COOLING SINGAPORE 2017

STRATEGIES FOR COOLING SINGAPORE

A CATALOGUE OF 80+ MEASURES TO MITIGATE URBAN HEAT ISLAND AND IMPROVE OUTDOOR THERMAL COMFORT

LEA A. RUEFENACHT & JUAN A. ACERO

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EDITED BY
LEA A. RUEFENACHT & JUAN A. ACERO

This research is supported by the National Research Foundation (NRF), Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme.

We thank our colleagues from SEC, SMART, TUM CREATE and NUS who provided insights and expertise that greatly assisted the research.

FOREWORD

Cities are usually warmer than the rural areas that surround them. This phenomenon, which is known as the 'urban heat island' effect (UHI), occurs because cities consume huge amounts of energy in electricity and fuel, have less vegetation to provide shade and cooling, and are built of materials that absorb and store energy from the sun.

The urban heat island effect over much of Singapore averages about 4°C, though it can exceed 7°C at certain times of the day. This warming reduces thermal comfort, discourages people from walking or cycling, and increases the energy used for air conditioning. It is also responsible for more intense storms, which sometimes lead to flooding. And as the economy develops Singapore's urban heat island effect will only grow larger, unless mitigating action is taken.

Many people believe the time has come for Singapore to develop a strategy to combat urban warming. This would bring benefits, not only in liveability, but also in reducing carbon emissions. To contribute to such a strategy, a research project 'Cooling Singapore' was launched in 2017, with the aim of providing actionable knowledge for policymakers.

The project forms part of the NRF's CREATE programme, and brings together research teams from the Singapore-ETH Centre, SMART, TUM CREATE and NUS. One of its goals is to build an expert community within academia and government that can help guide policy about the urban heat island effect in the longer term. To meet this goal, it has set up a 'UHI task force' composed of representatives from governments agencies and universities that facilitates the exchange of knowledge and helps ensure the policy 'roadmap' is realistic.

This report is the first publication of the Cooling Singapore team. It presents a comprehensive review of potential measures to tackle the urban heat island effect, focusing especially upon the needs of cities such as Singapore located in the humid tropics.

by Peter Edwards
Cooling Singapore Lead PI

MOTIVATION

Cooling Singapore aims at developing a roadmap towards reducing the urban heat island (UHI) effect in Singapore and thereby also improving outdoor thermal comfort (OTC). Both UHI and OTC are complex topics that can be addressed in many ways. Research efforts in Singapore (and elsewhere) typically focus on these topics to promote a better understanding of them and to discover new and viable solutions for keeping residents comfortable indoors and outdoors.

In contrast with the existing and on-going research on UHI and OTC, the main objective of Cooling Singapore is not to gain new scientific insights or to add new solutions for reducing UHI or improving OTC to this already well developed body of knowledge. Instead, Cooling Singapore aims at providing a comprehensive overview of solutions that are relevant in a tropical context and provide guidelines that translate the existing body of scientific knowledge into actionable knowledge that is directly applicable to Singapore.

A major goal of Cooling Singapore is to develop a catalogue of solutions and guidelines for reducing UHI and improving OTC that are applicable to the local context of Singapore. The purpose of this catalogue is to give policy makers a comprehensive overview of mitigation strategies and measures that are available. With this catalogue, we hope to support the urban planning and design process with actionable knowledge. In its current form, the catalogue lists a series of mitigation strategies and measures to serve as a basis for further discussion so as to prioritise and select the most relevant and promising ones that apply to the Singapore context. In the next iteration of this working document, the selected mitigation strategies and measures will be evaluated in terms of their applicability, estimated effectiveness and economic impact in relation to the specific areas of interest in Singapore.

As it is now, the catalogue contains 86 strategies and measures for mitigating the UHI effect and/or for improving OTC. These are grouped into seven clusters: vegetation, urban geometry, water features and bodies, materials and surfaces, shading, transport, and energy. These clusters are based on strategic sectors, for example urban geometry, transport and energy, and the physical aspects, such as albedo, shading and ventilation, which influence the urban climate. Each strategy describes its impact towards UHI and OTC, its applicability in the tropical context of Singapore, its integration into urban planning, and its current research status. While many of the items in the catalogue may also be applicable to non-tropical cities, mitigation strategies and measures that are not applicable to tropical cities have been excluded.

The individual catalogue items have been compiled by reviewing current scientific articles that study and measure the causes of UHI and OTC, with special focus on Singapore and tropical regions. To verify and extend the list of the collected strategies, a questionnaire within the scientific community of SEC, SMART, TUMCREATE and NUS was conducted. The content within this document is based on literature review and expert knowledge from various perspectives on urban design, transport, energy, building construction, and urban climatology.

Heiko Aydt
Cooling Singapore Project Leader

001
VEGETATION

VEGETATION

Vegetation has been used extensively as a UHI mitigation strategy worldwide. Properties of vegetation include high albedo and low heat admittance that have the effect of reducing accumulation of incoming solar energy in the urban area. Additionally, certain types of vegetation such as trees can provide shade and minimise the heat gain from solar radiation, which then improves thermal comfort significantly. Also, the ambient air temperature reduction and building shading by vegetation can lower building energy demand for indoor cooling purpose.

Singapore, an urban area located in the tropics, has a regional climate that is close to the level of thermal discomfort due to high air temperatures and humidity. Along with this fact, the huge extension of the city and the presence of artificial materials worsens the situation. However, high levels of precipitation in Singapore aid vegetative growth, and as such require minimal maintenance and pose lower investment costs for agencies as compared to dry climates. This is certainly an opportunity for the whole urban area to consider mitigation strategies related to vegetation during urban planning and the local/microscale urban design. Expanding green areas would be positive but considering the strategic locations of the vegetation can increase even more the benefits and improve the local thermal comfort in open spaces while reducing building cooling energy demand.

The Vegetation category has been divided into three sub-categories: Planting Greeneries, Parks and Open Spaces, and Green Corridors. The first deals with the inclusion of vegetation in the urban design. Most of the strategies can be applied from a retrofitting point of view (e.g. incorporating green roofs, vegetation around buildings). Depending on their spatial extension these strategies can address the whole UHI and/or locally the OTC. The second sub-category, describes the possibilities of managing and improving the thermal performance of open spaces. Finally, the last sub-category focuses on integrating green corridors in the entire city as a way of improving OTC.

Juan Angel Acero
Cooling Singapore Researcher

PLANTING GREENERIES

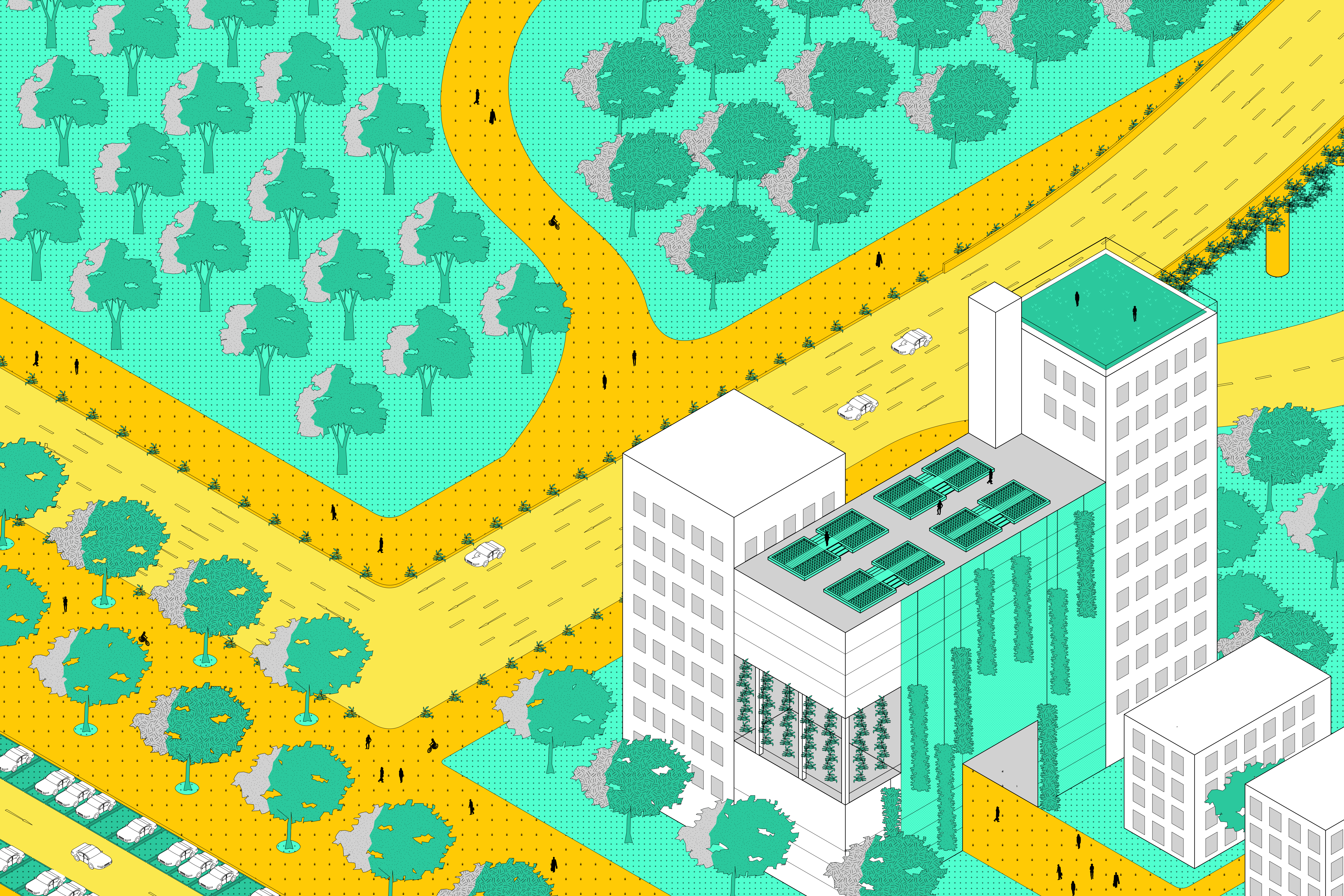
Green roofs
Vertical greeneries
Green walls/facades
Vegetation around buildings
Selective Planting
Green pavements
Infrastructure greenery

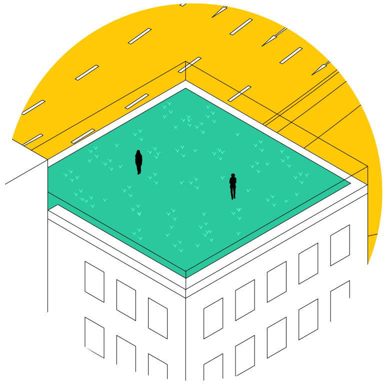
PARKS AND OPEN SPACES

Macroscale urban greening
Local scale urban greening
Microscale urban greening
Green parking lots
Tree species
Urban farming

GREEN CORRIDORS

Transport corridors





PLANTING GREENERIES
GREEN ROOFS

Incorporating green roofs involves placing a vegetative layer such as plants, shrubs, grass, and/or trees on building rooftops. They are also called 'rooftop gardens' or 'eco roofs'. Green roofs can be installed as a thin layer (around 5 cm) of groundcover up to a thick layer (around 1m) of intensive vegetation and trees. The thickness depends on the chosen soil type, drainage system, and vegetation species.

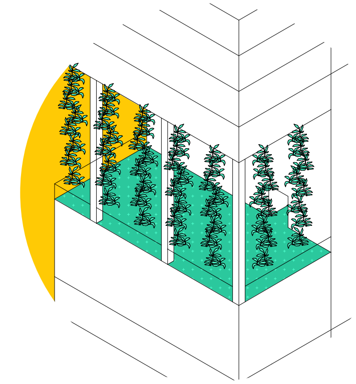
UHI & OTC effect
This strategy allows for the reduction of the urban heat accumulation due to a lowering of the temperature of roof surfaces. Similarly, nearby air temperature is also influenced by evapotranspiration. It produces benefits in terms of UHI mitigation and the reduction of building energy consumption.

Tropical climate
This strategy has special interest for application in Singapore for two reasons: one, the elevated position of the sun along the year that produces intense vertical radiation over planar surfaces such as roofs and overheating; and two, the high performance and growth of vegetation in humid tropics.

Urban planning
Implementation should be aided by the development of building codes and energy efficiency guidelines. Green roofs can be developed both in public and private buildings.

State of the art
Numerous studies have proven the benefits of green roofs. However, there is still insufficient studies that combine the UHI benefits with the reduction in building energy demand. Different authors have shown that the surface temperature of an individual green roof can be reduced by 15-45°C compared to conventional or non-green roofs. Additionally, the nearby air temperature can be reduced by 2-5°C. Reduction of energy consumption can be close to 10 per cent (Refahi and Talkhabi 2015), but could reach 80 per cent depending on the building type (Peng and Jim 2013). Additionally, if extensive use of green roof is undertaken in an urban area, air temperature at pedestrian level could be reduced by 0.5-1.7°C (Peng and Jim 2013).

PLANTING GREENERIES
VERTICAL GREENERY



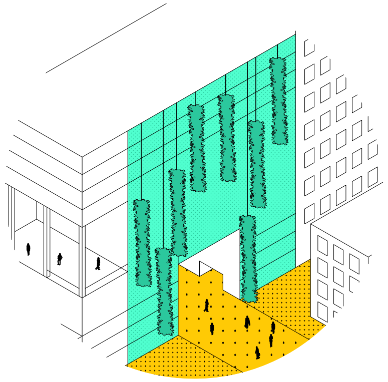
Vertical greenery is defined as the growing of vegetative elements on the external facade of the building envelope. There are two kinds of systems: support system that allows plants to climb through them, and carrier system where plants can settle and develop.

UHI & OTC effect
These systems allow for a reduction of the external surface temperature of the building façades, especially in the case where intense sun radiation occurs, such as on the south facing façades. Consequently, the temperature inside the building can remain more stable and thus there is a reduction in the building energy consumption for cooling. Similarly, there is a reduction of the nearby air temperature providing benefits for pedestrians' thermal comfort.

Tropical climate
It is an interesting strategy for humid tropics because water access can be provided naturally through atmospheric precipitation (high levels in Singapore) and thus avoiding extra and/or complicated landscaping maintenance.

Urban planning
Implementation should be aided by the development of building codes and energy efficiency guidelines. Adequate greenery systems should be selected in accordance to the building structure, the maintenance required, and safety. They could be developed both at public and private buildings at low costs.

State of the art
The performance of vertical greenery can vary significantly because of the weather conditions that influence plant characteristics or because of the plant species used (Pérez et al. 2014). Studies in Singapore have shown that thicker greenery is key to getting positive results when shading a building and that reductions between 10–31 per cent energy cooling load can be achieved due to the effect of vertical greeneries (Wong et al. 2009).



PLANTING GREENERIES

GREEN FAÇADES

Green facades are vegetative layers such as small plants, grass and/or moss attached to external building façades. They are also called 'living walls' and 'vertical gardens'. Green façades can be considered as an alternative to insulating construction materials and reducing indoor overheating.

UHI & OTC effect

The strategy allows for a reduction in the temperature of façades especially those exposed to intense sun radiation, such as the south facing façades. Consequently, the temperature inside the building can remain more stable and thus there is a reduction in the energy consumption required for cooling indoors. Similarly, there is a reduction of the nearby air temperature providing benefits of thermal comfort for pedestrians.

Tropical climate

It is an interesting mitigation strategy for the tropics since reducing direct exposure to sun radiation is a basic requirement in isolating the thermal effect on buildings from the warm exteriors. Its implementation (depending on the case) may not require sophisticated design and maintenance, especially in low-rise buildings.

Urban planning

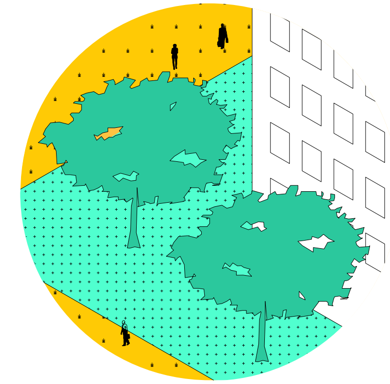
Implementation should be aided by the development of building codes and energy efficiency guidelines. Green walls/façades can be developed both in public and private buildings.

State of the art

The benefits of green walls/façades have been reported in different studies. A reduction of 6.2 per cent in energy consumption was reported by Pan and Xiao (2014), but this could be doubled in tropical climates. During high outdoor temperatures, indoor temperatures can be mitigated between 3-5°C using this measure, thus improving indoor thermal comfort. Pan and Xiao (2014) also estimated that outdoor temperature close to the façade could be reduced between 0.5-4°C. The benefits in terms of cooling and thermal isolation, reduction of energy consumption, mitigation of UHI and improvement of thermal comfort can be relevant.

PLANTING GREENERIES

VEGETATION AROUND BUILDINGS



Arranging adequate vegetation elements around buildings can provide shade to pedestrians, building and ground surfaces. The effect can vary depending on the vegetation coverage, size and distribution.

UHI & OTC effect

Vegetation can absorb the incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shadowing, especially trees. Similar to green façade, the reduction of solar radiation (shade) in buildings will reduce the energy demand for indoor cooling.

Tropical climate

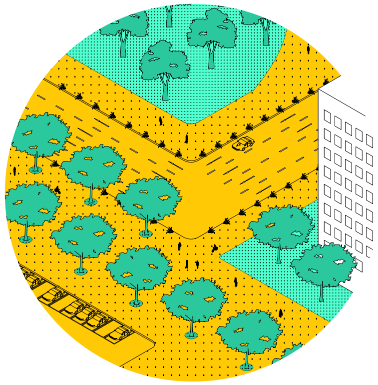
It is an interesting mitigation measure since reducing direct exposure to sun radiation is one of the most beneficial actions to improve OTC in Singapore.

Urban planning

In planning, it is required that urban design considers carefully the exposure of buildings to direct solar radiation. On the whole, urban design needs to look for thermal pleasure by developing an urban asymmetrical thermal environment dominated by cool spots in urban spaces (Emmanuel 2016) and at the same time enabling low-energy cooling within indoors (Kikegawa et al. 2006) that depend on the building structure (Castleton et al. 2010).

State of the art

Gillner et al. (2015) estimated that tree-shadowed streets could reduce the air temperature between 0.9-2.6°C. The highest benefit of the shadow provided by trees is improving local thermal comfort during daytime (Shashua-Bar et al. 2012), especially in tropical and subtropical areas.



PLANTING GREENERIES
SELECTIVE PLANTING

Planting vegetation in selective areas can provide beneficial shade but also obstruct the wind flow. This measure concerns choosing the more effective vegetation species as well as the optimal orientation and arrangement.

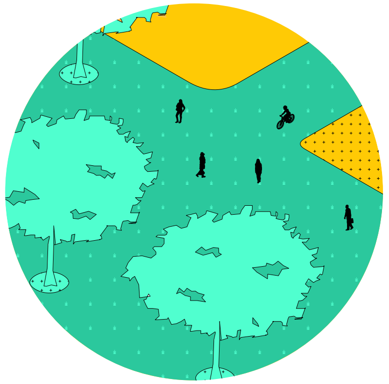
UHI & OTC effect
Vegetation allows for the following: a reduction in urban heat accumulation; shadowing that increases pedestrian thermal comfort; and reduction in building energy consumption. Combination of the different types of vegetation species and the way they are arranged can improve the thermal performance of the surrounding considering their ability to influence the urban energy balance.

Tropical climate
This measure is relevant for application in Singapore because of the high growth of vegetation in the humid tropic.

Urban planning
Implementation should be aided by the development of building codes and energy efficiency guidelines. New development or retrofit should consider the disposal of vegetation in a way that can provide the highest environmental benefits. The selection of species should factor in their adaptation to the tropical climate in Singapore. In any case, any urban greening programme implemented would need to be appropriately designed to get the most benefit out of reducing temperature (Bowler et al. 2010).

State of the art
The disposal of vegetation (for example, individual, linear, group, surface plantation) and the species characteristics have significant influence on reducing temperature. Species differ significantly in their ability to reduce air and surface temperatures as well as to increase relative humidity. Trees showing both a high leaf-area density and a high rate of transpiration are more effective in cooling the air temperature. Differences in the surface temperatures of the tree shaded areas are more pronounced compared to the air temperatures of sunlight exposed areas (Gillner et al. 2015). In this sense, a combination of different vegetation elements seems beneficial for outdoor thermal comfort.

PLANTING GREENERIES
GREEN PAVEMENTS



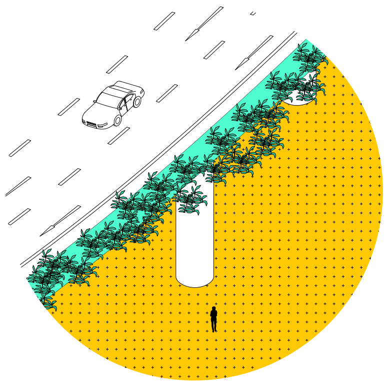
This measure reduces the amount of artificial material on urban pavements with the replacement of natural soil elements with grass. But it can also be installed by using permeable pavers, pervious concrete or porous asphalt in order to increase the permeability of the pavement.

UHI & OTC effect
Any urban greening programme implemented would need to be appropriately designed to achieve the full benefit of reducing temperature (Bowler et al. 2010).
It allows for the reduction of urban heat accumulation by decreasing pavement temperature, thus influencing pedestrians' thermal comfort and to a large extent the UHI.

Tropical climate
This strategy has special interest for application in Singapore because greenery there develops with little maintenance due to the sufficient access to water.

Urban planning
Implementation should be focused on areas/pavements with little shadowing (low-rise building development, for example) because the accumulation of heat can rise in pavements under these conditions.

State of the art
Urban pavements are generally made of materials that can reach peak summertime temperatures of 50-70°C. The use of grass pavement or other cool materials can reduce the UHI significantly (Flower et al. 2010) because nearly 30-45 per cent of urban areas is covered by pavements.



PLANTING GREENERIES

INFRASTRUCTURE GREENERY

This measure covers elements that are not part of natural growing vegetation. Greenery can be added on existing infrastructure such as bridges, tunnels, highways and bus stations.

UHI & OTC effect
It allows for the reduction of the urban heat accumulation by decreasing surface temperature, and thus influencing pedestrians' thermal comfort.

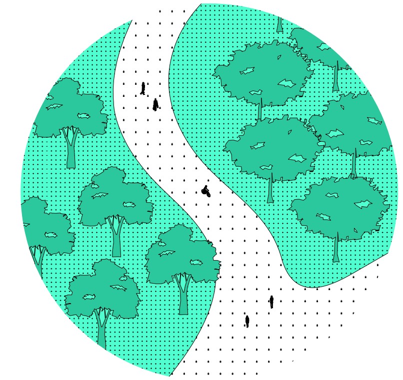
Tropical climate
Although design with greenery is generally considered to be a good strategy, shadowing green elements would be even more beneficial to improve outdoor thermal comfort.

