urban areas, especially in the Singapore context, and also the above mentioned relevant mitigation and solution strategies.

Urban Climatic Map (UCMap): Analysis Method to Investigate Microclimate Impact on Urban Planning

Urban climate is one of the elements of urban physical environment, which is often ignored in urban planning. To design a sustainable city, it is necessary to factor the climatic information holistically and strategically into the planning process. Both macro and microclimatic analysis have become essential due to rapid urbanization, higher density, and more compact cities; hence the concept of UCmap was developed to understand the climate phenomenon in the urban areas.

The UCMap was developed by German researchers in the 1970s to provide a strong focus on applied urban climatology. It is considered as an appropriate tool for translating climatic phenomenon and problem into 2-D images and symbols with land use and spatial information for urban planning use.

It can help urban planners, architects and governors to understand and evaluate the effect of urban climatic issues on decision-making and environment control. Given its development UCMap has become a worldwide research interest since the 1990s, in which Germany, Hong Kong, and Japan have been the exemplars in conducting urban climate analysis and application. One important research focus under the urban climate scope is the UHI phenomenon.

We have developed a method on how to use the UCmap concept integrated with the established prediction models to analyze both outdoor temperature and thermal comfort, the aspects that are highly affected by the UHI. The prediction models, Screening Tool for Estate Environment Evaluation (STEVE Tool) and Thermal Sensation Votes (TSV), have been developed using Singapore climate as the model of tropical high density urban areas. The purpose is to bridge research findings, particularly in air temperature prediction models, with urban planners. The STEVE Tool is used to simulate the ambient temperature condition with wind consideration, surface customization, and proposed greenery options.

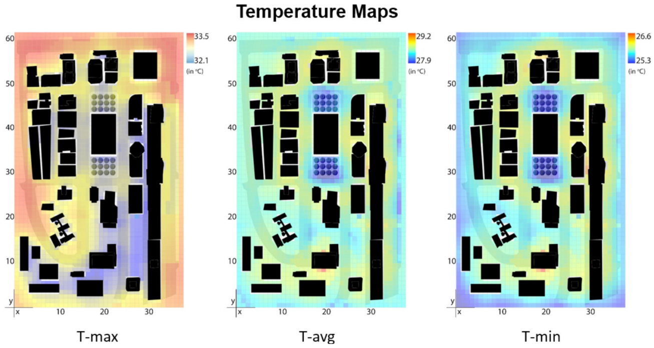


Fig. 2. Temperature maps of an urban area.

The air temperature prediction models can calculate the daily minimum (t_{min}), average (t_{avg}) and maximum (t_{max}) temperature of each point of measurement based on climate predictors and urban morphology predictors. The model was developed based on field measurements from weather sensors and loggers which were installed at different areas representing land uses (e.g. business parks, industrial estates, CBD, parks, and housing estates). This amalgamates the data on the microclimate and urban morphological parameters gathered from both the current and past field measurements.

Besides outdoor temperature, another important aspect that is affected by the UHI is thermal comfort. As we may know, urban spaces such as streets, plazas, squares and parks, are the major outdoor spaces for people to take a walk or engage in recreation and social activities. A comfortable thermal environment is extremely important for people to enjoy the outdoor urban spaces. Understanding the characteristics of urban outdoor microclimate and the thermal comfort implications for people opens up new possibilities for the development of urban spaces. However, the quantification of outdoor thermal comfort is a relatively new area of inquiry. Although several thermal indices have been developed to assess outdoor thermal comfort, all the indices are not directly linked with human thermal sensation, which makes them difficult to be interpreted by urban designers.

TSV range	Perception
-3 ~ -2	cold to cool
-2 ~ -1	cool to slightly cool
-1 ~ 0	slightly cool to neutral
0 ~ 1	neutral to slightly warm
1 ~ 2	slightly warm to warm
2 ~ 3	warm to hot

Table 1: TSV index categories of outdoor thermal comfort.

The analysis of outdoor thermal comfort utilizes the TSV. The model is used for predicting and evaluating people's thermal sensation, and was proposed for Singapore under certain outdoor thermal conditions.