Urban planning
Implementation should be focused on areas/pavements with little shadowing (low rise building developments) because the accumulation of heat can rise in pavements with these conditions. Additionally, the development of small green urban areas that are located strategically or grouped around buildings should be encouraged. These are more easily implemented when retrofitting in comparison with the development of big urban parks inside urban areas (Wong and Chen 2009).

State of the art
Greenery does not only have positive effects on thermal comfort (Tallis et al. 2015), it also removes air pollutants and gives positive psychological effects. In this sense, during heat stress periods, Lafortezza et al. (2009) found that urban vegetation provided people the perception of well-being.

PARKS AND OPEN SPACES

MACROSCALE URBAN GREENING



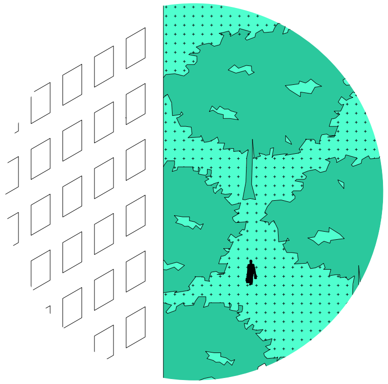
Macro scale urban greening concerns the large-scale increase of the presence of vegetation in urban areas focusing on big urban parks, forests and natural reservoirs. They can be located at the edge or in central areas of the city with different effects in the local climate. They are also called 'cold islands'.

UHI & OTC effect
Areas like forests and green belts do not only assure a better thermal perception inside them, but can also provide coolness to nearby urban areas, thus helping to regulate the accumulation of heat in the whole urban area.

Tropical climate
This measure could be more of interest in dry tropical climates where the effects of reduced heat accumulation and the provision of fresh air into the city can always help improve OTC and reduce UHI. In this sense, in humid tropical areas, this measure can be considered low cost, considering the potential growth of vegetation and the low irrigation needs for maintenance as compared to those in non-humid areas.

Urban planning
Implementation of macroscale urban greening should be considered carefully and in relation to general climate patterns (such as wind pattern) to maximise the cooling benefits that could extend to the entire urban area. The collaboration among several ministries is crucial for the successful implementation of urban greening on a large scale.

State of the art
The cooling effect of vegetation on the urban surface temperature and air temperature is mainly determined by the species group, canopy cover, size and shapes of the parks (Feyisa et al. 2014). An experimental study by Lin and Lin (2010) also indicated that the cooling efficiency of urban parks is mostly influenced by leaf colour and foliage density. In any case, the generalisation of the cooling effects of big parks is difficult since it depends on the biophysical characteristics of vegetation in relation to the regional climate. However, the benefits of big urban green areas have been determined (Rosenzweig et al. 2006) and the temperature difference between urban and park areas has been found to be from 1.5-4°C (Jonsson 2004).



PARKS AND OPEN SPACES

LOCAL URBAN GREENING

Local urban greening involves the increase of the presence of midsize parks inside the urban area to provide areas of thermal comfort for leisure and recreation. They are commonly located close to residential areas or along sea shores with a compact or linear shape.

UHI & OTC effect
Urban greening in local contexts are expected to provide thermal comfort within them, but little effect is expected far away from their boundaries. The combination of vegetation, shadowing and adequate ventilation can increase significantly the outdoor thermal comfort with respect to the nearby artificialised area.

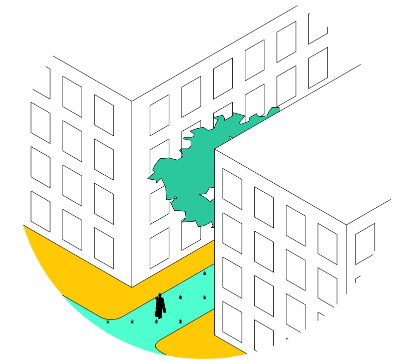
Tropical climate
Similar to other vegetation strategies, the shadowing effect of local urban greening can be used with clear benefits in thermal comfort. In humid tropics mostly all year through, the vegetation is in suitable condition to provide benefits of thermal comfort.

Urban planning
The implementation of local urban greening should be carefully considered and in relation to the urban extension. These areas should be considered as providing thermal comfort inside them. They could be developed within specific urban development guidelines that enforce their presence in every new planning/project.

State of the art
The performance of these parks is similar to big nature parks, but their effects are expected to be more localised. Numerous studies have proven their benefits (Robitu et al. 2006; Feyisa et al. 2014; Klemm et al. 2015).

PARKS AND OPEN SPACES

MICROSCALE URBAN GREENING



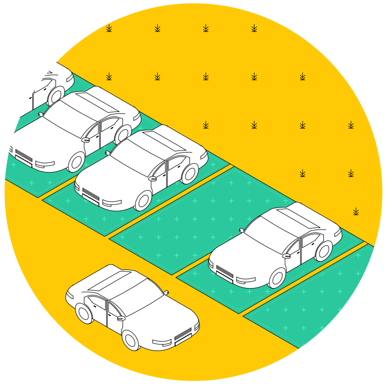
Microscale urban greening can be used to increase small vegetation presence inside the urban area. In addition to having vegetation around buildings, other uses can be pocket parks and green courtyards.

UHI & OTC effect
Despite the benefits on OTC can only occur in a small area when implemented adequately and/or interconnecting different microscale greening along the city, the effects on UHI could actually increase.

Tropical climate
Similar to other vegetation measures, the shadowing factor presents clear benefits in improving OTC. Additionally, it can prevent the overheating of surface materials.

Urban planning
There can be two kinds of implementation: first, in developed areas where urban retrofitting is possible to improve the thermal comfort along pedestrian paths and in other pedestrian areas; second, in new urban areas to interconnect parks and bigger vegetation areas to create suitable thermal comfort pathways along the whole urban area.

State of the art
A study compared two streets in Rio De Janeiro, Brazil where one had aligned trees and the other no trees. The results showed that 69 per cent of the people surveyed had a neutral thermal sensation on the street with trees while fewer people (18 per cent) experienced the same sensation on the street without trees (Drach et al. 2014). The finding was that the number of people with discomfort increased significantly on the street without trees and vegetation (microscale greenery).



PARKS AND OPEN SPACES

GREEN PARKING LOTS

This concerns reducing the amount of artificial material in parking lots while substituting them with ground vegetation (natural soil and grass) and/or trees and other vegetative infrastructure.

UHI & OTC effect
The use of vegetative elements and/or soils with higher albedo has the effect of reducing the urban heat accumulation compared to conventional dark asphalt at parking lots. By decreasing the pavement temperature and extending the use of tree shadows, the heat accumulated by the cars can also be reduced.

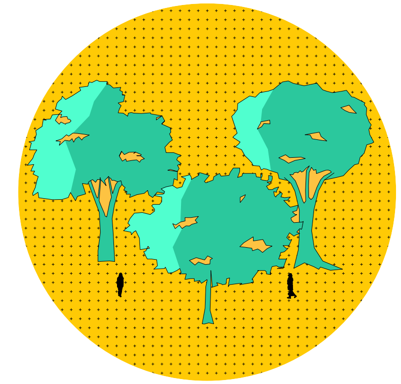
Tropical climate
This measure has special interest for application in Singapore because of the elevated position of the sun along the year, and the high growth of vegetation in humid tropics.

Urban planning
Implementation should be focused on parking lots with little shadowing (low-rise building developments) where heat accumulation could be higher.

State of the art
Urban pavement and parking lots have traditionally been using asphalt -- a dark, heat absorbing material (Gibbons 1999). However, new green parking lots are being developed worldwide with better thermal performance regarding accumulation of heat and environmental benefits.

PARKS AND OPEN SPACES

TREE SPECIES



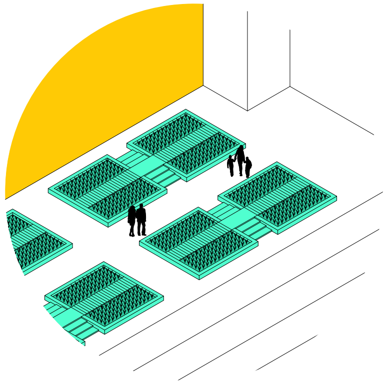
The selection of adequate species should be related to environmental tolerances, functional requirements, and urban design requirements in order for trees to obtain the best results for generating outdoor thermal comfort. For the environmental tolerance, aspects like climate, geology and topography have to be taken into consideration. For the functional requirements, criteria such as leave density, maintenance and availability are key. Urban design requirements include the relation to the existing or planned landscape, size and form of tree canopy.

UHI & OTC effect
Different positive effects on heat accumulation and OTC can be achieved depending on not only the number of trees per square meter, but also their typology, size and adaptation to tropical areas. The previous mitigation measures have shown that trees can benefit the urban climate, but with varying results depending on how they are conditioned by their location and also by their actual characteristics.

Tropical climate
This is an important mitigation measure since reducing the direct exposure to sun radiation through the adequate selection of trees species is one of the most beneficial actions to improving thermal comfort in Singapore. Additionally, the high growth of vegetation in humid tropics should be exploited while determining the tree characteristics (height, width, crown, leaf size) to the expected thermal performance.

Urban planning
It is required that urban design takes into careful consideration the exposure to direct solar radiation. On the whole, the aim is to look for thermal pleasure by developing an urban asymmetrical thermal environment dominated by cool spots in urban spaces (Emmanuel 2016) and also enabling low-energy cooling indoors.

State of the art
An experimental study by Lin and Lin (2010) indicated that the cooling efficiency of trees in parks was mostly influenced by leaf colour and foliage density. Additionally, the cooling potential of trees can be conditioned by the temperature of their foliage, which is related to their access to water. Street trees can be an average of 1°C hotter than park trees due to the exposure of street trees to radiation reflected and emitted by surrounding urban structures. Also trees with smaller leaves generally have lower crown temperatures than those with larger leaves (Leuzinger et al. 2010). Thus, not only the location inside the urban area but also tree characteristics determine the background meteorological conditions including temperature (Tallis et al. 2015) and local thermal comfort.



PARKS AND OPEN SPACES

URBAN FARMING

Urban farms concern the practice of growing or producing food within urban areas. It can be installed in under-utilised urban spaces including rooftops, abandoned buildings and vacant lots. Urban agriculture has different climatic opportunities and constraints compared to rural agriculture that need to be understood.

UHI & OTC effect
Urban farms can serve as green islands within the urban landscape that can offer shade and protect impervious surfaces from the effects of solar radiation. Like other urban greenery, urban farms can produce similar local thermal comfort benefits and if highly extended to a relevant part of the urban area, it can lower the UHI effect and thus reduce building energy consumption for cooling.

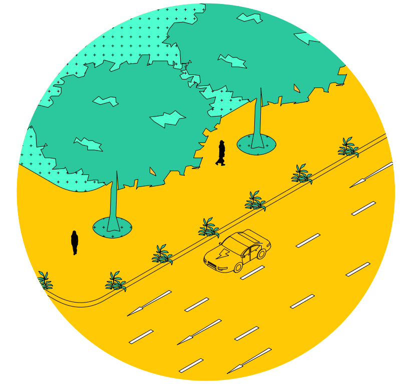
Tropical climate
The climate in Singapore is conducive to integrating urban farming within urban areas due to the frequent rain precipitation. This makes water access possible, which makes the implementation affordable, possibly even more effective than in other regions of the world.

Urban planning
Urban farming presents many benefits and opportunities, particularly to Singapore. It helps to green the city, increase the amount of food grown and produced locally, thus preventing CO2 emissions in food transport from distant producers, and improving food security for this land-scarce island city. Suitable building codes, guidelines for new/retrofit areas and/or economic policy can help develop green farming spaces.

State of the art
The thermal comfort and UHI benefits of urban farming could be similar to other mitigation measures based on the extension of vegetation elements inside the urban area. Additionally, the production of crops could be likely supported in cities with appropriate microclimate combined with UHI effects that would not grow successfully if these extra warming would not occur (Waffle et al. 2017).

GREEN CORRIDORS

TRANSPORT CORRIDORS



The vegetation arrangement along transport corridors can provide shade to the infrastructure surface. The effect can vary depending on the vegetation density, height and species. But it is also key to combine the reduction on incoming solar radiation with the natural ventilation capacity of these spaces.

UHI & OTC effect
Vegetation can absorb incoming solar radiation and thus reduce heat accumulation in urban materials. At the same time, it provides shadowing (in the case of trees). Thus, considering local pedestrian OTC, an increase in the number of trees makes sense. However, transport corridors are often open spaces that can be used as ventilation paths to introduce fresh air into the urban area and/or help remove the accumulation of heat. Thus, these transport corridors should be carefully designed with respect to UHI and OTC.

Tropical climate
Adequate use of transport corridors can be useful in reducing the heat trapped in the urban surfaces in the whole urbanised area of Singapore.

Urban planning
In planning for arranging vegetation along transport corridors, the exposure to direct solar radiation and wind enhancement should be considered carefully. A combination of different heights of vegetation elements together with their strategic location can allow for suitable airflow inside the transport corridor and thus pose higher benefits for this mitigation measure. These planted trees along ventilation areas should not form dense windbreaks.

State of the art
It is important to be aware that good ventilation leads to positive effects in terms of temperature and air quality (Ng and Ren 2015). Additionally, cooler surfaces with low roughness such as grass may allow air to move gently along corridors, thus avoiding turbulent vertical air movements produced by hot surfaces.

REFERENCES

Bowler, D.E., Buyung-ali, L., Knight, T.M., Pullin, A.S. (2010). 'Urban greening to cool towns and cities: A systematic review of the empirical evidence', Landscape and Urban Planning, 97(3): 147–155. doi: 10.1016/j.landurbplan.2010.05.006.

Castleton, H.F., Stovin, V., Beck, S.B.M., Davison, J.B. (2010). 'Green roofs; Building energy savings and the potential for retrofit', Energy and Buildings, 42(10): 1582–1591. doi: 10.1016/j.enbuild.2010.05.004.

Drach, P.R.C., Barbosa, G.S., Corbella, O.D. (2014). Densification Process of Copacabana Neighbourhood over 1930, 1950 and 2010 Decades: Comfort Indexes. paper presented at UH2UHI: 3rd Intl. Conference on Countermeasures to Urban Heat Island, Venice, 1–12.

Emmanuel, R. (ed) (2016). Urban Climate Challenges in the Tropics: Rethinking Planning and Design Opportunities. London: Imperial College Press.

Feyisa, G.L., Dons, K., Meilby, H. (2014). 'Efficiency of parks in mitigating urban heat island effect: An example from Addis Ababa'. Landscape and Urban Planning, 123: 87–95. doi: 10.1016/j.landurbplan.2013.12.008.

Flower, W., Burian, S.J., Pomero,y C.A., Pardyjak, E.R. (2010). 'Surface Temperature and Heat Exchange Differences between Pervious Concrete and Traditional Concrete and Asphalt Pavements', paper presented at Low Impact Development International Conference (LID), VA, 1417–1430.

Gibbons, B. J. (1999). Parking Lots. Haddam: University of Connecticut.

Gillner, S., Vogt, J., Tharang, A., et al. (2015). 'Role of street trees in mitigating effects of heat and drought at highly sealed urban sites', Landscape and Urban Planning, 143: 33–42. doi: 10.1016/j.landurbplan.2015.06.005.

Jonsson, P. (2004). 'Vegetation as an urban climate control in the subtropical city of Gaborone, Botswana', Intl. Journal of Climatology, 24(10): 1307–1322. doi: 10.1002/joc.1064.

Kikegawa, Y., Genchi, Y., Kondo, H., Hanaki, K. (2006). 'Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning', Applied Energy 83(6): 649–668. doi: 10.1016/j.apenergy.2005.06.001.

Klemm, W., Heusinkveld, B.G., Lenzholzer, S., et al. (2015). 'Psychological and physical impact of urban green spaces on outdoor thermal comfort during summertime in The Netherlands', Building and Environment, 83: 120–128. doi: 10.1016/j.buildenv.2014.05.013.

Lafortezza, R., Carrus, G., Sanesi, G., Davies, C. (2009). 'Benefits and well-being perceived by people visiting green spaces in periods of heat stress'. Urban Forestry & Urban Greening, 8(2): 97–108. doi: 10.1016/j.ufug.2009.02.003.

Leuzinger, S., Vogt, R., Körner, C. (2010). 'Tree surface temperature in an urban environment', Agricultural and Forest Meteorology, 150(1): 56–62. doi: 10.1016/j.agrformet.2009.08.006.

Lin, B.S., Lin, Y.J. (2010). 'Cooling effect of shade trees with different characteristics in a subtropical urban park', HortScience, 45: 83–86.

Ng, E., Ren, C. (eds) (2015). The Urban Climatic Map for Sustainable Urban Planning. London and New York: Routledge.

Pan, X.C., Xiao, Y.X. (2014). 'Simulation Analysis of Building Green Facade Eco-Effect', Applied Mechanics and Materials, 548–549: 1701–1705. doi: 10.4028/www.scientific.net/AMM.548-549.1701.

Peng, L., Jim, C. (2013). 'Green-Roof Effects on Neighborhood Microclimate and Human Thermal Sensation', Energies 6(2): 598–618. doi: 10.3390/en6020598.

Pérez, G., Coma, J., Martorell, I,. Cabeza, L.F. (2014). 'Vertical Greenery Systems (VGS) for energy saving in buildings: A review', Renewable and Sustainable Energy Reviews, 39: 139–165. doi: 10.1016/j.rser.2014.07.055.

Refahi, A.H., Talkhabi, H. (2015). 'Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs', Renewable Energy, 80: 595–603. doi: 10.1016/j.renene.2015.02.030.

Robitu, M., Musy, M., Inard, C., Groleau, D. (2006). 'Modeling the influence of vegetation and water pond on urban microclimate'. Solar Energy 80(4): 435–447. doi: 10.1016/j.solener.2005.06.015.

Rosenzweig, C., Solecki, W., Slosberg, R. (2006). 'Mitigating New York City's heat island with urban forestry, living roofs, and light surfaces'. presented at 86th AMS Annual Meeting, Atlanta.

Shashua-Bar, L., Tsiros, I.X., Hoffman, M. (2012). 'Passive cooling design options to ameliorate thermal comfort in urban streets of a Mediterranean climate (Athens) under hot summer conditions', Building and Environment, 57: 110–119. doi: 10.1016/j.buildenv.2012.04.019.

Tallis, M.J., Amorim, J.H., Calfapietra, C., et al. (2015). 'The impacts of green infrastructure on air quality and temperature', Handbook on Green Infrastructure. Edward Elgar Publishing, 30–49.

Waffle, A.D., Corry, R.C., Gillespie, T.J., Brown, R.D. (2017). 'Urban heat islands as agricultural opportunities: An innovative approach', Landscape and Urban Planning, 161: 103-114. doi: 10.1016/j.landurbplan.2017.01.010.

Wong, N.H., Chen, Y. (2009). 'Tropical Urban Heat Islands - Climate Buildings and Greenery', Intl. Journal of Ventilation, 7(4): 379–380. doi:10.1080/14733315.2009.11683826.

Wong, N.H., Tan, A.Y.K., Tan, P.Y., Wong, N.C. (2009). 'Energy simulation of vertical greenery systems', Energy and Building, 41(2): 1401–1408. doi: 10.1016/j.enbuild.2009.08.010.

002 URBAN GEOMETRY

URBAN GEOMETRY

Urban geometry can provide numerous opportunities in promoting liveable environments and can be effective in getting the most out of natural effects/elements to counter UHI and promote OTC. The building layout, the location of urban elements, the building height and geometry are variables that condition the thermal performance of the urban area. The arrangement of these elements affects the spatial coverage of the shadowed areas as well as the wind environment. These two aspects are the more important ones to improve OTC locally. Additionally, at coarser spatial scale, adequate urban planning is crucial to take advantage of the regional climate and air flow, develop suitable air paths that enter the urban area and remove the accumulated urban heat.

Typical mean daytime temperatures are 28˚C reaching mean maximum values of 30-31˚C. During the night, the mean values can drop to 26˚C with mean minimum vales of 23-24˚C. Singapore has generally low winds due to its geographical location near the equator. These conditions are near the human discomfort range. However, the presence of the surrounding sea air generates local to regional wind circulation patterns that can bring cool air into the city and improve thermal comfort. Thus, it is relevant that urban planning considers regional climate characteristics and enhances air movement in between buildings through suitable urban design of street canyons and building geometry. The wind environment should be considered adequately together with the shade provided by buildings since both aspects influence thermal comfort. In this sense, in Singapore, narrow streets and high buildings have been tested to provide benefits on local thermal comfort due to shading.

The Urban Geometry category has been divided into three sub-categories: Geometry of Urban Canyons, Breezeways and Surface Coverage. The first sub-category deals with the building form and the characteristics of the urban canyons. The second sub-category focuses on the arrangement of buildings and other elements in the urban fabric regarding their effect on air flow at the surface level. Finally, the last sub-category describes the effect of varying the proportion of elements inside the urban area.

Juan Angel Acero, Lea A. Ruefenacht & Muhammad Omer Mughal
Cooling Singapore Researchers

GEOMETRY OF URBAN CANYON

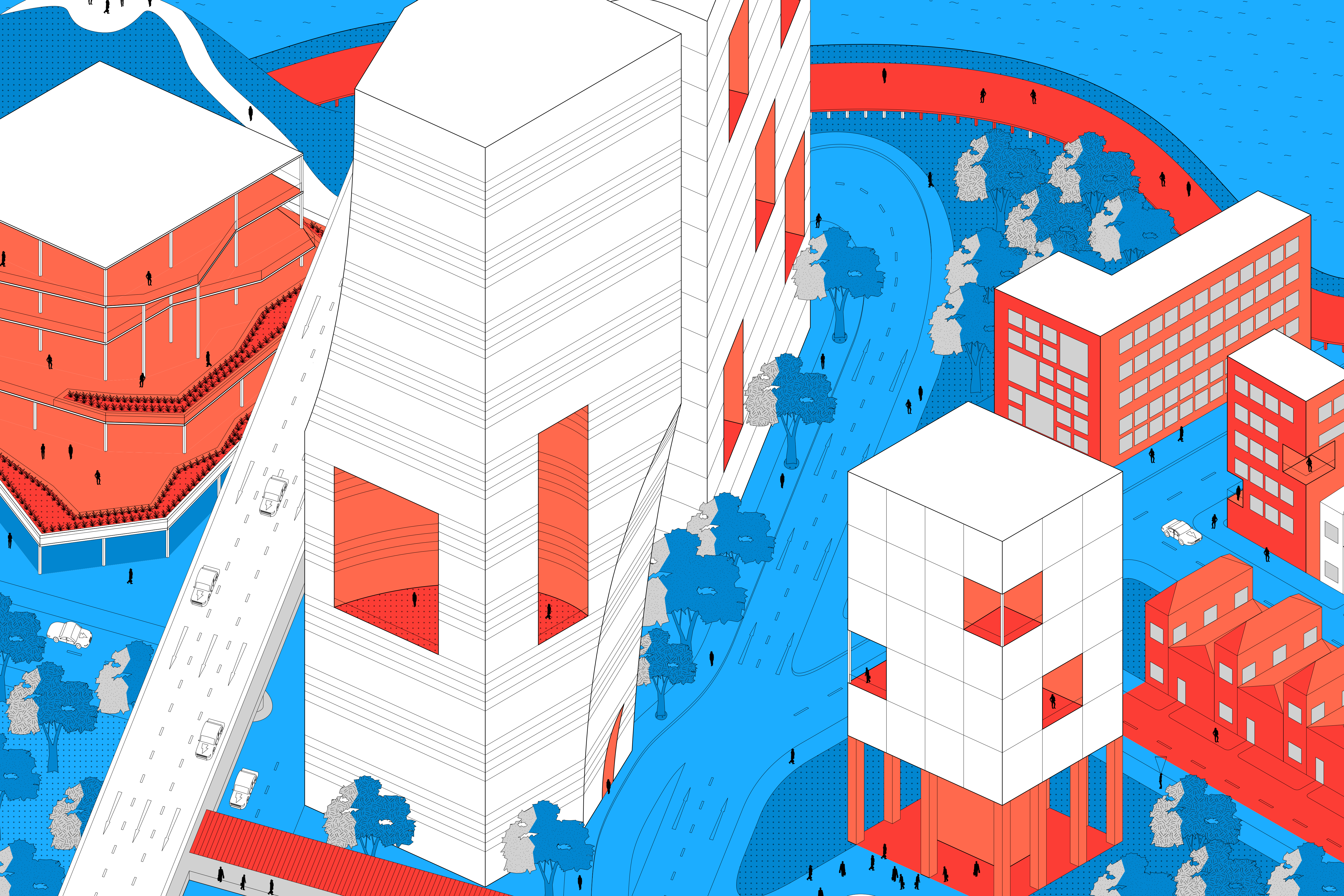
Sky view factor
Aspect ratio
Mean building/tree height
Building form
Variation between building heights
Wider streets

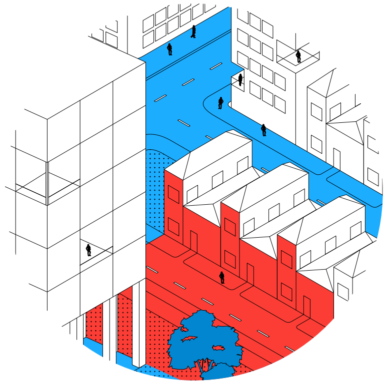
BREEZEWAY

Avoid obstruction
Open spaces along sea shore
Building porosity
Street axes orientation
Well-ventilated sidewalks
Building arrangement
Open spaces at road junctions
Guide wind flows with urban elements
Passive cooling systems

SURFACE COVERAGE

Urban density by Local Climate Zones
Building Surface Fraction
Green Plot Ratio
Topography





GEOMETRY OF URBAN CANYON
SKY VIEW FACTOR

The sky view factor (SVF) is defined as the ratio of the radiation received by a planar surface to the radiation emitted by the entire hemispheric environment. It is calculated as the fraction of sky visible from the ground. SVF is a dimensionless value that ranges from 0 to 1. For instance, an SVF of 1 means that the sky is completely visible and there are no obstacles around.

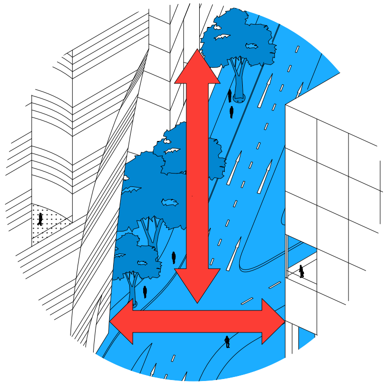
UHI & OTC effect
SVF conditions the amount of radiation received at the ground level during daytime (e.g. solar radiation) as well as the release of accumulated urban heat during the night (e.g. nocturnal cooling). Lower SVF can provide more shadow inside the street canyon during daytime and thus curtail the rise of ground temperature. However, trapping of the outgoing radiation during night-time can occur and thus the decrease of ground temperature will be lower during this time. Lower SVF can worsen the UHI during night-time but improve OTC during daytime due to shade provided by urban elements. SVF also has a relevant influence on lowering surface temperature and thus reducing building energy consumption.

Tropical climate
This is relevant for Singapore due to its tropical climate and the necessity of shade to improve thermal comfort and reduce significantly building cooling energy demand.

Urban planning
Implementation should be aided by the development of building codes and energy efficiency guidelines to ensure that solar heat gain is reduced. However, this should be balanced with indoor artificial light demand, which also requires significant amount of energy.

State of the art
Studies have proven the effects that condition outdoor thermal comfort levels depending on the SVF. From a city planning perspective, Ketterer and Matzarakis (2014) stated the need to focus on the analysis of UHIs and intra-urban air temperature differences. At Malaysia's new federal administrative capital, high temperatures were evaluated that have the effect of increasing human heat stress and thermal discomfort. The capital suffers from high surface and air temperatures during the day due to the orientation of streets and buildings, the low aspect ratio and the wide SVF (Qaid and Ossen 2015).

GEOMETRY OF URBAN CANYON
ASPECT RATIO



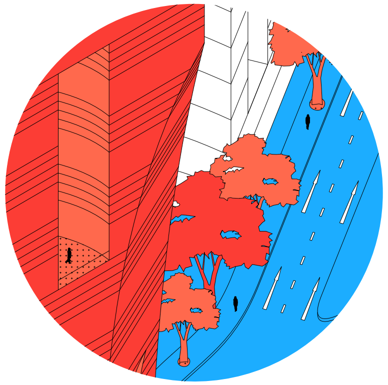
Aspect ratio (H/W) is the most important geometrical characteristic of a street canyon and is defined as the ratio of the canyon height (H) to the canyon width (W). It is usually calculated by dividing the mean height of buildings by the width of the street.

UHI & OTC effect
Similar to the Sky View Factor (SVF), aspect ratio conditions the incoming and outgoing radiation and thus the energy heat flux at the lowest level of a street canyon. The combination of low buildings and wide streets (or lower aspect ratio) can increase the entrance of wind flowing above the buildings and thus help remove urban accumulated heat and air pollutants. Such street canyons can also improve the nocturnal cooling of the ground surface. On the other hand, urban canyons with high aspect ratio can provide more shade during daytime and thus improve thermal comfort and reduce building energy consumption.

Tropical climate
This strategy is applicable for Singapore due to its high solar radiation and high urban density. Another relevant factor is that there is very little seasonal variation offering similar climatic conditions all-year long.

Urban planning
This measure can be combined with others such as passive design techniques for lasting comfort. It is important to evaluate the different options of the urban canyon aspect ratio to find the best fit that provides shading and increases wind flows. According to Mesa et al. (2011), the optimum ratio of the distance between buildings and the building height is between 2 and 3 (aspect ratio 1). The resulting aspect ratio may also affect the intensity and quality level of natural illumination reaching indoor spaces.

State of the art
Qaid and Ossen (2015) have investigated the different street aspect ratios in Malaysia to improve the day microclimatic conditions and mitigate the night-time UHI. The results showed that different air temperatures at ground level in streets with different aspect ratio could be reached by capturing wind and providing shadows. Temperature difference between streets could reach as high as 4.7 ˚C. For Old Town of Camagüey-Cuba, a hot-humid climate, aspect ratios between 1 and 1.5 offered a quite acceptable thermal performance for summer and winter (Rodríguez Algeciras et al. 2016). Also, a study showed that the geometry of urban canyons can reduce the total energy consumption by up to 30 per cent in commercial buildings and 19 per cent in residential buildings (Gago et al 2013).



GEOMETRY OF URBAN CANYON

MEAN BUILDING/TREE HEIGHT

The relation between building and tree height will condition the amount of façade that is shaded by the trees and thus control the overheating of its surface.

UHI & OTC effect
Trees reduce direct solar insolation thereby decreasing the surface temperature, both of building façades and in the tree surroundings. This way a reduction in UHI and an increase in local thermal comfort is expected together with benefits of indoor cooling energy demand.

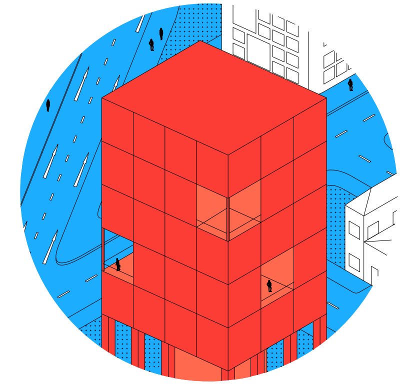
Tropical climate
The combination of greenery shade in relation to building geometry is considered to provide the best benefits in tropical areas because the regional air temperature and levels of humidity are already high next to the thermal discomfort levels.

Urban planning
Implementation should be aided by the development of building codes and energy efficiency guidelines. Adequate tree heights should be implemented in each area and other issues such as natural lighting should be considered.

State of the art
Trees are considered suitable passive elements that help improve not only outdoor thermal comfort but also indoors. The average transmissivity of direct solar radiation through the foliated and defoliated tree crowns was estimated to range from 1.3 to 5.3 per cent and from 40.2 to 51.9 per cent respectively (Konarska et al. 2014). In his study based on measurements, Morakinyo et al. (2013) found that in comparison with a shaded building, an unshaded building had higher indoor air temperatures and these remained as such for a longer time. Indoor–outdoor temperature differences showed a peak of 5.4 °C for the unshaded building while the tree-shaded building did not exceed 2.4 °C.

GEOMETRY OF URBAN CANYON

BUILDING FORM



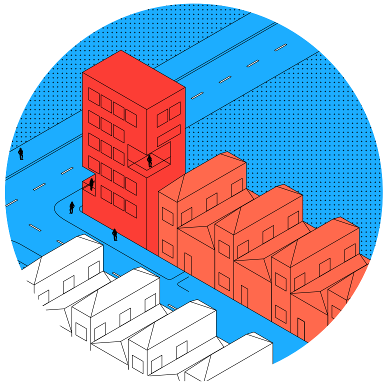
Building form refers to the geometrical configuration and shape of a building or of multiple buildings. It can be linear, block or isolated punctual, and can be arranged in many different combinations.

UHI & OTC effect
The building form in combination with the arrangements of neighbouring buildings can contribute significantly to the formation of wind streams and the removal of urban heat accumulation through ventilation. Depending on the building form, it can also provide shade to itself or to its urban context and thus influence the energy consumption, reduce CO_2 emission and improve OTC.

Tropical climate
This strategy can have a positive effect in tropical countries such as Singapore, where solar radiation during the day is extremely high. It can provide additional benefits if the building form is combined with other mitigation measures related to suitable building arrangements and urban greenery.

Urban planning
It is important that urban design considers the different options regarding building layout and façade orientation. The building form should be defined in relation to the direct solar radiation and thus shade the façades that are mainly exposed to the sun. This way, higher indoor and outdoor comfort can be achieved, plus indoor energy demand can be reduced. This is essential in deciding the layout of buildings and the internal distribution in relation to the different occupation times during the day.

State of the art
Cheng et al. (2006) evaluated 18 different combinations of building forms (different horizontal and vertical layouts, either uniform or random) and density (in relation to plot ratio and site coverage). The best fit was the one with horizontal layout, vertical randomness, and low site coverage. Also, Wong et al. (2016) showed that the indoor air temperature was conditioned by the outdoor wind speed and thus by the building geometric form. A similar work considering natural indoor ventilation was performed by Sujatmiko et al. (2015) resulting in an improvement in thermal comfort. Anand et al. (2017) analysed the use of different rooms inside a building and arrived at different levels of thermal comfort requirements for each room.



GEOMETRY OF URBAN CANYON

VARIATION BETWEEN BUILDING HEIGHTS

The act of varying between different building heights and building forms (e.g. stepping building heights or podium structures) can improve wind capture with benefits of OTC.

UHI & OTC effect
Wind speed varies with altitude that increases its intensity exponentially. Local OTC can be enhanced by adequate air movement. In this sense, the variation between low- and high-rise buildings allows for increasing wind velocity due to the air dynamics between buildings.

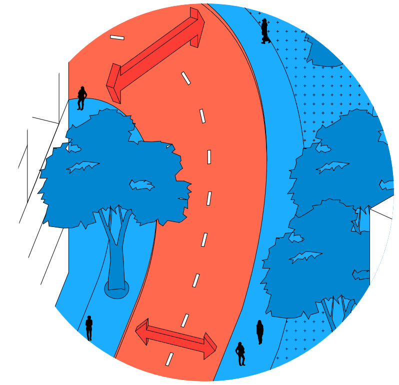
Tropical climate
While shading is a relevant feature to use for improving thermal comfort in Singapore, it is also relevant to capture and increase wind speed in certain areas.

Urban planning
New development or building retrofit should consider arranging buildings according to ascending heights with respect to wind direction to allow adequate wind to reach the rear blocks. An option would be to stagger building heights and void decks to increase the airflow. Also, downwash wind (bring upper wind to the ground level) triggered by the building geometry and layout allows for the ventilation of streets and generates air movement into the buildings.

State of the art
Ali-Toudert and Mayer (2007) showed that the use of asymmetrical canyon shapes and the use of galleries can have a strong effect on thermal comfort due to the variation of wind speed. A terrace podium was recommended for Hong Kong to enhance the air movement at pedestrian level (Ng 2009).

GEOMETRY OF URBAN CANYON

WIDER STREETS



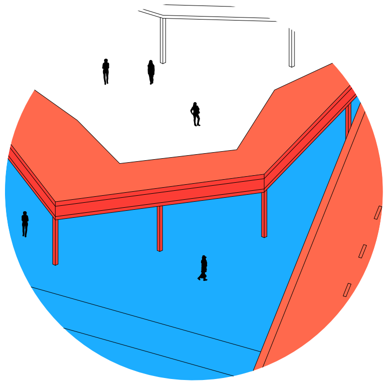
By widening the streets, the exchange of air inside the street canyons can be generated and increased at the same time. Allowing more air to come in creates effective wind corridors in the dense urban fabric.

UHI & OTC effect
The higher the air movement inside a street canyon, the higher the release of urban heat accumulation that will happen, thus reducing the UHI effect and building energy demand. Additionally, it permits a higher influence of non-urban breezes in the inner part of the city. Of course, OTC can improve locally with increasing wind speed and air pollutants will have better dispersion conditions.

Tropical climate
This strategy is applicable to the island city of Singapore because local to regional breezes occur frequently, including sea-breeze. In any case, wind corridors from the rural area to the inner part of urban area are always beneficial together with improving the air exchange inside the street canyons with air flowing above the buildings. However, increasing street width will reduce shadowing, which is a relevant aspect for thermal comfort and energy consumption in Singapore.

Urban planning
The implementation of street widening should be carried out in new developments with the help of building codes and urban design guidelines. Void decks at the ground floor of buildings or at different levels such as sky gardens can also increase the building permeability, in case streets are not wide enough and thus encourage the air flow through and around the buildings.

State of the art
Rizwan et al. (2010) demonstrated by modelling that air temperatures rose as high as 1.3 °C when ambient wind speed decreased from 4 m/s to 0.5 m/s. Additionally, Abreu-Harbich et al. (2014) showed that urban design parameters such as width modifies thermal conditions inside the street canyon. The findings also revealed that wide street canyons require greenery to promote shade on pedestrian areas and on façades, and to mitigate bioclimatic thermal stress.



BREEZEWAY
AVOID OBSTRUCTION

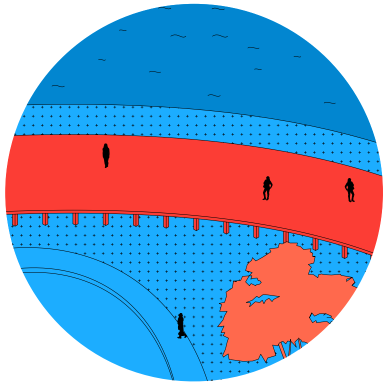
Obstructing the breezeway with buildings or other urban elements can block most of the wind to pedestrians thus affecting comfort and air quality. It can also minimise the air volume near the pedestrian level, which affects air quality. The effect of building layout, especially in terms of building site coverage, has a greater impact than building height on pedestrian wind environment.

UHI & OTC effect
Any obstruction or stagnation of natural air movement might lead to a decrease in OTC and an increase in UHI. To maximise the wind availability to pedestrians, towers should preferably be adjacent to the podium edge that faces the main pedestrian area/street so as to enable most of the downwash wind to reach the street level.

Tropical climate
The average wind speed in Singapore during the Northeast and Southwest monsoon periods ranges from 0 to 3 m/s and 0 to 2.5 m/s respectively. In these considerably low mean wind speeds, avoiding obstruction and stagnation of air should be a priority.

Urban planning
The obstructions can be avoided by stepping building heights in rows so as to create better wind at higher levels. Adopting a terraced podium design to direct downward airflow can help enhance the air movement at the pedestrian level and disperse the pollutants emitted by vehicles. Another option could be to align streets in parallel or up to 30˚ to the prevailing wind direction in an array of streets to maximise the penetration of wind through the district. Also aligning the longer frontage of building plots in parallel to the wind direction and introducing non-building areas and setbacks are appropriate measures.

State of the art
A study in Hong Kong (Ng et al. 2011) showed that the breezeways should be designed to avoid obstructions and aligned primarily along the prevailing wind direction routes, and as far as possible, preserve all natural air flows into the developed area. Similarly, Mochida et al. (2011) conducted a study in the subtropical city Sendai in Japan to evaluate the distributions of wind velocity vectors around buildings to evaluate ventilation paths without obstructions. Wind and ventilation have also been studied in the tropical cities of Phoenix (Pardyjak et al. 2005), Sao Paulo (Oliveira et al. 2003) and Buenos Aires (Ulke 2004).



BREEZEWAY
OPEN SPACES ALONG SEASHORE

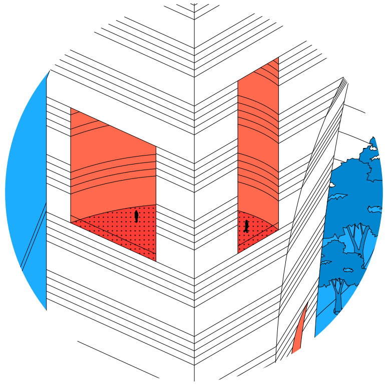
Open spaces along the seashore enhance the amount of wind entering the urban area with the effect of improving OTC. In general, seashores are considered prime areas in a city with high density and are often excluded from public use.

UHI & OTC effect
The waterfront sites are the gateways of sea breezes and this can be enhanced for benefits of UHI and OTC. They help regulate the urban climate by incorporating cold air within the urban fabric.

Tropical climate
In general, in a tropical climate such as Singapore, higher wind speeds allow a person to tolerate higher air temperatures and still achieve OTC. Singapore's open spaces along its shoreline should be maintained and it is best to avoid any type of natural or artificial wind obstruction.

Urban planning
According to urban planning prospect, the open spaces along the seashore should face the sea to offer residents beachside enjoyment while being exposed to maximum wind from the open sea to create a positive thermal sensation. To achieve this, incompatible land uses that obstruct the continuity of harbour front promenade and major infrastructure projects should be avoided. Also, an integrated network of open spaces and pedestrian pathways can allow for the better movement of air in a dense urban area.

State of the art
Zhang (1999) proposed that wind conditions in the surrounding area may induce convectional heat reduction, and air currents further promote water evaporation, affecting temperature and humidity in the littoral zone. Xu et al. (2010) considered wind speeds and showed that during the high temperature hours of a hot summer day, a water body can effectively improve human comfort in certain littoral zones.



BREEZEWAY

BUILDING POROSITY

Building porosity can be achieved by generating adequate openings or gaps in buildings, either in horizontal or vertical direction. This strategy can maximise the air permeability of the urban area and minimise its impact on wind capture and air flow reduction.

UHI & OTC effect

Compact building blocks create stagnant air that worsens OTC. In the tropics, a decrease in wind speed from 1.0 m/s to 0.3 m/s is equal to 1.9˚C temperature increase, and outdoor thermal comfort under typical summer conditions requires 1.6 m/s wind speed. Therefore, according to Yuan and Ng (2012) building setback and building permeability are helpful in improving the pedestrian-level wind environment.

Tropical climate

Singapore's tropical climate is generally hot and humid throughout the year. Sky gardens and double height void decks can increase the permeability of buildings in Singapore and thus channel airflow to rear blocks.

Urban planning

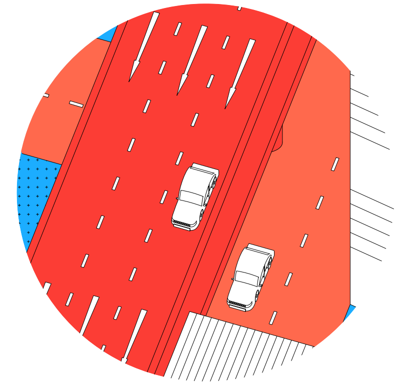
The provision of permeability closer to the pedestrian level is far more important than that at high levels as it helps to remove pollutants and heat generated at ground level. The permeability can be increased by creating voids in building blocks at ground level to improve natural ventilation for pedestrians and thus their comfort. Combining voids with appropriate wing walls permit air to flow through the openings of the buildings. Mid-level voids are especially relevant for very deep canyons or extremely tall building blocks.

State of the art

Ng (2009) showed that tall and bulky high-rise building blocks with limited open spaces in between them, uniform building heights, and large podium structures have led to lower permeability for urban air ventilation at the pedestrian level. Priyadarsini and Wong (2005) found 90 per cent improvement in wind velocity for parallel flow and temperature decrease by up to 1˚C by placing a few blocks of high-rise towers within the street canyon. For perpendicular flow, the velocity is increased by up to 10 times and the temperature is decreased by 1.1˚C. Robins and Macdonald (1999) discovered that by designing a few tall buildings among surrounding buildings restricted in the urban canopy layer, additional wakes create additional air exchange and U-shaped vortices.

BREEZEWAY

STREET AXES ORIENTATION



Choosing the appropriate geometry and the orientation of street canyon can improve outdoor and indoor environments, solar access inside and outside the buildings, the permeability to airflow for urban ventilation, and the potential for cooling of the whole urban system.