The TSV calculation output represents an index that can be categorized based on different human perceptions of comfort, which can be seen in Table 1, where the values range from -3 to 3, representing different human perceptions from cold to hot.

The TSV model is based on a very large survey of more than 2,000 occupants conducted in different outdoor urban spaces like parks, gardens, river side, squares, university campuses, etc. Air temperature, relative humidity, wind speed, globe temperature and

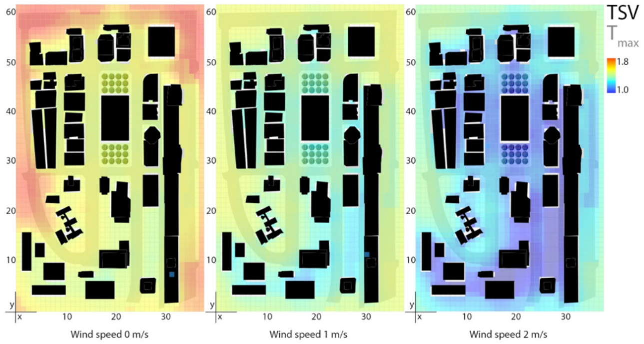


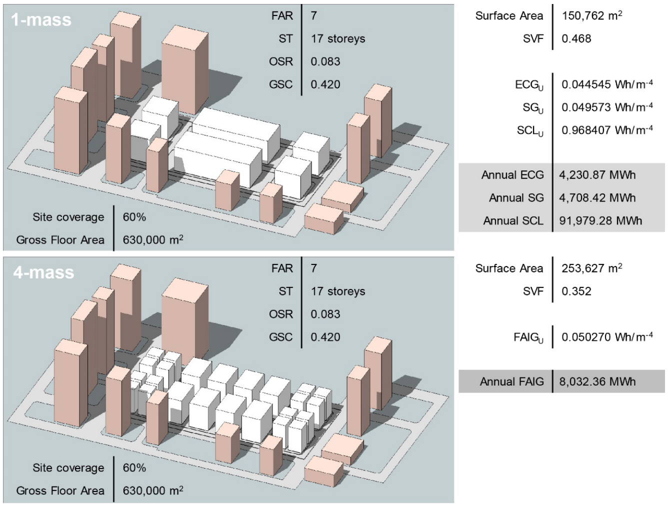
Fig. 3. TSV maps generated based on different wind conditions during the hottest period of the day.

Fig. 4. Urban texture variables.

solar radiation were measured at the surveyed places.

Urban Texture Analysis and its Relation to Building Energy Consumption

It is common for urban dwellers to adapt to overheating from hot weather by utilizing air conditioning to achieve comfortable internal condition. However, with the intensification of UHI phenomenon, the temperature increase in urban areas intensifies the building energy performance due to the workload increase of the air conditioning.



1-mass

FAR	7
ST	17 storeys
OSR	0.083
GSC	0.420
Site coverage	60%
Gross Floor Area	630,000 m^2
Surface Area	150,762 m^2
SVF	0.468
ECG$_U$	0.044545 Wh/m^{-4}
SG$_U$	0.049573 Wh/m^{-4}
SCL$_U$	0.968407 Wh/m^{-4}
Annual ECG	4,230.87 MWh
Annual SG	4,708.42 MWh
Annual SCL	91,979.28 MWh

4-mass

FAR	7
ST	17 storeys
OSR	0.083
GSC	0.420
Site coverage	60%
Gross Floor Area	630,000 m^2
Surface Area	253,627 m^2
SVF	0.352
FAIG$_U$	0.050270 Wh/m^{-4}
Annual FAIG	8,032.36 MWh

Fig. 5. Planners can come up with two different design schemes with the same density, but the energy performance would differ significantly due to the building geometry arrangement.

A study has been conducted to observe UHI effect on district energy performance, which focuses on non-domestic/office function. The temperature increase at urban areas has direct impact on the heat received by the buildings through the building envelopes, in which also affects the load of air conditioning (the cooling load). Hence, the urban texture (buildings placements, sizes, and arrangements) has great influence on determining the amount of heat received by the buildings.