UHI & OTC effect

Street geometry and orientation influence the amount of solar radiation received by street surfaces and also airflow in urban canyons, which significantly affects local thermal comfort and building energy consumption. Streets aligned to breezeways can promote air movement into and within the urban areas, thus reducing UHI. An array of main streets, wide main avenues and/or breezeways aligned up to 30˚ to the prevailing wind direction maximises the penetration of prevailing winds and reduces the UHI effect.

Tropical climate

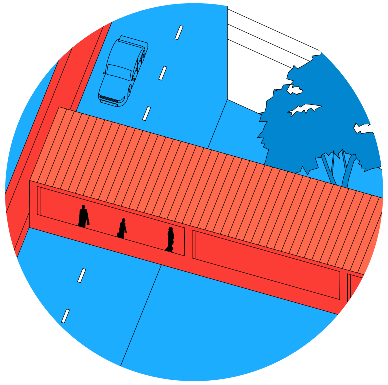
In a hot and humid climate, a good street layout from the urban ventilation aspect, is to orientate wide main avenues at an oblique angle of about 30˚. This enables wind penetration into the urban fabric while maintaining building ventilation. The increase of local wind speed helps improve thermal comfort.

Urban planning

This strategy should be considered during the first phase of the planning of a new development. It cannot be incorporated in urban retrofitting. The effort should be placed on the widening of streets orientated along the prevailing wind direction. Also, shortening the length of the street grid perpendicular to the prevailing wind direction minimises stagnation. It is important to explore the urban breezeway patterns to optimise the arrangement of both the street and corridor networks.

State of the art

Shishegar (2013) established that the street design influences the thermal comfort at the pedestrian level and the global energy consumption of urban buildings. A wider street provides better mixing of air and consequently better airflow in the urban canyon. Ali-Toudert and Mayer (2006) proved that street orientation affects the permeability to airflow for urban ventilation as well as the potential for cooling of the whole urban system. Wind alters in the street canyon depending on the angle of incidence of free air and it decreases substantially within large streets for perpendicular incidences (Oke 1988; Yoshida et al. 1991).



BREEZEWAY

WELL-VENTILATED WALKWAYS

Well-ventilated pedestrian walkways can be achieved by aligning them parallel to the prevailing wind and positioning them in adequate locations.

UHI & OTC effect
The reduction in prevailing wind speed due to urbanisation reduces ventilation in walkways and can cause discomfort. Underpasses, sidewalks, skywalks and overpasses should be orientated and located in relation to the wind flow patterns, since wind flows are better at certain levels. At the same time, these pedestrian walkways should be protected from diagonal rain and sun radiation.

Tropical climate
A pedestrian walkway system, in a hot-humid climate, should have five essential characteristics: continuity, safety, comfort, convenience and delight. Together with shading, increasing local wind speed is suitable for improving thermal comfort in walkways in Singapore. Elevated structures or skywalks like those in Orchard Road and the UPS in Marina Square gain from these benefits.

Urban planning
Pedestrian trajectories inside the urban area should be taken into consideration in the early stages of planning. Also, the technical aspects of walkways should be considered, such as materials used for paving. Multilevel pedestrian links and elevated walkways are important components of alternative walkway system that help in increasing pedestrian outdoor comfort. In high-density urban areas, carefully-designed walkway systems create a relatively pedestrian-friendly environment that also needs to distance people from vehicles, pollution and noise.

State of the art
Mirzaei and Haghighat (2010) developed a novel sidewalk ventilation system guiding air through a designed vertical duct from the roof of the building to the street level. Yang et al. (2016) studied an elevated walkway in China and proposed combining active energy measures with shading devices to increase air movement and reduce sensible heat. Mirzaei and Haghighat (2012) observed that wind comfort index increases in sidewalks from 0.1 to 1.4 m/s using pedestrian ventilation system with benefits of thermal comfort as wind flows.

BREEZEWAY

BUILDING ARRANGEMENT

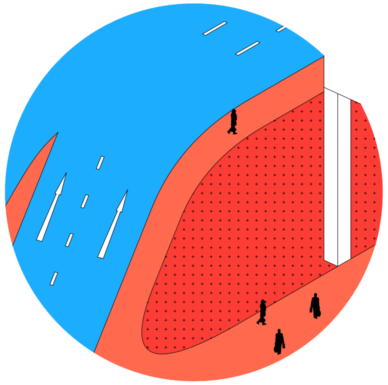
The building arrangement refers to the adequate location of buildings with respect to each other and thus in relation to the prevailing winds to improve ventilation as well as shade where required.

UHI & OTC effect
A possible cause of increase in UHI is an improper building arrangement that can reduce the wind speed and thus increase the thermal capacity of the city. It is important that the axis of the buildings should be parallel to the prevailing wind to avoid sea breeze obstruction. Inadequate arrangement can reduce wind speed and have impact on building energy consumption. Similarly, exhausted heat from air conditioning has to be taken into consideration while arranging a group of buildings.

Tropical climate
The current trend of higher density and high-rise buildings in Singapore as well as the increasing usage of air conditioning is a challenge in relation to its impact on UHI while worsening the OTC.

Urban planning
It is necessary to include these issues in the first stage of the urban planning. An effective arrangement of buildings to improve wind ventilation is to stagger the arrangement of the blocks such that the rear blocks are able to receive the wind penetrating through the space between the blocks in the front row. The building arrangement can direct or redirect the wind flows. Generally, buildings with smaller footprints and low-rise buildings should also be considered to improve ventilation in the urban area.

State of the art
Priyadarsini et al. (2008) found that the possible causes of the increase in temperature in Singapore's CBD area are, among others, the lack of ventilation from improper building-street layout and orientation, and the impact of heat rejection from the air conditioning systems. In deep street canyons, the variation in wind speed can create significant temperature differences over the street canyon than inside of it (Gago et al. 2013). Wong and Jusuf (2010) studied two sites in Singapore and found that the high-density area with less greenery had more wind speed than the site with greenery due to less obstruction.



BREEZEWAY

OPEN SPACES AT ROAD JUNCTIONS

The prevailing wind travelling along breezeways and major roads can penetrate deep into the district by the appropriate linking of open spaces. Such linkage and alignment can take place at road junctions in such a way as to form breezeways or ventilation corridors.

UHI & OTC effect
Linking open spaces with road junctions can produce higher benefits in reducing urban temperatures and improving thermal comfort outdoors. OTC can be improved as this linkage will provide abundant wind to pedestrians and cyclists crossing these junctions or to people resting in the open spaces.

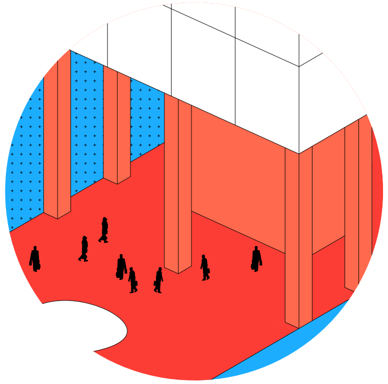
Tropical climate
Singapore has many parks and gardens embedded into the urban fabric, including park connectors that serve as green linkages between parks and other land uses (Yuen et al. 1999). This provides the concept of a 'garden city', which by incorporating the urban climate issue could improve pedestrian thermal comfort.

Urban planning
An effective linkage of open spaces and road junctions can enhance suitable ventilation paths. In any case, the buildings along breezeways or ventilation corridors should be low-rise to avoid breezeway obstruction.

State of the art
Jim and Chen (2003) proved the relationship between open spaces and road junctions by proposing a greenspace system comprising three parks and six green corridors where the parks are small linear entities located at road junctions adjacent to the canal.

BREEZEWAY

GUIDE WIND FLOWS WITH URBAN ELEMENTS



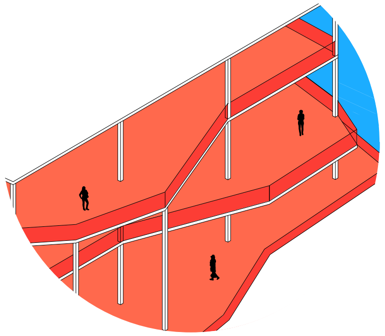
Guiding and increasing the wind flow through specific urban elements such as void decks can improve the wind volume near the ground and the urban air ventilation.

UHI & OTC effect
Introducing void decks and improving the building permeability on the ground not only improves the wind condition at the pedestrian level but it also adds value in mitigating UHI by lowering the air temperature. Singapore Housing Development Board (HDB) designed void decks in buildings to improve wind flows. Increasing building permeability can serve as effective wind flow guidance mechanisms.

Tropical climate
This strategy can be particularly important for tropical cities such as Singapore where the hot and humid climate is offset through either natural ventilation or through chillers. The new neighbourhoods must have in place an improved building arrangement, porosity, vegetation and coatings to lower the temperature.

Urban planning
The provision of building permeability nearer to the pedestrian level is far more important than that at high levels to improve the pedestrian comfort due to the stack effect. This can be achieved by creating voids at ground level to improve ventilation for pedestrians and the residential units at the lower floors.

State of the art
Lee et al. (2009) suggested that the high-rise buildings should be well arranged with respect to the main wind directions to increase the natural ventilation inside the residential complex. However, according to Hee (2016), void decks are being replaced by Precinct Pavilions (a common space shared by several blocks for residents' use such as gatherings and events), which have the effect of increasing noise pollution instead of improving wind ventilation.



BREEZEWAY

PASSIVE COOLING SYSTEMS

Passive cooling systems are design techniques that prevent heat to enter into the building or promote heat removal from the building envelope or open spaces through natural cooling. Cost-effective sources of passive cooling could be the orientation and arrangement of buildings and vegetation, water bodies and reflective coatings, but also the use and combination of open and semi-open spaces allowing cross-ventilation.

UHI & OTC effect
Higher UHI is expected if there is little emphasis on integrating passive cooling systems in the urban and building design. By utilising only mechanical systems such as air conditioners or chillers as primary sources for improving indoor thermal comfort, there would be adverse impacts on UHI and OTC.

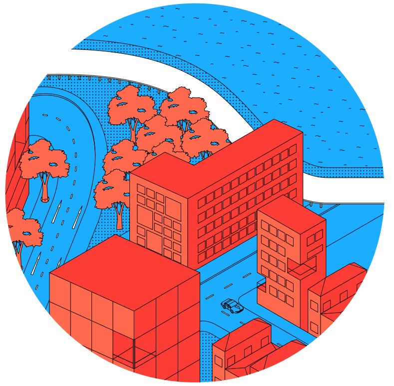
Tropical climate
Passive cooling can be particularly important for tropical cities such as Singapore where the hot and humid climate is offset through either natural ventilation or mechanical cooling. It is important to combine both systems to provide comfort while simultaneously reducing the negative impacts on the environment.

Urban planning
New neighbourhood planning should include passive techniques such as improved building arrangement, porosity, vegetation and coatings to reduce urban heat accumulation. Also in the case of urban retrofitting, certain passive cooling systems could be considered.

State of the art
There are a number of good examples for the implementation of this strategy. Fahmy and Sharples (2009) investigated how the urban form can be designed to act as a passive thermal comfort system in Cairo. They found evidence of more acceptable comfort levels and cooling potential with certain orientation and degree of urban compactness due to the clustered form with green cool islands and wind flow through the main canyons. Also, Santamouris et al. (2007) investigated the potential of more promising new developments in passive cooling. Results show a high potential for improving indoor environmental conditions and contributing towards higher passive survivability levels (meaning the building's ability to maintain critical life-support conditions in the event of extended loss of power, heating fuel, or water).

SURFACE COVERAGE

URBAN DENSITY BY LOCAL CLIMATE ZONES



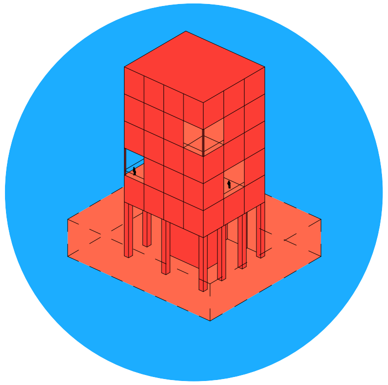
Stewart and Oke (2012) developed the Local Climate Zone (LCZ) classification scheme that organises a city into zones according to specific climates and is based on the properties of surface structure and surface cover.

UHI & OTC effect
The LCZ scheme allows for the assessment and comparison of UHI magnitude objectively through inter-zone temperature differences (Stewart and Oke 2012). This framework can be applied easily to different urban densities using the standardised description of geometric and surface cover properties. The 17 LCZs have different urban densities and therefore a different impact on the UHI. A balanced distribution of LCZs/ urban densities within a city is important for monitoring and controlling the impacts on the UHI and OTC.

Tropical climate
It is difficult to apply the traditional rural-urban comparison method in Singapore as it is highly urbanised with no clearly defined rural area. However, the absence of seasonal variation makes it easy to adopt the LCZ framework using the best fit properties.

Urban planning
Singapore's increasing land-scarcity forces planners to optimise land use and increase urban density. Therefore, it is expected that more LCZ 1 (compact high-rise), LCZ 2 (compact mid-rise), LCZ 3 (compact low-rise) and LCZ 4 (open high-rise) will dominate Singapore's urban development (Ng 2015).

State of the art
Ng (2015) studied UHI in Singapore by using the LCZ method. LCZ 1 (compact high-rise) was applied in the CBD area, LCZ 4 (open high-rise) in an HDB residential estate, and LCZ 9 (sparsely built) in a green space. The study showed that LCZ 4 had higher mean air temperature than LCZ 1 probably due to tailpipe heat emissions at the HDB car park between 7-9 pm. LCZ 9 had the lowest temperatures and greatest UHI intensity, with a difference of 2.01°C in mean air temperature between LCZ 4 and LCZ 9. Also, Chow (2006) proved that the highest UHI magnitude of 7°C was measured at 3 to 4 hours after sunset in Orchard Road, while in the CBD area 6 hours after sunset. It concluded that to control OTC, height variation and low-rise buildings are needed along with the preservation of green spaces.



SURFACE COVERAGE
BUILDING SURFACE FRACTION

The Building Surface Fraction (BSF) is the ratio between the horizontal area of buildings (building footprint) on a given area and the total area. BSF is considered a physical parameter to measure Local Climate Zones (Stewart & Oke 2012).

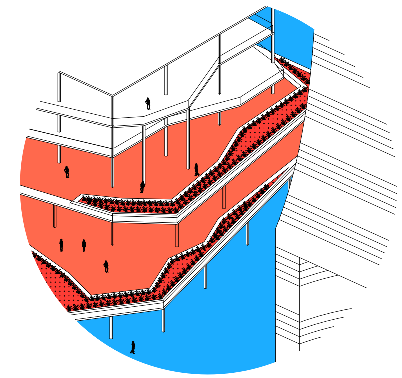
UHI & OTC effect
High density influences the ground space and the space between buildings. Lowering the BSF will provide more open space around the building volume and therefore decrease the air temperature by avoiding heat accumulation during the day as well as heat release during the night (Buchholz and Kossmann 2015). This will facilitate greater natural ventilation of pedestrian spaces and improvement in the OTC.

Tropical climate
Due to land scarcity in Singapore, the use of land is being maximised, thus increasing density and land reclamation. Over the last 40 years, the built area has increased from 28 to 50 per cent, leaving pockets of tropical rainforest in the northwest (Chow & Roth 2006). This development has led to an increase in heat concentration within the dense urban fabric.

Urban planning
Planners Singapore take into consideration the Gross Plot Ratio (GPR), which measures the ratio of the Gross Floor Area (GFA) of a building or various buildings to the land area of the site. By taking into consideration the surface fraction, planners can estimate the heat intensity caused by lowering or increasing the BSF.

State of the art
To conduct this study, data regarding surface fraction partitioning is needed but not always available (Stewart 2011). A German-based study showed that neighbourhoods with a BSF above 50 per cent should consider 30 per cent green areas (Buchholz and Kossmann 2015). A Shanghai research found that at night, urban areas with low BSF have lower mean temperatures due to their openness, while during the day they are exposed to higher radiation (Wei et al. 2016). For Singapore, Ignatius et al. (2015) suggested the use of more open space with around 40 per cent site coverage comprising taller buildings and abundant greenery. Therefore, the BSF needs to be evaluated in relation to the SFV and aspect ratio to find the optimum urban morphology.

SURFACE COVERAGE
GREEN PLOT RATIO



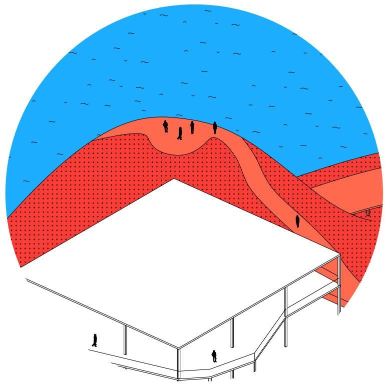
The Green Plot Ratio (GnPR) is a three-dimensional ratio between the greenery in a given area and the total area. It is measured through the Leaf Area Index (LAI). It includes vertical and horizontal landscaping, lawns and trees, raised planters and urban farms.

UHI & OTC effect
This strategy gives incentives to increase the amount of greenery in urban areas. Increasing the greenery and integrating it into the architectural design can provide cooling to the immediate surrounding environment and the surface temperature. Introducing building greenery on walls, balconies, sky terraces and roofs has a significant effect on the outdoor thermal comfort and in mitigating the UHI. A study comparing well-planted areas and urban concrete zones in Singapore has presented a temperature difference of 4°C (IGRN).

Tropical climate
The tropical rainforest climate of Singapore offers a uniform temperature all-year round, high humidity and abundant rainfall. This has a positive effect in the city's flora abundance and diversity, with a count of 2,100 native vascular plants, of which 1,500 species still exist (NParks).

Urban planning
GnPR is part of BCA's Green Mark since 2005 and rates different building typologies by the amount and type of surrounding greenery such as grass, bush or tree. NParks has also developed LAI values for the most common species available in Singapore (Tan and Sia 2009).

State of the art
Ong, Ho and Ho (2016) studied the LAI values of around 50 different plant species, covering four plant categories that are common in Singapore: groundcover, shrub, palm and canopy. They revealed that groundcover plants and shrubs have higher LAI than palms and canopy trees. Also, low growing plants have higher LAI. GnPR can quantify the number of plants but does not define the plant species. Finally, plants are typically chosen for their appearance rather than their environmental and social benefits (Ong, Ho and Ho 2016). The different plant categories should be applied based on the given conditions. Ho (2016) proposed to define a Green Index that sums the LAI with a weightage that considers social, ecological, and environmental benefits e.g. species, typology and function.



SURFACE COVERAGE
TOPOGRAPHY

The topography can be an integral part of the urban fabric, which is not a direct component of microclimate but an indirect one.

UHI & OTC effect
The combination between the elevation of the terrain and the urban fabric influences the microclimatic phenomena such as wind drafts and rainfall, generating an indirect effect on UHI and OTC. The effect of topography in UHI can be more appreciated when a topographic depression is found (Serrano et al. 2003) and also during daytime hours (Geiger et al. 1995 and Nitis et al. 2005).

Tropical climate
The Singapore landscape does not have any large and pronounced topography. Bukit Timah at 161 meters above sea level might not generate significant effects in UHI variation. This topographical condition makes the temperature difference and the convective cooling less significant. There is no study in tropical climates that singles out the effect of topography on the UHI or OTC.

Urban planning
Wall et al. (2015) shows evidence of urban design projects where natural and human made topographical features such as hills, buildings and vegetation were introduced to induce cool winds into the urban fabric.

State of the art
Goldreich (1984) found that topography effects cannot be isolated from the urban typology to understand changes in microclimate. The author identified an average delta of 0.4˚C in ambient temperature every 100 meters for both rural and urban areas in South Africa. The topography has effects on prevailing wind speeds and rainfalls, which influences indirectly the UHI and outdoor thermal comfort. Geiger et al. (1995) studied the relations of the terrain slope and solar radiation. The authors determined the effects of topography on incident winds and their cooling effect especially during daytime hours. The literature presents studies in which topographic features are intertwined with other natural structures such as vegetation. Serrano et al. (2003) found the percentage of thermal spatial variance explained by vegetation cover and elevation to be of 54 per cent for Zaragosa, Spain. Nitis et al. (2005) depicted the spatial variation in temperature of Zagreb, Croatia to be influenced by topological barriers like mountains, which influenced wind flows daytime.

REFERENCES

Abreu-Harbich, L.V., Labaki, L.C, Matzarakis, A. (2014). 'Thermal bioclimate in idealized urban street canyons in Campinas, Brazil', Theoretical and Applied Climatology 115(1-2): 333–340. doi: 10.1007/s00704-013-0886-0.

Ali-Toudert, F., Mayer, H. (2006). 'Numerical study on the effects of aspect ratio and orientation of an urban street canyon on outdoor thermal comfort in hot and dry climate', Building and Environment, 41(2): 94–108. doi: 10.1016/j.buildenv.2005.01.013.

Ali-Toudert, F., Mayer, H. (2007). 'Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons', Solar Energy, 81(6): 742–754. doi: 10.1016/j.solener.2006.10.007.

Anand, P., Deb, C., Alur, R. (2017). 'A simplified tool for building layout design based on thermal comfort simulations', Frontiers of Architectural Research, 6(2): 218–230. doi: 10.1016/j.foar.2017.03.001.

Fahmy, M., Sharples, S. (2009). 'On the development of an urban passive thermal comfort system in Cairo, Egypt', Building and Environment, 44(9): 1907–1916. doi: 10.1016/j.buildenv.2009.01.010.

Buchholz, S., & Kossmann, M. (2015). 'Research note: Visualisation of summer heat intensity for different settlement types and varying surface fraction partitioning'. Landscape and Urban Planning, 144: 59–64. doi: 10.1016/j.landurbplan.2015.08.002.

Cheng, V., Steemers, K., Montavon, M., Compagnon, R. (2006). 'Urban form, density and solar potential', presented at PLEA2006 - The 23rd Conference on passive and low energy architecture, Geneva.

Chow, W. T. L., Roth, M. (2006). 'Temporal Dynamics Of The Urban Heat Island Of Singapore', International Journal Of Climatology, 26: 2243–2260. doi: 10.1002/joc.1364.

Gago, E. J., Roldan, J., Pacheco-Torres, R., Ordóñez, J. (2013). 'The city and urban heat islands: A review of strategies to mitigate adverse effects', Renewable and Sustainable Energy Reviews, 25(2013): 749–758. doi: 10.1016/j.rser.2013.05.057.

Goldreich, Y. (1984). 'Urban topoclimatology', Progress in Physical Geography, 3: 336–364. doi: 10.1177/030913338400800302.

Geiger, R., Aron, R. H., Todhunter, P. (1995). 'The Influence of Topography on the Microclimate', The Climate Near the Ground, 35: 327–406. doi: 10.1007/978-3-322-86582-3_8.

Hee, L. (2016). Constructing Singapore Public Space. Singapore: Springer.