The findings serve to identify the relevant urban texture variables (see Figure 4) which characterize urban density and form, such as Floor Area Ratio (FAR), Open Space Ratio (OSR), Story Height (ST), Gross Site Coverage, (GSC), and Sky View Factor (SVF). Thermal load calculation method is developed to illustrate how a combination of several urban texture variables affects or influences the cooling load and heat gain for the whole precinct.

This analysis method will benefit planners particularly at the early design stage, where microclimatic analysis should be first conducted at the city scale. Hence, design problems related to high energy usage from any initial design proposals can be identified and proper adjustments can be made immediately. Moreover, this approach ensures planners are well informed regarding their design implications, and also helps to promote good and environmentally friendly designs, where design benchmarking can be made between various urban designs to select the most compatible design program.

Physically Based Urban Climatic Modeling

This study aims at developing an urban climatic model to assess building energy use using geographic and meteorological data of Singapore. Through this physically based model, it is intended to evaluate the efficiency of UHI mitigation strategies in terms of improvements of outdoor comfort and reductions of indoor energy use.

Geographic and meteorological information are mainly obtained by remote sensing. Geographic Information System (GIS) based information are processed to have high resolution pictures of the land use in Singapore. In the urban climatic model, geographic and meteorological data are first employed as inputs of the Weather Research and Forecasting (WRF) model. The latter is used to estimate the microclimate condition (temperature, wind, humidity, etc.) above a specific location in Singapore. This estimation process is using the urban canopy model, where the results are being used to feed the lumped thermal parameter model for building energy simulation.

The objective of this method is to compute weather conditions that surround a specific building, hence the building energy simulation can be conducted with proper microclimatic data for better estimation of heat transfer process, which determines the UHI impact on buildings. Moreover, planners will be able to evaluate energy savings achieved by UHI mitigation strategies that are defined within the urban canopy model.

Landscape Optimization Through Strategic Plant Selection and Placement

Urban greenery can bring about benefits to the microclimate through processes of shading and evapotranspiration. With the benefits of greenery widely acknowledged, the next challenge is to translate this knowledge into industry practice. While there are existing frameworks to objectify landscape planning processes such as maintainability and irrigation, methodologies for assessing landscape proposals in terms of plant cooling potential have yet to be exhaustively formalized. The problem of visualizing the thermal impact of any landscape design is exacerbated by the inclusion of alternate forms of vegetation such as vertical and rooftop greenery.

The proposed climate-responsive landscape design framework is developed to enable landscape designers to evaluate the thermal impact of their design proposal. This framework utilizes mean radiant temperature (t_{mrt}) as a measure of plant cooling potential, as this quantity plays a crucial role not only in indoor situations but also outdoors as indicated in several studies which have stressed that outdoor thermal comfort is highly dependent on the short wave and long wave radiation fluxes from its surroundings.

In the hypothetical urban model (Figure 6), four design iterations have been conducted for an area slated to be park space by means of thermal simulation. In iteration 1, trees with small canopies (5 m diameter) are placed at locations designated by the landscape planner. In iteration 2, trees with larger canopies (15 m diameter) are assumed at the same spots. The t_{mrt} reduces drastically near the trees. In iteration 3, more trees (20 m diameter canopy) are added to areas that have larger pedestrian flow. As a result, thermal conditions of these areas are shown to have improved significantly. In iteration 4, thermal effects of shrubbery are factored into the t_{mrt} map via an empirical model developed by building scientists from the National University of Singapore's Department of Building.

Comparison of all four iterations reveals the immense positive impact of tree and shrub allocation using the proposed landscape planning framework. The proposed landscape design framework allows designers to understand the impact of their choice of plant selection and allocation before eventually committing to a final decision. This can help minimize undesirable outcomes such as lack of shading provision at prominent locations or inadequate light provision for plants due to excessive overshadowing from adjacent buildings.

Objective plant selection and placement are important factors in landscape planning. In the above example, scientific objectives are proposed to lend sophistication to the landscape design process. Introduction of thermal simulation in this study has highlighted the importance of context and locality. Adjacent buildings can affect solar exposure significantly, thereby influencing the plant placement process, dispelling the common myth that plants can improve the environment by cooling temperature indiscriminately.

The proposed framework for climate-responsive landscape planning seeks to more effectively realize the cooling effects of greenery as an urban heat mitigation technique and to optimize urban greenery as an ecosystem resource.

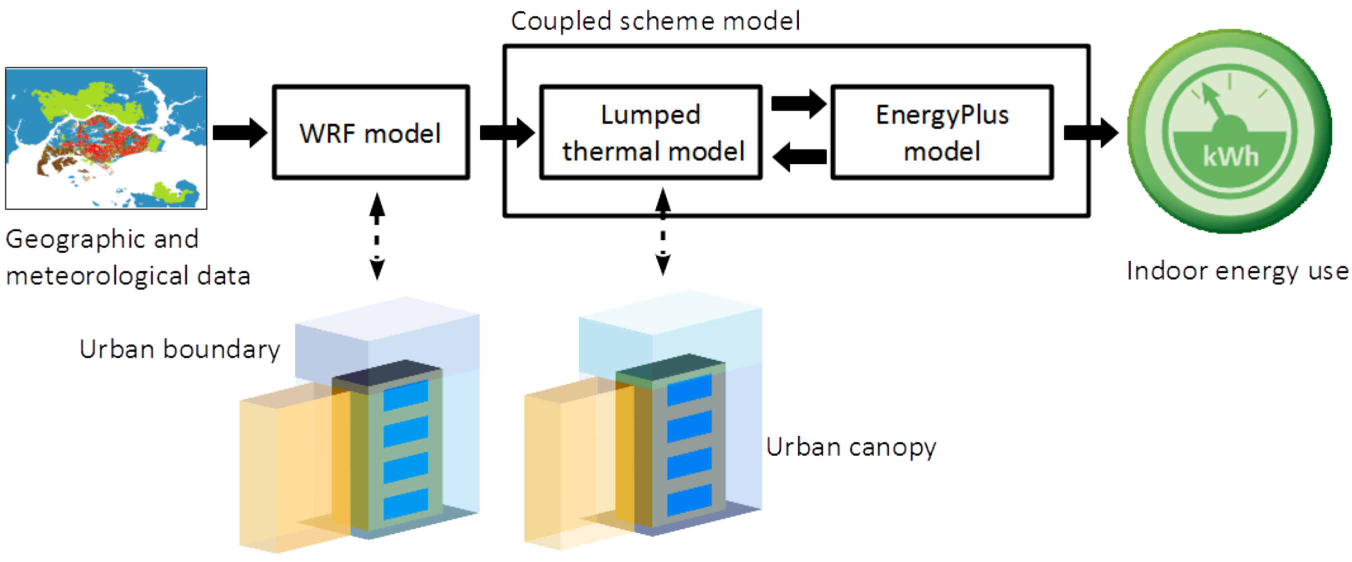
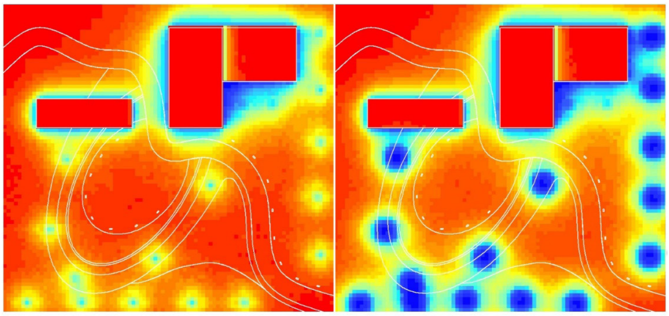
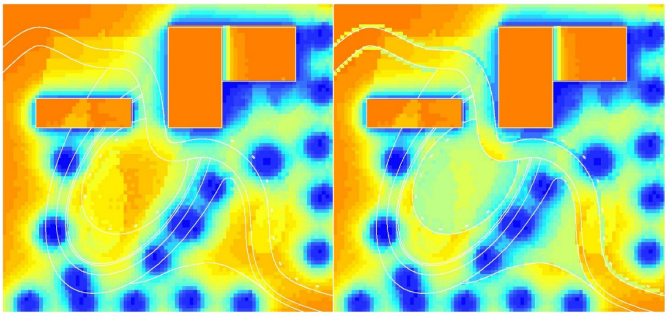


Fig. 6. Coupled-scheme model workflow.