Ignatius, M., Wong, N. H., Jusuf, S. K. (2015). 'Urban microclimate analysis with consideration of local ambient temperature, external heat gain, urban ventilation, and outdoor thermal comfort in the tropics', Sustainable Cities and Society, 19: 121–135. doi: 10.1016/j.scs.2015.07.016.

IGRN - International Green Roof City Network. Case Study Singapore. Accessed on May 30, 2017. http://www.igra-world.com/images/city_network/IGRN-Case-Study-Singapore-IGRA.pdf.

Jim, C.Y., Chen, S.S. (2003). 'Comprehensive greenspace planning based on landscape ecology principles in compact Nanjing city, China', Landscape and Urban Planning, 65(3): 95–116. doi: 10.1016/S0169-2046(02)00244-X.

Ketterer, C., Matzarakis, A. (2014). 'Human-biometeorological assessment of heat stress reduction by replanning measures in Stuttgart, Germany', Landscape and Urban Planning, 122: 78–88. doi: 10.1016/j.landurbplan.2013.11.003.

Konarska, J., Lindberg, F., Larsson, A., et al. (2014). 'Transmissivity of solar radiation through crowns of single urban trees-application for outdoor thermal comfort modelling', Theoretical and Applied Climatology, 117(3): 363–376. doi: 10.1007/s00704-013-1000-3.

Lee, S-J., Park, C-W., Kang, J-H. (2009). 'Evaluation of wind environment around a residential complex using a PIV velocity field measurement technique', Environmental Fluid Mechanics ,9: 655–668. doi: 10.1007/s10652-009-9133-8.

Mesa, N.A., Corica, L., Pattini, A. (2011). 'Evaluation of the potential of natural light to illumination buildings in dense urban environment: A study in Mendoza, Argentina', Renewable Energy, 36(9): 2414-2423. doi: 10.1016/j.renene.2011.02.005.

Menz, S. (2015). Public Space Evolution in High-Density Living in Singapore: Ground and Elevated Public Spaces in Public Housing Precincts, Singapore: Singapore-ETH Centre (SEC), 25-26.

Mirzaei, P.A., Haghighat, F. (2010). 'A novel approach to enhance outdoor air quality: Pedestrian ventilation system', Building and Environment, 45(7): 1582–1593. doi: 10.1016/j.buildenv.2010.01.001.

Mirzaei, P.A., Haghighat, F. (2012). 'A procedure to quantify the impact of mitigation techniques on the urban ventilation', Building and Environment, 47: 410–420. doi: 10.1016/j.buildenv.2011.06.007.

Mochida, A., Iizuka, S., Tominaga, Y., Lun, IY-F. (2011). 'Up-scaling CWE models to include mesoscale meteorological influences', Journal of Wind Engineering and Industrial Aerodynamics, 99(4): 187–198. doi: 10.1016/j.jweia.2011.01.012.

Morakinyo, T.E., Balogun, A.A., Adegun, O.B. (2013). 'Comparing the effect of trees on thermal conditions of two typical urban buildings', Urban Climate, 3: 76–93. doi: 10.1016/j.uclim.2013.04.002.

Ng, E. (2009). 'Policies and technical guidelines for urban planning of high-density cities – air ventilation assessment (AVA) of Hong Kong', Building and Environment, 44(7): 1478–1488. doi: 10.1016/j.buildenv.2008.06.013.

Ng, E., Yuan, C., Chen, L., et al. (2011). 'Improving the wind environment in high-density cities by understanding urban morphology and surface roughness: a study in Hong Kong', Landsc Urban Plan 101(1): 59–74. doi: 10.1016/j.landurbplan.2011.01.004.

Ng, Y.X.Y. (2015). 'A Study of Urban Heat Island using "Local Climate Zones" – The Case of Singapore', British Journal of Environment and Climate Change 5(2): 116–133. doi: 10.9734/BJECC/2015/13051.

Nitis, T., Klaic, Z.B., Moussiopoulos, N. (2005). 'Effects of topography on urban heat island', presented at 10th International Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes, Sissi.

Oke, T.R. (1988). 'Street design and urban canopy layer climate', Energy and Buildings, 11(1-3): 103–113. doi: 10.1016/0378-7788(88)90026-6.

Oliveira, A.P., Bornstein, R.D., Soares, J. (2003). 'Annual and diurnal wind patterns in the city of São Paulo', Water, Air and Soil Pollution: Focus, 3(5): 3–15.

Ong, B.L., Hin, K., & Ho, D. (2016). 'Green Plot Ratio - Past , Present & Future', presented at Conference iNTA2012 - Tropics 2050, Singapore.

Pardyjak, E., Fernando, H.J.S., Hedquist, B.C., et al. (2005). 'Evening transition observations in Phoenix, Arizona', Journal of Applied Meteorology, 44(1): 99–112. doi: 10.1175/JAM-2180.1.

Priyadarsini, R., Hien, W.N., Wai David, C.K. (2008). 'Microclimatic modeling of the urban thermal environment of Singapore to mitigate urban heat island', Solar Energy, 82(8): 727–745. doi: 10.1016/j.solener.2008.02.008.

Priyadarsini, R., Wong, N. (2005). 'Parametric studies on urban geometry, airflow and temperature', International Journal on Architectural Science, 6(3): 114–132.

Qaid, A., Ossen, D.R. (2015). 'Effect of asymmetrical street aspect ratios on microclimates in hot, humid regions', International Journal of Biometeorology, 59(6): 657–677. doi: 10.1007/s00484-014-0878-5.

Rizwan, A.M., Leung, D.Y.C., Liu, C.-H. (2010). 'Effects of building aspect ratio and wind speed on air temperatures in urban-like street canyons', Building and Environment, 45(1): 176–188. doi: 10.1016/j.buildenv.2009.05.015.

Robins, A., Macdonald, R. (1999). 'Review of Flow and Dispersion in the Vicinity of Buildings', Report No. ME-FD/99.93, University of Surrey.

Rodríguez Algeciras, J.A., Gómez Consuegra, L., Matzarakis, A. (2016). 'Spatial-temporal study on the effects of urban street configurations on human thermal comfort in the world heritage city of Camagüey-Cuba', Building and Environment, 101(15): 85–101. doi: 10.1016/j.buildenv.2016.02.026.

Santamouris, M., Pavlou, K., Synnefa, A., et al. (2007). 'Recent progress on passive cooling techniques. Advanced technological developments to improve survivability levels in low-income households', Energy and Buildings, 39(7): 859–866. doi: 10.1016/j.enbuild.2007.02.008.

Shishegar N (2013) Street design and urban microclimate: analyzing the effects of street geometry and orientation on airflowand solar access in urban canyons. J Clean Energy Technol 1:52–56. doi: 10.7763/JOCET.2013.V1.13.

Stewart, I. D., & Oke, T. R. (2012). Local climate zones for urban temperature studies. Bulletin of the American Meteorological Society, 93 (12), 1879–1900.

Sujatmiko, W., Dipojono, H.K., Soelami, F.X.N., Soegijanto, (2015). 'Natural Ventilation and Temperature Conditions in Some High-rise Building Flats in Bandung and Jakarta in Perspective of Adaptive Thermal Comfort', Procedia Environmental Sciences, 28: 360–369. doi: 10.1016/j.proenv.2015.07.045.

Tan, P.Y., Sia, A. (2009). Leaf area index of tropical plants: a guidebook on its use in the calculation of green plot ratio, Singapore, Centre of Urban Greenery and Ecology, Singapore: Centre of Urban Greenery and Ecology.

Ulke, A.G. (2004). 'Daytime ventilation conditions in Buenos Aires city, Argentina', International Journal of Environment and Pollution 22(4): 379–395.

Vicente, S.M., Cuadrat, J.M.C., Saz, M.A., (2003). 'Topography and vegetation cover influence on urban heat island of Zaragoza (Spain)', presented at 5th International Conference on Urban Climate, Lodz.

Walls, W., Parker, N., Walliss, J. (2015). 'Designing with thermal comfort indices in outdoor sites', presented at Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015, 1117–1128.

Wei, R., Song, D., Wong, N.H., Martin, M. (2016). 'Impact of Urban Morphology Parameters on Microclimate', Procedia Engineering, 169: 142–149. doi: 10.1016/j.proeng.2016.10.017.

Wong, N.H., Jusuf, S.K. (2010). 'Study on the microclimate condition along a green pedestrian canyon in Singapore', Architectural Science Review, 53(2): 196–212.

Wong, N.H., Tan, E., Gabriela, O., Jusuf, S.K. (2016). 'Indoor Thermal Comfort Assessment of Industrial Buildings in Singapore', Procedia Engineering, 169: 158–165. doi: 10.1016/j.proeng.2016.10.019.

Xu, J., Wei, Q., Huang, X., et al. (2010). 'Evaluation of human thermal comfort near urban waterbody during summer', Building and Environment, 45(4): 1072–1080. doi: 10.1016/j.buildenv.2009.10.025.

Yang, F., Qian, F., Zhao, W. (2016). 'Towards a Climate-Responsive Vertical Pedestrian System: An Empirical Study on an Elevated Walkway in Shanghai China', Sustainability 8(8): 744. doi: 10.3390/su8080744.

Yoshida, A., Tominaga, K., Watatani, S. (1991). 'Field measurements on energy balance of an urban canyon in the summer season', Energy and Buildings 15(3-4): 417–423. doi: 10.1016/0378-7788(90)90016-C.

Yuan, C., Ng, E. (2012). 'Building porosity for better urban ventilation in high-density cities–A computational parametric study', Building and Environment, 50: 176–189. doi: 10.1016/j.buildenv.2011.10.023.

Yuen, B., Kong, L., Briffett, C. (1999). 'Nature and the Singapore resident', GeoJournal, 49: 323. doi: 10.1023/A:1007060728210.

Zhang, S. (1999). 'The forecasting basis of weather and health care. Beijing', Meteo. Press.

003 WATER BODIES & FEATURES

WATER BODIES & FEATURES

Water bodies and features can act as countermeasures to improve overheated building environments to some degree. Water facilities have been installed in Singapore mainly for landscaping purposes and not necessarily for improving the urban thermal comfort. The effect of water is related to its surface temperature, which does not increase as much as the rest of the urban area. Thus, it can be considered as a cool sink. Also, water evaporates and increases the humidity of the air. Depending on the regional context, this can have a positive impact on the local thermal comfort. Additionally, depending on the size of the water body, specific wind circulation patterns can be developed with its corresponding consequences in the nearby environment.

The hot-humid climate of Singapore limits the benefits of this mitigation measure that is more suitable for hot-dry climates. However, the strategic use of existing water bodies in relation to the nearby urban design and its use to reduce surface temperature can be implemented adequately in Singapore.

The Water Features and Bodies category has been divided into two sub-categories: Features, and Bodies. The first deals basically with urban elements that use water and can provide some benefits in local thermal comfort. The second sub-category tries to describe mitigation measures focusing on large water areas that are basically natural elements.

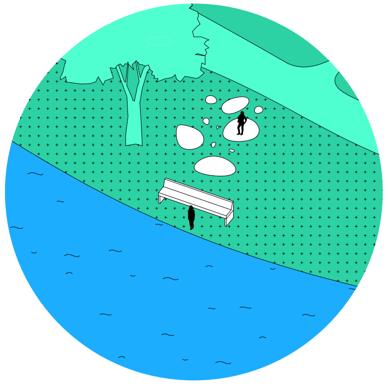
Juan Angel Acero
Cooling Singapore Researcher

BODIES

Cool sinks
Blue and green spaces
Wetlands
Water catchment areas

FEATURES

Ponds on roofs/ground floor
Evaporative cooling
Fountains



BODIES
COOL SINKS

Natural surface water accumulation can act as a cool sink to prevent the overheating of urban surfaces.

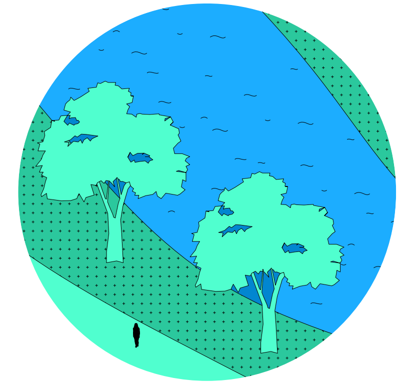
UHI & OTC effect
Large water masses can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, a mass of water can reduce the accumulation of heat and thus contribute to reduced UHI and improved thermal comfort. Additionally, if water bodies are sufficiently extended by, for example several square kilometres, local breezes can be developed and wind speed increased with benefits in thermal comfort and urban heat removal.

Tropical climate
Due to the high solar radiation in the tropics, the overheating of surfaces can be significant. Thus, changing their characteristics and avoiding their overheating can contribute positively to the urban climate and to the city's energy consumption.

Urban planning
Implementation should be considered at an inter-ministerial context. Different agents should be involved in the design and implementation of this measure in relation to other requirements of Singapore. Thus, the planning of new developments can consider the possibility of strategic natural water accumulation, which if combined with local wind flow patterns, can benefit nearby outdoor thermal comfort.

State of the art
The cooling effect of water bodies depends nonlinearly on the fractional water cover, size, and distribution of individual lakes within the city with respect to wind direction. Relatively large lakes show a high temperature effect close to their edges and in downwind areas. The littoral zone of Shanghai was studied and the greatest effects in thermal comfort were for an area 10-20 m from the water's edge. These results provided scientific guidance for the design of littoral zones near waterbodies in the garden of the Shanghai World Expo 2010 (Xu et al. 2010). Also, several smaller lakes equally distributed within the urban area can have a smaller temperature effect, but collectively can influence a larger area of the city (Theeuwes et al. 2013).

BODIES
BLUE AND GREEN SPACES



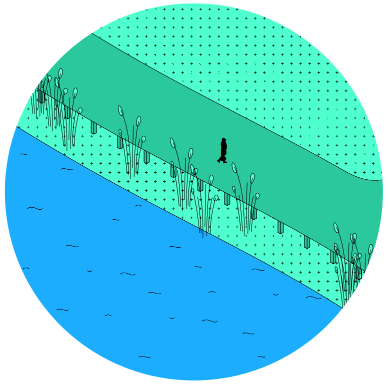
Combining blue and green mitigation strategies in urban areas can bring about integrated solutions and distinct benefits from their characteristics.

UHI & OTC effect
Water (blue) and vegetation (green) strategies can affect climate variables differently and thus the UHI effect. Differences between both do not only refer to the amount of energy dissipated but also on their suitability through the day. For example, water can have a nocturnal warming effect during certain periods of the year. Also, vegetation can provide shade during daytime and improve thermal comfort but during night-time it will trap heat at surface level and worsen nocturnal urban heat island.

Tropical climate
A valid issue to consider is the high temperatures, low diurnal variation and high humidity in the tropics that to some extent make the measure little profitable. For example, trees can be very useful in providing shade for thermal comfort and reduced building energy consumption, but the increased evapotranspiration from vegetation does little to help considering the prevalent humidity in Singapore.

Urban planning
Knowing the limitations of each mitigation measure and the benefit of combining them is crucial for developing ad-hoc urban design to protect and enhance the wellbeing of inhabitants by optimising ecosystem services. Thus, urban planning guidelines that include these issues would help their implementation.

State of the art
When considered individually, green mitigation strategies (tree based) is of greater benefit to heat risk mitigation than blue/water strategies. When employed together, both green and blue strategies provide mutually dependent environmental capital, offering many benefits including synergistic cooling and other valued ecosystem services (Gunawardena et al. 2017).



BODIES

WETLANDS

Wetlands are the link between land and water and they contribute towards flood control, carbon sink and shoreline stability. This measure concerns the conservation of natural water surfaces with high presence of vegetation and negligible surface overheating.

UHI & OTC effect
Water has negligible diurnal temperature variation compared to land surface and thus it does not accumulate heat during daytime hours. In this context, the proximity to wetlands with high presence of vegetation can be more comfortable.

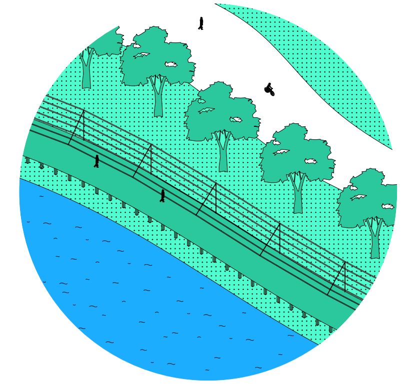
Tropical climate
Wetlands can be developed further in tropical areas such as Singapore. Their ecosystem can provide certain shadowing due to the presence of vegetation (and trees) and thus be a reservoir of regional undisturbed climate. They can also be considered as a sink of CO_2 and other greenhouse gases, thus improving the air quality and temperature.

Urban planning
Care should be taken not only when developing natural areas that can provide thermal comfort, but also the surroundings where their effect can be extended, for example, cool air transportation due to wind.

State of the art
The preservation of wetlands should be considered not only from a natural ecosystem perspective but also from the UHI mitigation perspective. The effects of water surfaces and vegetation are presented in the other mitigation strategies.

BODIES

WATER CATCHMENT AREAS



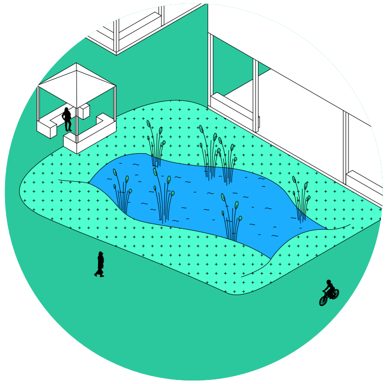
Water catchment area is an area of land integrated into the natural landscape that collects rainwater and drains off into other water bodies. The accumulation of water catchment areas as a pre-emptive measure can prevent the overheating of urban surfaces.

UHI & OTC effect
Large water masses can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, extending water catchment areas can increase the non-heated surfaces and hence contribute to reducing UHI and improving the thermal comfort of residents outdoors.

Tropical climate
Due to high sun radiation in the tropics, the overheating of surfaces can be significant. Thus, changing their characteristics and avoiding their overheating can contribute positively to the urban climate and to the city's energy consumption.

Urban planning
Implementation should be considered at an inter-ministerial context. Different agents should be involved in the design and implementation of this measure in relation to other requirements of Singapore such as water supply. Thus, the planning of new developments can consider the possibility of strategic water accumulation.

State of the art
Similar to natural water bodies, the cooling effect depends on the size and distribution of individual water catchments within the city with respect to wind direction. Large ones will show high temperature effect close to their edges and in downwind areas, but several smaller lakes equally distributed within the urban area can produce a smaller temperature effect, but collectively influence a larger area of the city.



FEATURES

PONDS ON ROOFS/ GROUND FLOOR

Ponds are an accumulation of water that prevent the overheating of urban surfaces. They can be located on ground floor areas or on building roofs.

UHI & OTC effect
Water can absorb thermal energy from the incoming solar radiation due to its heat capacity. Also, water evaporation is a sink for sun radiated energy. Thus, a mass of water can lessen the accumulation of heat and thus contribute to reducing UHI. Additionally, reducing roof surface temperatures with the use of water bodies would lower energy demand, especially in low-rise buildings.

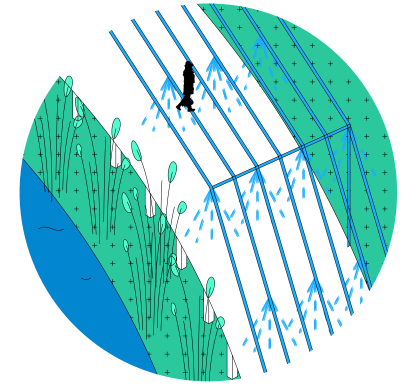
Tropical climate
The evaporation of water does not have significant benefits of thermal comfort in hot humid tropics such as Singapore, since the presence of humidity in the air is already high. However, in addition to preventing overheated surfaces, water storage infrastructure might be a beneficial measure to counter the incidences of droughts and flooding.

Urban planning
The implementation of water features on rooftops or ground floor should be aided by the development of building codes and energy efficiency guidelines. Also, the planning of new developments or urban retrofit can consider the possibility of strategic water accumulation both from a public and private perspective. In this sense, including the interaction of local wind with the water features would improve its performance regarding thermal comfort.

State of the art
A study done in Bucharest demonstrated the cooling effect of a pond measuring 4 m × 4 m. The cooling effect was about 1°C at a height of one metre, measured at 30 m distance from the pond (Robitu et al. 2006). Other studies have concluded that the effectiveness of this measure is dependent on the weather circumstances (Kleerekoper et al. 2012).

FEATURES

EVAPORATIVE COOLING



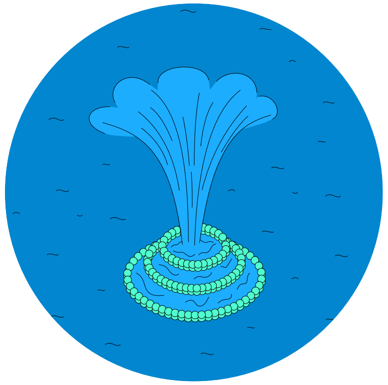
Evaporative cooling systems are devices that cool the air through the evaporation of water. It can increase locally the levels of humidity through water misting and/or spray.

UHI & OTC effect
Evaporative cooling dampens the positive effect on thermal comfort by eliminating heat or reducing temperature on the surface of the body's skin. In hot environments, evaporative cooling can play a role in creating a calming effect.

Tropical climate
This measure is frequently used in hot environments but is less effective in humid areas since the presence of water in the air is already high and the cooling effects are reduced. However, there is evidence that tropical areas experiencing severe UHI effects can profit from this mitigation measure to provide instant cooling outdoors (Farnham et al. 2015).

Urban planning
Since this measure provides benefits to the outdoor environment, the planning of new developments or urban retrofit could consider the possibility of including it locally so as to create cool spots that enable the enjoyment of the outdoors, both in public and private areas.

State of the art
Farnham et al. (2015) found that the cooling effect of water mist and fan combination is highly efficient in almost instantly decreasing the skin temperature. Such outdoor technology has the potential to reduce heat stress and discomfort, particularly at large outdoor events such as festivals.



FEATURES

FOUNTAINS

Fountains are watering surfaces to prevent overheating and increase locally the levels of humidity.

UHI & OTC effect
Water can prevent urban surfaces from heating due to its heat capacity and the evaporation process. Thus, a fountain can be considered a heat sink. In this sense, it can improve thermal comfort in the close surroundings similar to other water features, depending on its size, shape and water movement characteristics.

Tropical climate
It is expected that only fountains providing spray water or water mist will present thermal comfort effects in hot humid climates such as Singapore's.

Urban planning
Strategic locations for fountains providing spray water are necessary if thermal comfort benefits are to be expected. One important consideration is the wind environment since it conditions the transport and impact of water spray.

State of the art
Nishimura et al. (1998) found that the fountain effects on thermal comfort are higher when the water spray is working with a temperature reduction of 1-2 °C. Depending on the size of the fountain, the effect could be felt some tenths of metres away on the leeward side.