Iteration 1
Trees with 5m diameter canopy

Iteration 2
Trees with 15m diameter canopy



Iteration 3
Trees with 15m diameter canopy
+
Additional trees with 20m diameter canopy

Iteration 4
Trees with 15m diameter canopy
+
Additional trees with 20m diameter canopy
+
Cooling effect of shrubs
based on regression model

Fig. 7. Thermal results of iterative studies.

Anthropogenic Heat in the Dense Urban Environment

We have two heat sources in our environment, one coming from above us via solar and sky radiation while the other is generated by everyone of us. Just by being alive, we generate heat via metabolism while the activities we do daily generate heat in buildings and vehicles too. The magnitude of the heat we generated is much lower in comparison with what is coming from the climate. However, it becomes an issue if the human concentration is high and if heat is not welcomed in specific regions of the earth.

Singapore is located in a tropical hot and humid zone. As its population and built density is among the highest on earth, the heat concentration will affect pedestrian thermal comfort and intensifies cooling load demands. When having more people and buildings per area of land, it means the heat generation is intensified and harder to disperse because of the obstructions surrounding the city. At pedestrian level in dense streets, the vehicles are the major heat contributors. The building heat is normally rejected high above the roofs. Compared to an equivalent population and built density city like Hong Kong, we have double the vehicle ownership. This means the chances of exposure to vehicle heat is doubled for pedestrians on the streets.

There are two ways to overcome the problem, which is to tackle at the sources themselves or the environment where the sources are located. At the source level, policies can be implemented to minimize the presence of vehicles or to convert to lower heat types like electric vehicles. The research looks at the environment where the heat sources are located. It aims to investigate the contribution of the anthropogenic heat, especially to the increase of air temperature at pedestrian level in the densest streets in Singapore, which is typically located at the Central Business District. With the confirmation of air temperature increase, the next step is to use measured data as inputs for simulation studies to understand how the urban morphology impacts heat trap in the streets. This will help in planning the city more responsively in the future to avoid urban forms that trap heat (as well as pollution).

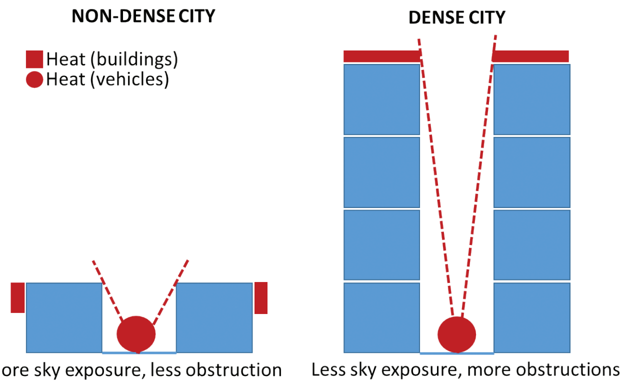


Fig. 8. A comparison between non-dense (left) and dense city (right) environment.

Impact of Building Facade Reflectivity on the Visual and Thermal Environment in Tropics

The scarcity of land in tropical urban areas has resulted in the building of high-rise in an increasingly dense manner. Among the consequences of such activities are the issues of glare toward neighboring buildings and pedestrians, and the resultant thermal impact due to the highly reflective nature of such building envelope or façade. The usage of materials with lower reflectivity (or albedo) and impermeable surfaces result in more heat being absorbed from the sun‘s radiation, consequently raising the temperature in urban areas and exaggerating the UHI problem. Furthermore, most mandatory building codes do not specify the threshold limits for façade material reflectance and some materials such as steel can be highly reflective, with reflectance values of up to 40%. In Singapore, Building and Construction Authority (BCA) has proposed *to permit* any *materials* (other than glass) with a specular reflectance of not exceeding 10%, without any limit on the daylight reflectance. Also, for the glass façade, BCA has