REFERENCES

Farnham, C., Emura, K., Mizuno, T. (2015). 'Evaluation of cooling effects: outdoor water mist fan', Building Research & Information, 43(3): 334–345. doi: 10.1080/09613218.2015.1004844.

Gunawardena, K.R., Wells, M.J., Kershaw, T. (2017). 'Utilising green and bluespace to mitigate urban heat island intensity', Science of The Total Environment, 584: 1–16. doi: 10.1016/j.scitotenv.2017.01.158.

Kleerekoper, L., Van Esch, M., Salcedo, T.B. (2012). 'How to make a city climate-proof, addressing the urban heat island effect', Resources Conservation and Recycling, 64: 30–38. doi: 10.1016/j.resconrec.2011.06.004.

Nishimura, N., Nomura, T., Iyota, H., Kimoto, S. (1998). 'Novel Water Facilities For Creation Of Comfortable Urban Micrometeorology', Solar Energy, 64(4): 197–207. doi: 10.1016/S0038-092X(98)00116-9.

Robitu, M., Musy, M., Inard, C., Groleau, D. (2006). 'Modeling the influence of vegetation and water pond on urban microclimate', Solar Energy, 80: 435–447. doi: 10.1016/j.solener.2005.06.015.

Theeuwes, N.E., Solcerová. A., Steeneveld, G.J. (2013). 'Modeling the influence of open water surfaces on the summertime temperature and thermal comfort in the city', Journal of Geophysical Research Atmospheres, 118(6): 8881–8896. doi: 10.1002/jgrd.50704.

Xu, J., Wei, Q., Huang, X., et al. (2010). 'Evaluation of human thermal comfort near urban waterbody during summer', Building and Environment, 45(4): 1072–1080. doi: 10.1016/j.buildenv.2009.10.025.

004
MATERIALS &
SURFACES

MATERIALS & SURFACES

Changes in urban surfaces and materials may affect the urban climate and thermal balance of a city. Therefore, urban space design or retrofitting has to take into account the thermal properties of the urban materials, and their selection has to be done according to the boundary climate conditions. Also, it is important to investigate the different physical and optical properties, which characterise the surfaces of the paving and building envelope. This allows the understanding of the thermal behaviour of the different urban surfaces, their interaction with the local microclimate, and how they affect the outdoor thermal comfort (OTC).

In a hot climate, characterised by high incident solar radiation, the presence of a high absorption material compared to a reflective material may produce significant differences in terms of surface and air temperature magnitude in the close surroundings. In tropical Singapore, where the building energy demand for cooling is relevant, passive cooling strategies could represent a suitable solution within the urban space (buildings and open spaces). This would mitigate the urban heat island (UHI) phenomenon and improve the OTC. These strategies can help in lowering the surface temperature of urban surfaces as well as the surrounding air temperature and in reducing the cooling energy consumption in buildings.

The Materials and Surfaces category has been divided into two sub-categories: Street and Open Spaces, and Buildings. The first sub-category presents measures based on different functioning principles that can be applied to urban pavements, by cooling streets and pavements to mitigate the UHI effect and, when possible, to improve the OTC for pedestrians. The second sub-category is mainly related to different measures and solutions that can be suitable for building applications. These can simultaneously reduce the heat gains into buildings, and the energy consumption and the cost for indoor cooling. All strategies can potentially contribute to the reduction of the UHI effect when applied at large scale.

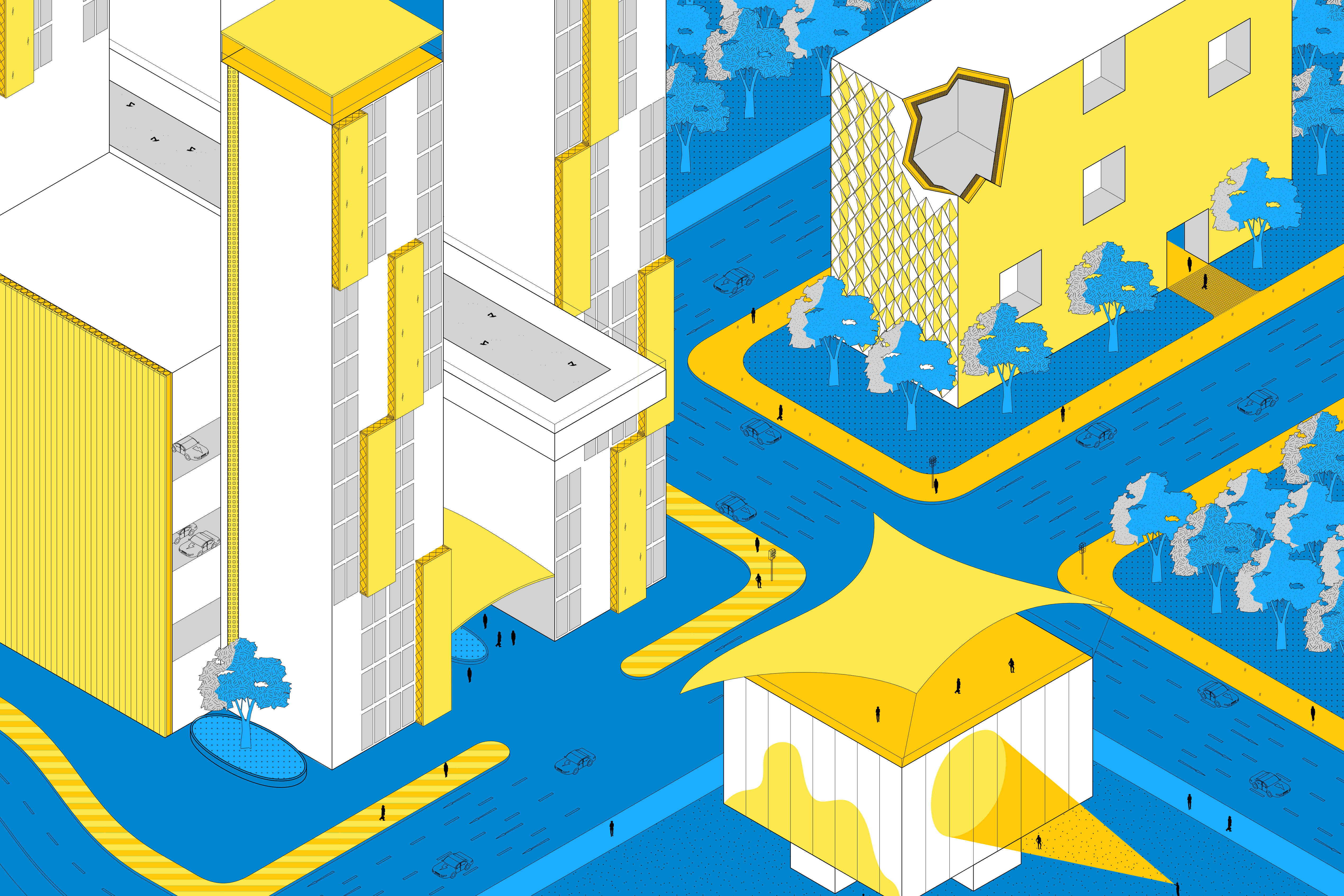
Gloria Pignatta
Cooling Singapore Researcher

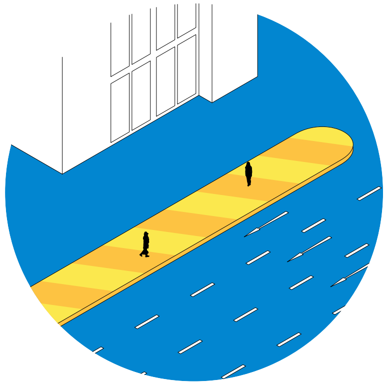
STREETS AND OPEN SPACES

Cool pavements
Permeable surfaces
Photocatalytic cool pavements

BUILDINGS

Cool roofs
Cool façades
Photocatalytic cool building envelope
Retro-reflective materials
Phase Change Materials
Desiccant systems
Water cooling façade system
Thermochromic/selective materials
Dynamic and active roofs
Dynamic and active façades or building components
Building envelop performance





STREETS AND OPEN SPACES
COOL PAVEMENTS

Cool pavements are made of materials that reduce their surface temperature by reflecting a significant percentage of solar radiation and releasing thermal heat into the environment. These surfaces are usually a light colour, or white.

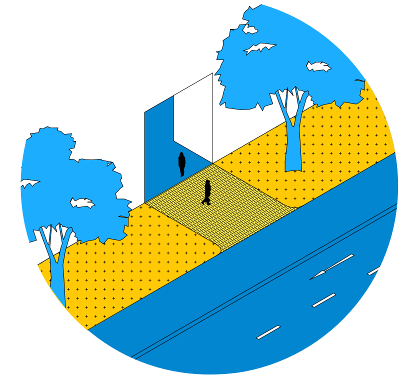
UHI & OTC effect
Cool pavements are characterised by high albedo (high solar reflectance) and high thermal emittance. Consequently, this reduces the urban heat accumulation responsible for UHI phenomena, especially in hot climates. However, this measure could worsen local OTC. The main positive effects of these materials are two-fold: one, reducing solar radiation absorbed by the pavements during the day, and two, releasing absorbed thermal heat into the atmosphere readily.

Tropical climate
This measure has special significance for Singapore because of the elevated position of the sun throughout the year, and the potential for lowering the outdoor temperature to improve liveability in the city.

Urban planning
Cool pavements could be obtained by implementing lighter coloured asphalt on streets and roads and also by the use of cool tiles or special coatings on urban pavements. An incorrect implementation of this measure, especially in high urban density areas such as urban canyons, could cause outdoor visual and thermal discomfort for pedestrians and drivers as well as an increase of cooling loads in surrounding buildings. Nonetheless, cool pavements could be developed in both public and private spaces.

State of the art
Conventional dark pavements absorb 80-95 per cent of sunlight, and thus show higher surface temperatures compared to cool pavements. The heat accumulated by the pavement surface throughout the day is then released into the air when the sun goes down and can affect urban night temperatures. This results in a warming of the surrounding air, and a contribution to the UHI effect (US Environmental Protection Agency 2008). Cool pavements, on the other hand are able to keep urban temperatures lower overnight (Asaeda and Ca 1993; Santamouris 2013). Other studies have also investigated the benefits of cool pavements using different high-albedo materials (Santamouris 2016) and the effect of ageing phenomena on their performance (Kyriakodis and Santamouris 2017).

STREETS AND OPEN SPACES
PERMEABLE PAVEMENTS



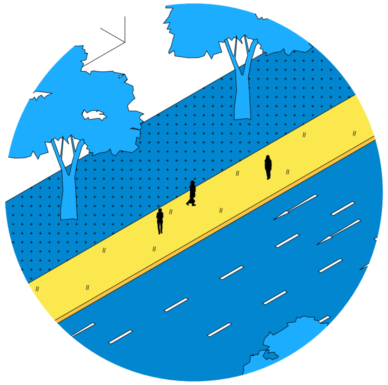
Water retentive and porous pavement systems, which include additional voids compared to conventional pavements, allow water to flow into the ground or into water holding fillers. This helps to store runoff so as to avoid pooling or ponding on the pavement surface. From a thermal perspective, these pavements also enhance water evaporation and therefore remain cooler than conventional pavements.

UHI & OTC effect
A permeable pavement measure provides benefits for pedestrians' thermal comfort allowing a reduction of the surface temperature of the pavements due to water evaporation and reduction in overheated material. When applied on large scale, it simultaneously contributes to UHI mitigation and also flooding risk reduction. It can also contribute to pollution control from surface runoff from roads and parking areas, and help with noise reduction.

Tropical climate
Avoiding extra and/or complicated maintenance is important for humid tropic scenarios. This environment can result in damage to the urban landscape. However, the evaporative cooling effect is more effective in hot climates. Negative effects include produced water vapour that acts as a greenhouse gas. Therefore, the greatest overall value of this measure may occur when multiple benefits, such as the improved stormwater management and outdoor thermal comfort, are factored into the measure evaluation.

Urban planning
This type of solution has become an important and integral part of sustainable urban drainage systems. Common applications can be public and private, such as vehicular access, parking, pedestrian access and bicycle trails (Scholz and Grabowiecki 2007). Implementation varies greatly across specific designs, and can be integrated with vegetation factors.

State of the art
According to Takahashi Katsunori and Yabuta Kazuya (2009), there are three key performance criteria for water retentive pavements: (a) ability to decrease surface temperature under good weather conditions; (b) capacity to suppress temperature rise after rainfalls; and (c) maximum durability and minimum decrease of performance over time. Studies carried out in California have shown that permeable pavements under wet conditions could give lower surface temperatures than impermeable pavements, but the cooling effect depends significantly on the availability of moisture near the surface layer and the evaporation rate (Li et al. 2013).



STREETS AND OPEN SPACES

PHOTOCATALYTIC COOL PAVEMENTS

Cool pavements are surfaces that have been treated, blended, coated, sprayed (before, during and/or after installation) with specific mixtures or additives that help them remain clean, and maintain a high level of solar reflectance over time. Generally, these treatments are based on photocatalytic properties.

UHI & OTC effect

Solar reflectance usually decreases over time, as soiling from traffic darkens the surfaces. Improving the self-cleaning capability of pavements and maintaining a high level of solar reflectance with photocatalytic treatments allows the original thermal and visual performance of the pavements to be retained. This helps maintain low values of surface temperature for pavements exposed to intense sun radiation and similarly, helps maintain low nearby air temperature values to improve pedestrian thermal comfort.

Tropical climate

Maintaining clean surfaces on cool pavements is an important part of the overall measure, and although applicable to all cities with different climates, can be considered a suitable solution for implementation in Singapore.

Urban planning

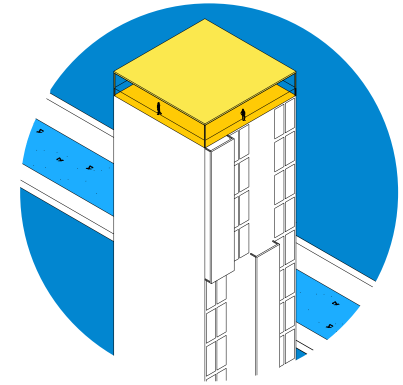
Implementation of photocatalytic cool pavements in Singapore is not regulated under any standards. Thus, they can be implemented both for private and public pavements, or in renovated or new pavement scenarios.

State of the art

Photocatalytic pavements have attracted much interest during the past decade. Their environmentally beneficial abilities to provide reactive (self-cleaning and smog-eating) and reflective (cooling) impacts have been deeply investigated (Sikkema et al., 2014). Some varieties of titanium dioxide (TiO2) are known for their ability to perform as photocatalytic agents in the oxidation reaction (Venturini and Bacchi 2009) and also to increase the solar reflectance and cooling property of the materials in which they are included. For these reasons, TiO2 is widely used as a component in photocatalytic cool pavements.

BUILDINGS

COOL ROOFS



Cool roofs are typically white or lightly coloured reflecting surfaces that are able to decrease their surface temperature and consequently heat transferred into the buildings below. They can be useful for reducing cooling energy consumption and energy costs in buildings.

UHI & OTC effect

Cool roofs can increase the albedo of the urban environment if widely applied, presenting a relatively high heat island mitigation potential. Cool roofs are characterised by high solar reflectance, but also by high thermal emittance. These positive effects reduce building energy consumption for cooling - thanks to their capability for increasing thermal losses and decreasing corresponding heat gains during sunny days (Santamouris, 2014; Akbari et al., 2006).

Tropical climate

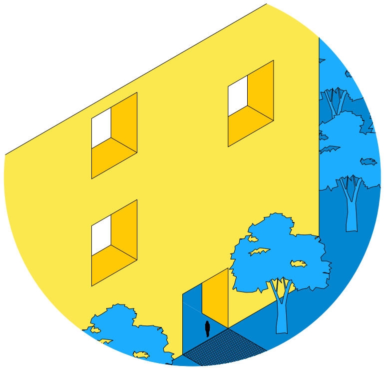
This measure has large potential in Singapore due to its equatorial position and sunlight hours, and to help mitigate major demand for cooling indoor spaces for both residential and commercial use.

Urban planning

The implementation of a cool roof measure is considered financially and technically viable, providing a cost-effective solution to increase building energy efficiency. It can be implemented both on flat and sloping roofs using cool solutions such as natural cool gravels, cool membranes in single ply or liquid mixtures, cool coatings, cool tiles and more (Pisello et al. 2014; Pisello et al. 2015).

State of the art

Reflective roofing materials have been extensively investigated to help improve the thermal comfort for occupiers of unconditioned buildings. Studies have shown that the expected decrease rate of the urban ambient temperature (at 2 meters height above ground at 12:00 LST) varies between 0.1 and 0.33 K per 0.1 increase of the roofs albedo with a mean value close to 0.2 K (Santamouris 2014). Recent studies involving the application of such solutions have resulted in important climatic benefits in Europe and US (Akbari and Levinson 2008; Synnefa and Santamouris 2012), and also in Asia (Jacey 2011).



BUILDINGS

COOL FAÇADES

Cool façades are covering layers of building façades that limit the absorption of solar radiance. They help reduce the surface temperature of façades and cut both the heat transferred into the building, and the energy consumption needed for interior cooling.

UHI & OTC effect
The benefit of this solution consists mainly in increasing solar reflectivity and promoting emission accumulated heat using high thermal emissivity. The result is a reduction of both the building energy consumption for cooling and the temperature of the air in the cool façades proximity. The analysis of thermal effects on buildings and outdoor dense urban environment has shown interesting prospects for urban heat island mitigation (Doya et al. 2012). Thus, an improvement in OTC and UHI is expected by the implementation of this measure on large scale.

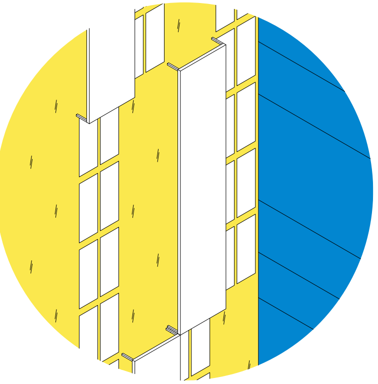
Tropical climate
The cool façade measure has considerable potential benefits for Singapore. It can be retrofitted, and can mitigate demand for indoor space cooling across a wide range of buildings.

Urban planning
The implementation of this measure is considered financially and technically viable, especially for south-oriented façades. It could be implemented by following specific façade design to avoid visual and thermal discomfort for passers-by.

State of the art
The potential of this technique has been proven in southern European climatic conditions (Georgakis et al. 2014). Cool façades considerably contribute to decreased surface temperatures and outdoor surface temperatures during summer (Pisello et al. 2017). Combining this solution with cool roofs (Pisello et al. 2015) showed significant indoor passive cooling and temperature reduction. Alchapar and Correa (2015) noted that the role of the vertical urban envelope is critical for reducing heat gains through multiple reflections within an urban canyon.

BUILDINGS

PHOTOCATALYTIC COOL BUILDINGS



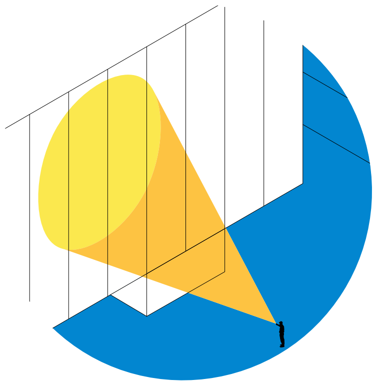
These are cool building envelopes such as cool roofs and cool façades that have been treated, blended, coated, sprayed with specific mixtures or additives that help building envelope surfaces remain clean and maintain a high level of solar reflectance unaltered in time. Generally, these treatments are based on photocatalytic reactions and they can be applied before, during and/or after installation.

UHI & OTC effect
Solar reflectance of cool roofs and cool façades decreases over time, as deposition from environmental agents darkens the surfaces. An improved self-cleaning capability can preserve a high level of solar reflectance to keep the original thermal and visual performance of such surfaces. This helps maintain low surface temperatures and reduce the potential building energy consumption particularly in hot climates where air conditioning is essential. The positive effects of this strategy in relation to the UHI phenomenon consist of limiting the potential increase of the phenomenon intensity and undesirable correlated effects.

Tropical climate
Cleaning cool roofs and cool façades should be part of cool building measures, although in many external applications, the photocatalytic effect allows self-cleaning, keeps painted surfaces cooler (thereby saving energy) and resists extreme weather conditions, requiring low maintenance. All these factors indicate it as a suitable solution for implementation in Singapore.

Urban planning
The implementation of photocatalytic cool surfaces in Singapore is not regulated by any standard. The treatments can be white or light coloured and they can be implemented in both private and public buildings, and in building envelopes to be renovated or that are new.

State of the art
Self-cleaning photocatalytic cool roofs and cool façades, based on the natural minerals calcium carbonite and titanium dioxide, have been developed to improve the environmental conditions meeting the growing demand for sustainable solutions. Several options can be found in the market. Titanium dioxide ($TiO2$) is widely used as components for the photocatalytic surface treatments (Fujishima et al. 2008) and its major applications include environmental pollution remediation, self-cleaning and self-disinfecting (Chen and Poon 2009).



BUILDINGS
RETRO-REFLECTIVE MATERIALS

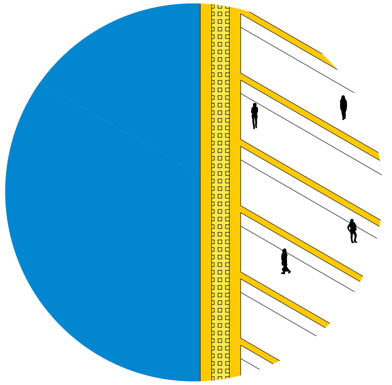
Retro-reflective materials are directionally reflective surfaces (non-diffusive surfaces) characterised by high albedo and the ability to reflect solar radiation back towards its source.

UHI & OTC effect
Retro-reflective materials contribute to the mitigation of extreme local overheating and UHI effects by lowering building cooling loads and electricity consumption (Synnefa et al. 2006). The decrease of building and urban surface temperatures, and consequently urban ambient temperatures, influence pedestrian thermal comfort in a positive way.

Tropical climate
This measure has a large potential benefit in Singapore because of the sun's intensity and the significant demand for resultant cooling.

Urban planning
Suitable applications in dense urban environments need to consider the negative effects such as overheating and glare in nearby buildings. Implementation should be focused on roofs, façades, and pavements paying attention to the directionality of the reflected radiation.

State of the art
Innovative technologies, policies and programs have been established internationally to encourage the use of such a solution for its effectiveness when applied within different climate boundary conditions (Akbari and Matthews 2012). The effect of directionally selective reflector materials on the decrease of buildings and urban surface temperatures and therefore on urban ambient temperatures has been largely demonstrated over the course of the years. They are able to maintain lower surface temperatures, around 45°C, especially in extremely hot climate conditions compared to materials with low solar reflectance and thermal emittance (Parker and Sherwin 1998). The benefits deriving from their application over built urban surfaces can be accounted at single-building, inter-building, and global scale (Santamouris et al. 2001). At single-building level, annual energy savings up to 19 per cent were calculated for 14 kWh/m^2 of reflective roofs area in the metropolitan context characterised by a humid tropical climate (Xu et al. 2012). At inter-building scale (district scale), this solution can have a non-negligible positive impact on the local microclimate generating a strong reduction of the UHI phenomenon. Its application at a wider urban scale has the potential to improve the environmental air quality because less cooling energy demand means less power plant emissions released into the atmosphere (Rosenfeld et al. 1995).



BUILDINGS
PHASE CHANGE MATERIALS

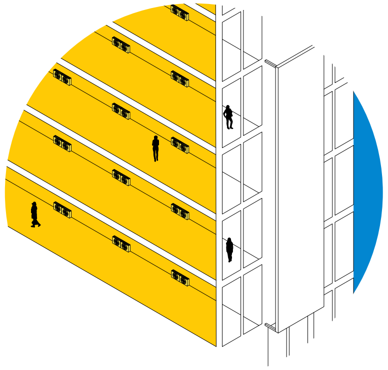
Phase change materials (PCMs) store and release massive latent heat during phase transition within a certain temperature range by increasing the building inertia and stabilising indoor air temperature.

UHI & OTC effect
PCMs help cut heat penetration into buildings and reduce the overall energy consumption, for both cooling and heating. It is considered a significant technology for the global warming solution (Lu et al. 2014). Indirectly, this solution will help mitigate UHIs and consequently improve the OTC.

Tropical climate
This measure, if well designed, can effectively reduce building cooling load in a tropical climate throughout the whole year when incorporated into building envelopes (Lei et al. 2016).

Urban planning
The integration of this measure needs to be done at building scale, incorporating the PCMs into the components of building envelope, such as roofs, walls, floors, and transparent surfaces and so on. The efficiency and selection of PCMs are subject to the local climate where they are applied, since the transition temperature can vary.

State of the art
Studies demonstrate that the integration of PCMs into the building envelope enhances the energy conservation and improves the indoor thermal comfort (Zhou et al. 2012; Kuznik et al. 2011; Baetens et al. 2010). The cooling effect provided by these materials in the tropics can be amplified when they are applied together with other passive measures such as cool coloured coating (Lei et al. 2017). However, few researches deal with the application of PCMs to buildings in tropical climates (Guichard et al. 2014; Pasupathy and Velraj 2008). The use of PCMs in Singapore faces unique challenges due to the small diurnal temperature variation that may reduce their efficiency and the relatively high night-time temperature that may not be adequate to remove the undesirable heat needed for PCM solidification at night.



BUILDINGS

DESICCANT SYSTEMS

Desiccant systems control moisture and use latent cooling to maintain a comfortable and healthy indoor environment. By absorbing water vapour from the air, the dehumidifying effect moves the workload from latent cooling to sensible cooling and delivers improvements in building energy efficiency.

UHI & OTC effect
A desiccant (hygroscopic material) is energy-efficient for dehumidification in air-conditioning systems in buildings (Gaoming Ge and Niu 2011). Desiccants remove moisture to reduce humidity and improve both air quality and energy efficiency. These systems offer thermal comfort in hot and humid climates along with lower primary energy resource consumption, compared to conventional cooling systems. The energy consumption savings allow reduced energy impact on the outdoor environment and therefore indirectly contribute to improving the OTC and mitigating the UHI.

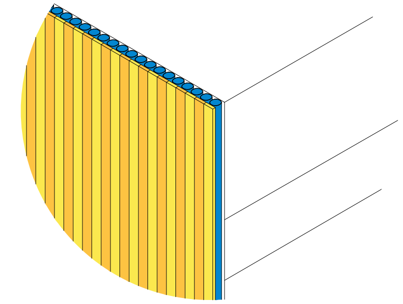
Tropical climate
A variety of dehumidification methods can be adopted in hot and humid climates. Desiccant systems, especially solid desiccant-based air conditioning systems, are feasible for use in Singapore.

Urban planning
Not applicable as this solution concerns indoor application.

State of the art
Desiccant materials - either solid or liquid – can be dried by adding heat supplied from natural gas, waste heat, or the sun, a free and clean energy (Sahlot and Riffat 2016, Rafique 2015). Solid desiccants like silica gel and molecular sieves are widely used in air-conditioning systems while liquid desiccants include lithium chloride (LiCl), lithium bromide (LiBr), calcium chloride (CaCl2), and triethylene glycol. Liquid desiccant dehumidification has some advantages over solid desiccant dehumidification (Factor and Grossman 1980) as liquid desiccant systems can be driven by low-grade heat sources such as solar energy or waste heat, and have the capacity for energy storage (Gaoming Ge and Niu 2011).

BUILDINGS

WATER COOLING FAÇADE SYSTEMS



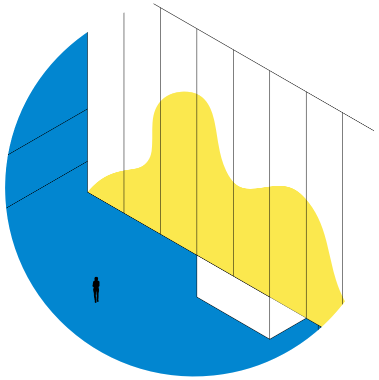
Water cooling façade systems transfer heat by evapo-transpiration outside the buildings by means of water integrated within the building façades. Evaporative cooling is a heat dissipation technique.

UHI & OTC effect
Water cooling façade systems allow a reduction in urban heat accumulation and consequent emissions from a building by decreasing the surface temperature. This has a consequent influence on pedestrian thermal comfort when applied at pedestrian level.

Tropical climate
This solution uses evaporation, so the potential application for tropical cities is substantial, especially if a large number of buildings could use such systems. At pedestrian level, the OTC can be improved, while indoor air temperature can also be reduced leading to a reduction in energy demand and cooling loads for many buildings, even those without the system in place.

Urban planning
Implementation should be focused on south-facing façades in particular where performance is enhanced by more intense solar radiation. Specific evaporative cooling solutions can be chosen and adapted for the purpose, in accordance with the architectural design of the building.

State of the art
Several solutions for evaporative cooling are available. Recent research proposes a double skin façade (usually characterised by air within the cavity and high thermal performance) with cooling pipes integrated within a shading device, such as a venetian blind, outside the façade. In this innovative system, cooling water produced by a cooling tower is circulated in the pipes to take away the radiant heat directly. The effectiveness of this type of façade cooling is more than 20 per cent across selected Chinese cities. In Urumchi, the effectiveness has been recorded up to 80 per cent due to its large solar radiation and efficient evaporative cooling. The innovative double skin façade is therefore energy-efficient, and has great potential for application in grand parts of the regions (Shen and Li 2016).



THERMOCHROMIC/SELECTIVE MATERIALS

This approach is suitable for building envelope application using reflective materials based on nanotechnological additives, such as thermochromic or selective materials. These respond thermally to their environment, changing colour (with reversibility) from darker to lighter tones according to the temperature increase. This passive cooling technique enables a decrease in heat gain by facilitating the elimination of excess heat in the indoor environment of a building to maintain high levels of thermal comfort.

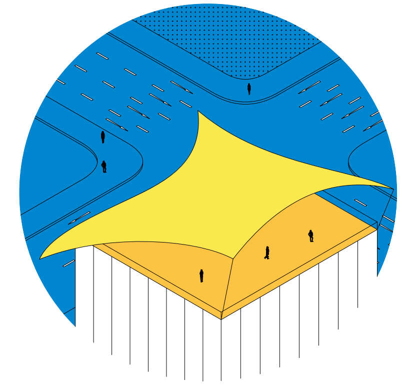
UHI & OTC effect
Thermochromic systems allow the prevention of heat gains inside a building. The use of thermochromic coatings can both contribute to energy savings and provide a thermally comfortable building environment (Ma et al. 2001). They also contribute to improvements in the urban microclimate.

Tropical climate
The application of thermochromic coatings (cool materials) in cities like Singapore, characterised by limited temperature variation, would not seem a cost-effective solution. Indeed, the benefit of colour change with temperature will be negligible, since the seasonality variation is limited.

Urban planning
Implementation should be focused on building envelope and urban structures in areas characterised by non-negligible air temperature variation. In this sense, including this aspect in building codes could help with their implementation.

State of the art
Most of the cooling energy demands in the tropics are directly related to building materials, particularly roofing. The passive cooling measure is a sustainable approach to cooling buildings and energy consumption reduction (Karmal 2012). Measurements carried out on spectral reflectance indicated that thermochromic coatings at the coloured phase (below the transition temperature of 30˚C) are energy-absorbing, while at the colourless phase (above the transition temperature of 30˚C) are energy-reflecting (Karlessi et al. 2009). Other measurements on the solar reflectance spectra of thermochromic building coatings showed that the solar energy absorption is higher below the transition temperature of 20˚C and lower above that of 20˚C (Ma et al., 2001).

DYNAMIC AND ACTIVE ROOFS



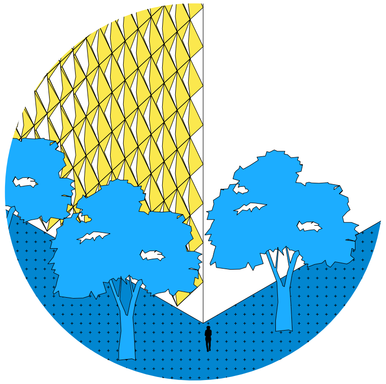
This measure concerns roofs that are characterised by the dynamic adaptation to environmental conditions, using manual, automatic or hybrid systems. The key purpose of these systems is to cool the roof by reducing heat accumulation, particularly when solar radiation intensity is high.

UHI & OTC effect
The advantage of this kind of dynamic measure is the ability to use roofs to adapt to the environmental conditions. This adaptation helps the roof maintain the optimal surface temperature and the building to exhibit better performance in terms of indoor cooling demand. This reduces CO2 emissions from cooling systems. The implementation of this kind of solution within the city could mitigate the UHI phenomenon and, as consequence, have a positive impact on the OTC.

Tropical climate
These solutions are more suitable for temperate rather than tropical climate as they need variable atmospheric conditions to be cost effective. This way, they can optimise the cooling and heating energy consumption. Nevertheless, some dynamic active roofs can also be effective in tropical climate if well designed, taking into account the low variability of atmospheric conditions.

Urban planning
Moveable systems can be applied to the roof, according to the local regulation on dynamic and active systems. The principle of functioning can differ from one solution to another (automatic systems, water systems, manual systems, hybrid systems, etc.).

State of the art
Dynamic active systems to make buildings more energy efficient have been developed in recent years, such as the Skytherm system (Raeissi and Taheri 2000). It is a roof covered with water-filled plastic bags equipped with moveable insulation to maintain good thermal behaviour. A study revealed that for a 140.55 m^2 one-storey house, the Skytherm system is capable of reducing heating demands by 86 per cent and cooling loads by 52 per cent. A similar and older solution was developed in Atascadero, California (Niles 1976) that consists of a roof with water-bags intermittently covered with 5 cm thick polyurethane insulation panels. The automatic control of the insulation guarantees the optimal cooling potentials of the system.



BUILDINGS

DYNAMIC AND ACTIVE FAÇADES

This approach uses manual, automatic or hybrid system building façades that can dynamically change their configuration to let the building adapt to the weather conditions. The optimal adaptation improves the thermal-energy performance of the building.

UHI & OTC effect
The UHI mitigation, and consequently the improvement of OTC, can be reached thanks to the use of dynamic building façades characterised by active systems that are able to improve the thermal-energy performance of the building envelope. Indeed, when the heat flux entering the building is reduced, the cooling energy consumption will be reduced accordingly, and less emissions would be released into the atmosphere by the cooling systems.

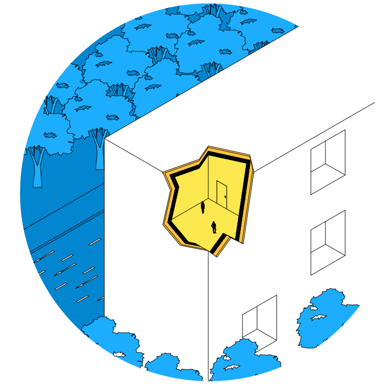
Tropical climate
These strategies produce benefits in tropical climates as well as in other climates. The benefits are higher when weather condition variability is high.

Urban planning
Implementation is related to building façades and can therefore be considered for both private and public applications. These solutions can be integrated into existing buildings or developed for new constructions.

State of the art
Dynamic solutions for building façades oriented to improve the energy efficiency of the building envelope can have different principles of functioning. An example is the Solaroof building developed in Canada (Solaroof building project 2010) that uses liquid bubbles to create insulation. When needed, a mass of soap bubbles held between two transparent skins on the building façade provides a thick transparent blanket of insulation or cooling shading. These systems require a small amount of electrical power for pumps and blower operation for bubble generation. They use some five per cent and 2.5 per cent of the normal consumption for cooling and heating, respectively. Such low energy requirements can be supplied from renewable sources.

BUILDINGS

BUILDING ENVELOPE PERFORMANCE



This measure improves the building envelope performance to minimise heat losses or heat gains through the use of high thermal-energy strategies such as specifying thick conventional insulations with very low U-values, innovative windows and doors, thermal plasters and more.

UHI & OTC effect
These solutions eliminate the risk of over-heating of the buildings during extreme heat periods. Therefore, the indoor cooling needs would be reduced, as well as the correlated emissions and heat released into the outdoor environment. The greater the use of this measure within a city, the greater the benefit for the urban environment in terms of UHI mitigation and improvement in OTC.

Tropical climate
High performance building envelopes protect the indoor environment from the prevailing outdoor conditions. This means super-insulation produces benefits in tropical climates where heat gains within the building can be minimised, and heat cannot be absorbed from the building envelope.

Urban planning
Implementation should focus on building roofs and façades and with the help of adequate building codes. Both public and private buildings can be improved from the application of high performing building envelopes. Some strategies can be also applied on both new constructions and retrofit applications.

State of the art
A building envelope isolates the indoor environment of a building from the variable outdoor conditions. Thermal insulation is a key factor that influences the heating and cooling loads of a building and therefore improving building envelope performance by increasing the thermal mass is an opportunity to reduce the energy demands. In a recent study, a composite material combining thermal insulation with cool material and photocatalytic coating has been developed to improve building energy efficiency and decrease both cooling and heating demands according to the climate (Chadiarakou and Antoniadou 2017). Another study proposes an energy-efficient technology, named Void Space Dynamic Insulation (VSDI), that couples low-cost conventional insulation materials with efficient ventilation to deliver high indoor air quality in thin wall constructions and works well both in cold and hot climates (Imbabi 2012).

REFERENCES

Akbari, H., Levinson, L. (2008). 'Evolution of Cool-Roof Standards in the US', Advances in Building Energy Research, 2(1): 1-32. doi:10.3763/aber.2008.0201.

Akbari, H., Matthews, H.D. (2012). 'Global cooling updates: Reflective roofs and pavements'. Energy and Buildings, 55: 2-6. doi:10.1016/j.enbuild.2012.02.055.

Alchapar, N.L., Correa, E.N. (2015). '6-Comparison of the performance of different façade materials for reducing building cooling needs', Eco-efficient materials for mitigating building cooling needs, Design, Properties and Applications, 155-194. doi:10.1016/B978-1-78242-380-5.00006-6.

Asaeda, T., Ca, V.T. (1993). 'The subsurface transport of heat and moisture and its effect on the environment: a numerical model', Boundary Layer Meteorology, 65: 159-179. doi:10.1007/BF00708822.

Baetens, R., Jelle, B.P., Gustavsen, A. (2010). 'Phase change materials for building applications: A state-of-the-art review', Energy and Buildings, 42(9): 1361-1368. doi:10.1016/j.enbuild.2010.03.026.

Chadiarakou, S., Antoniadou, P. (2017). 'Application of innovative composite cool thermal insulating material for the energy upgrade of buildings', Procedia Environmental Sciences, 38: 830-835. doi:/10.1016/j.proenv.2017.03.168.

Chen, J., Poon, C.S. (2009). 'Photocatalytic construction and building materials: from fundamentals to applications', Building and Environment, 44(9): 1899-1906. doi:10.1016/j.buildenv.2009.01.002.

Doya, M., Bozonnet, E., Allard, F. (2012). 'Experimental measurement of cool façades' performance in a dense urban environment', Energy and Buildings, 55: 42-50. doi:10.1016/j.enbuild.2011.11.001.

Factor, H., Grossman, G.A. (1980). 'A packed bed dehumidifier/regenerator for solar air-conditioning with liquid desiccant', Solar Energy, 24: 541-550. doi:10.1016/0038-092X(80)90353-9.

Fujishima, A., Zhang, X., Tryk, D.A. (2008). 'TiO2 photocatalysis and related surface phenomena', Surface Science Reports, 63: 515-582. doi:10.1016/j.surfrep.2008.10.001.

Gaoming, G.F.X., Niu, X. (2011). 'Control performance of a dedicated outdoor air system adopting liquid desiccant dehumidification', Applied Energy, 88: 143-149. doi:10.1016/j.apenergy.2010.06.019.

Georgakis, C., Zoras, S., Santamouris, M. (2014). 'Studying the effect of cool coatings in street urban canyons and its potential as a heat island mitigation technique', Sustainable Cities Society, 13: 20-31. doi:10.1016/j.scs.2014.04.002.

Guichard, S., Miranville, F., Bigot, D., Boyer, H. (2014). 'A thermal model for phase change materials in a building roof for a tropical and humid climate: model description and elements of validation', Energy and Buildings, 70: 71-80. doi:10.1016/j.enbuild.2013.11.079.

Imbabi, M.S-E. (2012). 'A passive-active dynamic insulation system for all climates', International Journal of Sustainable Built Environment, 1: 247-258. doi:10.1016/j.ijsbe.2013.03.002.

Jacey, P. (2011). 'Cool Roofs in APEC Economies: Review of experience, best practices, and potential benefits', APEC Energy Working Group.

Karlessi, T., Santamouris, M., Apostolakis, K., Synnefa, A., Livada, I. (2009). 'Development and testing of thermochromic coatings for buildings and urban structures', Solar Energy, 83(4): 538-551. doi:10.1016/j.solener.2008.10.005.

Karmal, M.A. (2012). 'An overview of passive cooling techniques in buildings: design concepts and architectural interventions', Acta Technica Napocensis: Civil Engineering & Architecture, 55(1): 84-97.

Katsunori, T., Kazuya, Y. (2009). 'Road temperature mitigation effect of "road cool," a Water-retentive material using blast furnace slag', JFE Technical Report, 13.

Kuznik, F., David, D., Johannes, K., Roux, J-J. (2011). 'A review on phase change materials integrated in building walls', Renewable and Sustainable Energy Reviews, 15: 379-391. doi:10.1016/j.rser.2010.08.019.

Kyriakodis, G-E., Santamouris, M. (2017). 'Using reflective pavements to mitigate urban heat island in warm climates - Results from a large scale urban mitigation project', Urban Climate. doi:10.1016/j.uclim.2017.02.002.

Lei, J., Yang, J., Yang, E-H. (2016). 'Energy performance of building envelopes integrated with phase change materials for cooling load reduction in tropical Singapore', Applied Energy, 162: 207-217. doi:10.1016/j.apenergy.2015.10.031.

Lei, J., Kumarasamy, K., Zingre, K.T., Yang, J., Wan, M.P., Yang, E-H. (2017). 'Cool colored coating and phase change materials as complementary cooling strategies for building cooling load reduction in tropics', Applied Energy, 190: 57-63. doi:10.1016/j.apenergy.2016.12.114.

Li, H., Harvey, J.T., Holland, T.J., Kayhanian, M. (2013). 'The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management', Environmental Research Letters, 8(1): 1-14. doi:10.1088/1748-9326/8/4/049501.

Lu, S., Li, Y., Kong, X., Pang, B., Chen, Y., Zheng, S., Sun, L. (2014). 'A review of PCM energy storage technology used in buildings for the global warming solution', Energy solutions to combat Global Warming, 33: 611-644. doi:10.1007/978-3-319-26950-4_31.

Ma, Y., Zhu, B., Wu, K. (2001). 'Preparation and solar reflectance spectra of chameleon-type building coatings', Solar Energy, 70: 417-422.

Niles, P.W.B. (1976). 'Thermal evaluation of a house using a movable-insulation heating and cooling system', Solar Energy, 18(5): 413-419. doi:10.1016/0038-092X(76)90007-4.

Parker, D.S., Sherwin, J.R. (1998). 'Comparative summer attic thermalp of six roof constructions report', The 1998 ASHRAE Annual Meeting, Toronto. 20-24.

Pasupathy, A., Velraj, R. (2008). 'Effect of double layer phase change material in building roof for year round thermal management', Energy and Buildings, 40: 193-203. doi:10.1016/j.enbuild.2007.02.016.

Pisello, A.L., Castaldo, V.L., Pignatta, G., Cotana, F., Santamouris, M. (2015). 'Experimental in-lab and in-field analysis of waterproof membranes for cool roof application and urban heat island mitigation', Energy and Buildings, 114:180-190. doi:10.1016/j.enbuild.2015.05.026.

Pisello, A.L., Castaldo, V.L., Piselli, C., Fabiani, C., Cotana, F. (2017). 'Thermal performance of coupled cool roof and cool façade: Experimental monitoring and analytical optimization procedure', Energy and Buildings. doi:10.1016/j.enbuild.2017.04.054.

Pisello, A.L., Castaldo, V.L., Piselli, C., Pignatta, G., Cotana, F. (2015). 'Combined thermal effect of cool roof and cool façade on a prototype building', Energy Procedia, 78: 1556-1561. doi:10.1016/j.egypro.2015.11.205.

Pisello, A.L., Pignatta, G., Castaldo, V.L., Cotana, F. (2014). 'Experimental Analysis of Natural Gravel Covering as Cool Roofing and Cool Pavement', Sustainability, 6: 4706-4722. doi:10.3390/su6084706.

Raeissi, S., Taheri, M. (2000). 'Skytherm: an approach to year-round thermal energy sufficient houses', Renewable Energy. 19(4): 527-543. doi:10.1016/S0960-1481(99)00079-8.

Rafique, M.M., Gandhidasan, P., Rehman, S., Al-Hadhrami, L.M. (2015). 'A review on desiccant based evaporative cooling systems', Renewable and Sustainable Energy Reviews, 45: 145-159. doi:10.1016/j.rser.2015.01.051.