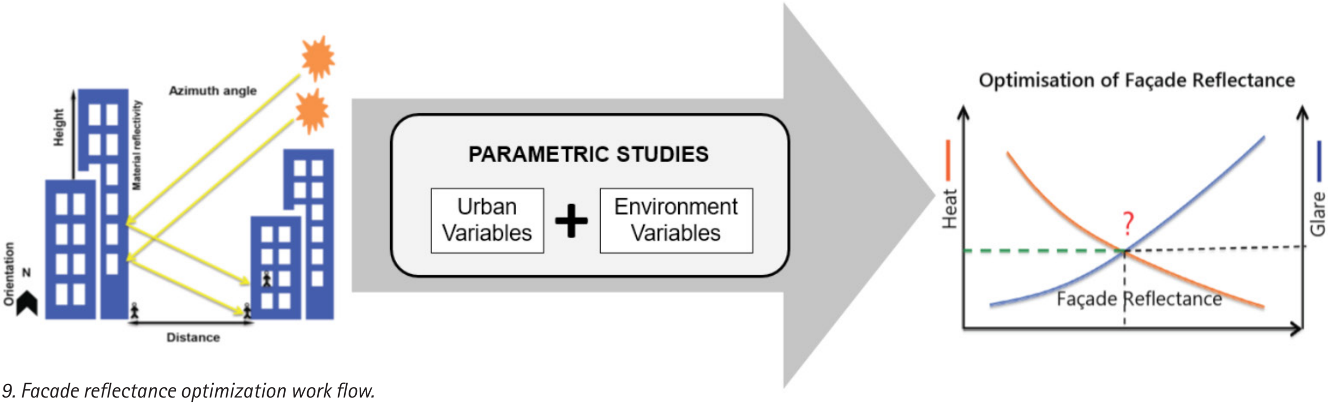


Fig.9. Facade reflectance optimization work flow.

proposed to retain the current daylight reflectance at not more than 20% in response to the complaints of the glare problem from the residents. However, according to a literature survey, there has been no in-depth scientific study in Singapore to support the reflectance limit of 20%.

The present study suggests a suitable method to measure and subsequently assess the visual glare and thermal impact of the daylight reflected onto the surrounding environment, leading to a recommendation for an optimal reflectance limit for building façades. This research focused on high-rise commercial buildings that are using highly reflective glazing façade in a tropical urban environment setting. A series of simulated parametric studies that take into account the urban characteristics include building height, façade shape, orientation, material, and street width are simulated.

The field measurement was carried out to validate the simulated results. This study will then propose the optimum façade reflectance to be adopted for efficient façade design and materials. It is hoped that this research will contribute to the further investigation in the field of façade reflectance and surrounding temperature rise that will also have an impact on UHI effect.

Conclusion

This study shows how microclimate analyses can be performed at the early stages of the planning process, when planners/designers could be well informed of the environmental impact of their design. Consequently, this study tries to balance design objectives by minimizing the external heat gains and reducing the heat island impact by enhancing the wind outflow and implementing greenery.

The assessment method used could benefit both the planner and researcher in providing environmental impact information relevant to a master plan or precinct design. It does not provide an exact overview of energy consumption figures at the district level, but rather comparative figures that will be useful for benchmarking different design options at the same time.

Although the methods explained here are context dependent, the strategy on analyzing microclimate condition is highly climate and geographical dependent, and differs from one region to another. For a given climate, it can only be assessed by a comprehensive analysis, which takes into account all the energy processes that happen in buildings.

This article has provided some insight into how several studies can be combined to create a more comprehensive urban micro-climate analysis from a different aspect. Hence, future research should focus on integrating these different analysis components within a simulation platform.

Wong Nyuk Hien is a Professor in the Department of Building, National University of Singapore. His areas of expertise and research interests include urban heat island, urban greenery, thermal comfort in the tropics and building energy simulation. He is the principal investigator of a number of research projects in collaboration with the various government agencies to study the UHI effect in Singapore and the mitigation measures. He has published more than 150 internationally referred journal and conference papers. He is also the co-author of four books on rooftop and urban greenery.

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