Rosenfeld, A., Akbari, H., Bretz, S., Fishman, B., Kurn, D., Sailor, D., Taha, H. (1995). 'Mitigation of urban heat islands: material, utility programs, updates', Energy and Buildings, 22: 255-265. doi:10.1016/0378-7788(95)00927-P.

Sahlot, M., Riffat, S.B. (2016). 'Desiccant cooling systems: a review', International Journal Low-Carbon Technology, 11(4): 489-505. doi:10.1093/ijlct/ctv032.

Santamouris, M. (2013). 'Using cool pavements as a mitigation strategy to fight urban heat island - A review of the actual developments', Renewable and Sustainable Energy Reviews, 26: 224-240. doi:10.1016/j.rser.2013.05.047.

Santamouris, M. (2014). 'Cooling the cities – A review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments', Solar Energy, 103: 682-703. doi:10.1016/j.solener.2012.07.003.

Santamouris, M., Kolokotsa, D. (2016). Urban Climate Mitigation Techniques. London and New York: Routledge.

Santamouris, M., Synnefa, A., Karlessi, T. (2011). 'Using advanced cool materials in the urban built environment to mitigate heat islands and improve thermal comfort conditions', Solar Energy, 85: 3085-3102. doi:10.1016/j.solener.2010.12.023.

Scholz, M., Grabowiecki, P. (2007). 'Review of permeable pavement systems', Building and Environment, 42: 3830-3836. doi:10.1016/j.buildenv.2006.11.016.

Shen, C., Li, X. (2016). 'Thermal performance of double skin façade with built-in pipes utilizing evaporative cooling water in cooling season', Solar Energy, 137: 55-65. doi:10.1016/j.solener.2016.07.055.

Sikkema, J.K., Alleman, J.E., Cackler, T., Taylor, P.C., Bai, B., Ong, S-K., Gopalakrishnan, K. (2014). 'Photocatalytic pavements', Green Energy and Technology, 204: 275-307. doi:10.1007/978-3-662-44719-2_9.

SolaRoof project (2010) SolaRoof keeps it cool and hot. http://www.solaripedia.com/13/231/2413/solaroof_illustration_winter.html. Accessed 05.May.2017.

Synnefa, A., Santamouris, M. (2012). 'Advances on technical, policy and market aspects of cool roof technology in Europe: The Cool Roofs project', Energy and Buildings, 55: 35-41. doi:10.1016/j.enbuild.2011.11.051.

Synnefa, A., Santamouris, M., Livada, I. (2006). 'A study of the thermal performance of reflective coatings for the urban environment', Solar Energy, 80: 968-981. doi:10.1016/j.solener.2005.08.005.

US Environmental Protection Agency (EPA) (2008). 'Cool Pavements', Reducing Urban Heat Islands: Compendium of Strategies.

Venturini, L., Bacchi, M. (2009). 'Research, design and development of a photocatalytic asphalt pavement', presented at the II International Conference Environmentally Friendly Roads (Enviroad), Warsaw.

Xu, T., Sathaye, J., Akbari, H., Garg, V., Tetali, S. (2012). 'Quantifying the direct benefits of cool roofs in an urban setting: Reduced cooling energy use and lowered greenhouse gas emissions', Building and Environment, 48: 1-6. doi:10.1016/j.buildenv.2011.08.011.

Zhou, D., Zhao, C.Y., Tian, Y. (2012). 'Review on thermal energy storage with phase change materials (PCMs) in building applications', Applied Energy, 92: 593-605. doi:10.1016/j.apenergy.2011.08.025.

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SHADING

SHADING

Shading is a key measure to improve OTC and mitigate UHI because it leads to the reduction of air and surface temperature and can therefore result in cooling benefits. Simultaneously, it affects the thermal sensation and adaption of pedestrians, mitigating heat stress. This measure is relevant during daytime, especially around noon when the sun angles are at the highest.

In Singapore, urban shading at street level can be provided by adequate urban geometry (e.g., aspect ratio) and building/street orientation. Additional physical control to solar access can be achieved through horizontal and vertical shading structures or devices. Nevertheless, any type of shading can affect other thermal comfort factors, such as natural ventilation and illumination. The shading provided by Singapore's high-density urban configuration can have a positive impact during the daytime, but a negative one during the night. Therefore, planning guidelines are necessary not only to promote but also control the shading of outdoor spaces, such as streets, plazas or parks, to improve the urban quality of the spaces.

This category has been divided into two sub-categories: Building Geometry and Shelter Design. The first deals with shading strategies provided by the orientation of buildings within an urban canyon and the integration of shading devices on building façades. These strategies address both UHI and OTC. The second sub-category, describes the different types of shading devices related to their location and functionality. These strategies are especially relevant for improving thermal comfort for the outdoors.

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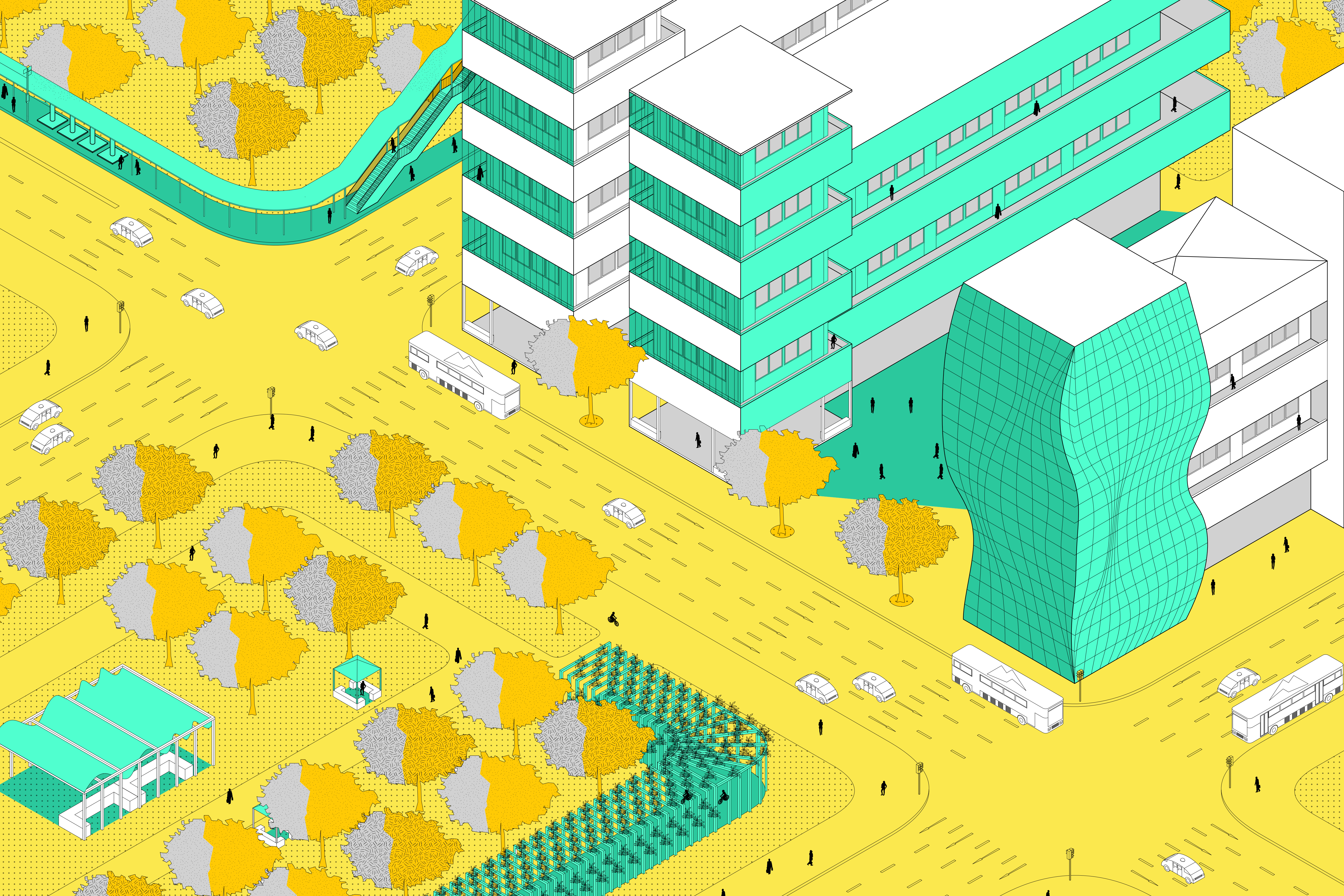
Cooling Singapore Researcher

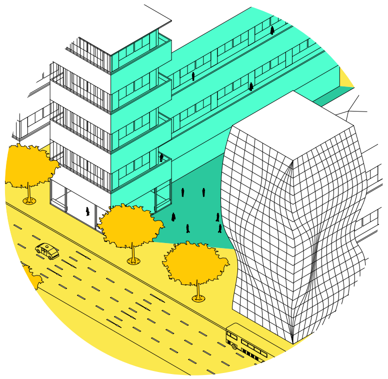
BUILDING GEOMETRY

Building orientation
Shading on buildings

SHELTER DESIGN

Permanent shading devices
Moveable shading devices
Smart shading devices
Shaded pedestrian spaces
Shaded bicycle lanes





BUILDING GEOMETRY
BUILDING ORIENTATION

Buildings can be positioned in relation to variations in the sun's path as well as prevailing wind patterns. An adequate orientation can increase the building performance and provide shade on nearby outdoor structures such as sidewalks, public spaces and streets,

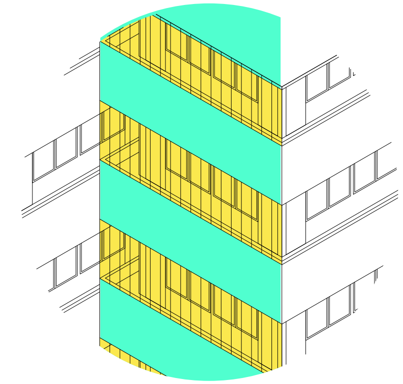
UHI & OTC effect
Optimised building orientation can lower the sun exposure and therefore minimise solar heat gains through the façades. Depending on the building orientation, direct, diffuse, and reflected radiation can be blocked, limiting short-wave radiation on surrounding/local outdoor spaces. Simultaneously, it can also decrease the surface temperature, contributing to the short-wave radiation reduction (Lin 2016). The orientation can also contribute to the shading of outdoor spaces and therefore increase the pedestrians' thermal comfort and reduce the air temperature.

Tropical climate
Because of the high temperatures, intense solar radiation, and high solar elevations during daytime, this measure is of special interest in Singapore. Building façades aim to exclude direct sunlight by using adjoining buildings, vegetation or devices as shading structures.

Urban planning
In relation to the sun path, buildings in Singapore should have a north-south orientation. East and west orientation (especially west orientation) should be minimised by providing sufficient shading or reducing the façade surface. Windows located on the west façade needs minimum shading of 30 per cent (BCA 2008). However, in relation to the wind patterns buildings should be oriented north-east and south-west in prevailing wind direction (BCA 2010).

State of the art
Emmanuel (2007) argues that urban shading at street level can be achieved through two strategies; (a) creating deeper street canyons; and (b) avoiding east-west orientation of outdoor spaces. Studies conducted by Yang (2016) in Singapore indicate that north-east, south-west and north-south orientation have better thermal environmental aconditions in the hot afternoon. The long façade should face towards the equator, while minimising the façade areas facing east and west. Haase and Amato (2008) show that the optimum building orientation in tropical climates ranges between 150° (Kuala Lumpur) and 188° (Bangkok) or south-southeast. Often the wind and sun parameters are contradictory, therefore a detailed analysis of the specific situation is needed.

BUILDING GEOMETRY
SHADING ON BUILDINGS



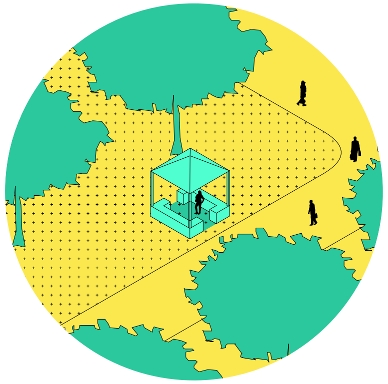
Building elements as shading devices can be installed outside or inside, on or around the building envelope. They can be fixed elements, such as canopies, brise-soleils, horizontal or vertical louvers, blinds, roof overhang, egg-crate; or moveable elements, such as sun baffles and shutters (Giguere 2009).

UHI & OTC effect
These elements function to control direct solar radiation as well as block and diffuse the reflective radiation of building envelopes (Stack et al.). They limit the heat gains and consequently improve the thermal comfort of both indoor and outdoor environments. They also increase the building energy performance by reducing the building peak cooling load, and therefore reducing the UHI effect.

Tropical climate
Between February and March, the average daily sunshine in Singapore typically lasts eight to nine hours, while during the rainy season between November and December, the average daily sunshine drops to four to five hours (Meteorological Service Singapore). Special attention has to be given to the east side façades in the mornings and the west façades in the afternoons.

Urban planning
Windows in façades facing east and west should be minimised and shading devices should be integrated to reduce solar heat gain. The most common shading elements used in the tropics are horizontal overhangs to block high-angle sunshine during midday and vertical fins to protect from low-angle sunshine during the morning and afternoon (BCA 2010).

State of the art
Seris showed that in the tropics, façades account for almost 50 per cent of the thermal loads in buildings. Particular attention has to be given to fully glazed curtain wall systems, commonly used in Singapore. Ali-Toudert and Mayer (2007) examined that overhanging façades, for instance on balconies, can lower the maximum Physiological Equivalent Temperature (PETmax) by around 4°C, especially when installed on the north-south and northwest-southeast façades. To eliminate the effect of absorbing solar heat, shading systems should be located on the external part of the window. The performance of shading devices is sensitive to factors such as local climate, building orientation, envelope design, materials and configurations of the shading itself. Although complete year-round shading is needed in Singapore, the design should not affect the natural illumination and ventilation of indoor spaces.



SHELTER DESIGN

PERMANENT SHADING DEVICES

Permanent shading devices are solid and fixed structures. They are horizontal or vertical shades that protect people from harsh sunlight all day. Some types of fixed devices are urban pergolas, shade sails, framed canopies, shelters, or even solar cells applied on façades. They are mainly permanent structures.

UHI & OTC effect
Shading devices can control the intensity of solar radiation, but should not obstruct the breezeway and allow a refreshing sensation to guarantee comfort. The effect of this measure depends on the material, geometry, dimension and location of the device. It is imperative to study the sun-path to define the type and properties of the shading device.

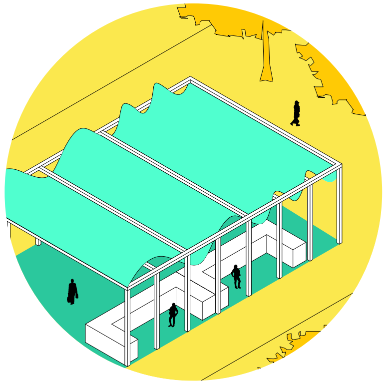
Tropical climate
Horizontal shading devices are especially important in Singapore to protect pedestrians and urban surfaces from the high sun angles during the solar noon. The size of the device can be determined by the shadow length needed.

Urban planning
Fixed devices can be applied to protect walkways, transport stops, park accesses, fixed urban furniture, or playgrounds. It is important that the design of fix shading devices can balance the amount of shade and natural light.

State of the art
Shading affects the experience and thermal perception of people in outdoor spaces. In hot and humid climates, it is key to assess the thermal sensation and adaptation of users in order to provide sufficient shading options. Emmanuel et al. (2007) studied the effect of urban shading in the tropics and concluded that horizontal shading is a necessary means to protect both pedestrians and urban surfaces especially around solar noon. The study also presents that shaded outdoor spaces can reduce the energy consumption of buildings. Nevertheless, Wong (2003) argues that while shading devices can give protection from solar radiation, they can also affect the availability of light and ventilation of urban spaces.

SHELTER DESIGN

MOVEABLE SHADING DEVICES



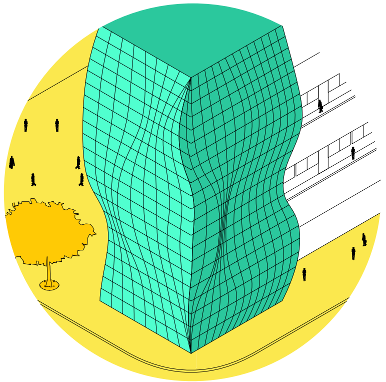
Moveable shading devices are operable, manual and automated shades. They allow users to adjust the spatial properties according to personal needs. Some types of mobile devices are autonomous canopies and temporary tents.

UHI & OTC effect
This measure fulfils similar purposes as the fixed shading device. It can adapt to the sky conditions, solar angle and time of the day, reducing direct sun exposure during extreme weather conditions. Additionally, it offers spatial and temporal flexibility, but is limited in the sense of dimension, material and durability. It can have a positive impact on the thermal comfort, especially in areas where permanent structures are not allowed or needed.

Tropical climate
Due to Singapore's proximity to the equator and the sea, its climate can vary within a day, offering clear or cloudy sky conditions. Therefore, moveable devices can serve as alternative shading structures that can adapt to the sun path, shading patterns and sky conditions to provide shading where it is needed at a particular time of the day.

Urban planning
Mobile devices are commonly light and simple to install. They can be applied in areas where additional shading is needed during the daytime, for example in parks, sports fields, or temporary public spaces. During night-time they can be removed. This allows flexibility and variety of shaded and sunlit areas all-day round.

State of the art
An option to improve the thermal comfort at street level is to modify the urban geometry by compromising the Sky View Factor (SVF). Instead, Swaid (1992) suggested having adjustable urban shading devices that can be attached to existing buildings when needed and retracted anytime. During day-time the street canyon can be reduced, providing more shading. This way the SVF during night-time will not be compromised, enabling sufficient ventilation. Moveable shading devices can adapt to different solar angles, providing shading where it is needed. Hyde (2000) recommends that horizontal shading devices be oriented towards the north and south, while vertical shading devices be oriented towards the east and west.



SHELTER DESIGN
SMART SHADING DEVICES

Smart shading refers to shading devices that apply materials to transform their properties by external stimuli, also called 'shape shifting materials'. Their transformation is reversible and can be repeated.

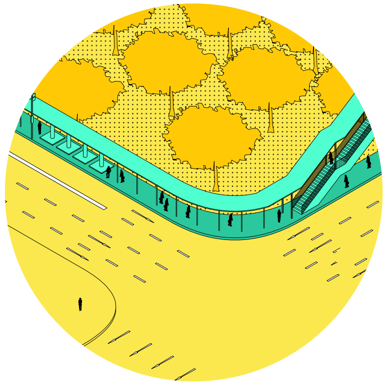
UHI & OTC effect
Smart materials can change colour, shape or density according to the temperature, humidity and light of the outside environment (BBC). Smart shading devices can adapt to the climatic condition and therefore control the solar heat gain.

Tropical climate
Smart shading can adapt towards the varying climatic condition in Singapore. On one hand, it provides protection from the intense heat during midday, while on the other hand it gives shelter from the afternoon monsoon rains.

Urban planning
This type of measure can be implemented in many scales, from roofs for public spaces to entire building façades.

State of the art
New high-tech smart materials have been developed that undergo changes upon exposure to temperature, such as Shape Memory Alloys (SMA), temperature-responsive polymers, chromogenic systems, magnetocaloric materials, and thermoelectric materials. Architect Decker Yeadon developed a Smart Screen and Homeostatic Façade System, based on R-Phase Shape Memory Alloys (SMA). The material expands or shrinks as temperature changes, allowing the façade to open and close to control solar heat gain through the façade (Yeadon Space Agency 2017). Architect Doris Kim Sung conducted research on thermobimetal, a material made by laminating two metals of differing thermal expansion coefficients. When the ambient temperature rises above 20°C or when sun penetrates the surface, the two different metals expand at different rates and cause the structure to curve (dO|Su Studio 2017). The Institute for Advances Architecture of Catalonia (IAAC) has been exploring the alternative uses of the composite material Shape Memory Polymers (SMP) that deforms and returns to original state as reaction to temperature, humidity, and light changes. IAAC (2017) is also investigating colour-changing materials like photochromic powders that allow for passive shading.

SHELTER DESIGN
SHADED PEDESTRIAN SPACES



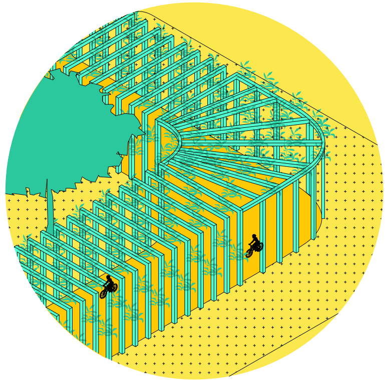
Shading or the protection against direct sunlight of pedestrian spaces can be provided by buildings, canopies or trees. Important locations of shaded spaces are schools, hospitals, elderly facilities, transit stops, parks and plazas, recreational spaces, food centres and shopping areas.

UHI & OTC effect
Shading of outdoor spaces can effectively reduce the air and surface temperature while enhancing the thermal satisfaction of pedestrians. Increased shading on street level can control the amount of solar radiation absorbed by the ground floor surfaces.

Tropical climate
Since the sun angles in the tropics are high, pedestrian streets should have north-south orientation. Buildings or vegetation can provide protection, especially on the east and west sides of the pedestrian spaces, to avoid heat gains. Shaded pedestrian walkways, such as walkways along Singapore's shophouses, are a good example for shading pedestrian areas.

Urban planning
The type of shading depends on the location, size, and function of the outdoor space. Different types of shading can have different impacts on pedestrians.

State of the art
The design of shaded pedestrian spaces should take into consideration the relationship between the year-long sun path and the users. Also, the time of exposure plays a significant role in the thermal comfort of outdoor spaces. The Malaysian Architect Ken Yeang has studied the covered walkway typology along shophouses, also called 'verandahway'. This typology allows pedestrians to wander the streets without being exposed to the direct sunlight. Due to high sun angles in Singapore, streets should be oriented north-south, providing shade in the morning and in the afternoon on one side of the street (Yang et al. 2016). Shading in urban spaces should be provided particularly between 12:00 pm and 3:00 pm, and preferably between 10:30 am and 15:30 pm (Ahmed 2003). A study on the thermal adaption of outdoor spaces found that pedestrians prefer spaces that have the availability of choice within different microclimatic conditions, such as areas with more sun or shade (Carmona 2014).



SHELTER DESIGN

SHADED BICYCLE LANES

The shading of bicycle lanes along designated lanes or along parks can be provided by buildings, trees, canopies or other existing infrastructure, such as bridges or elevated highways. They can shield cyclists from direct sunlight and high air temperatures, and help them have a comfortable ride, thus promoting active mobility.

UHI & OTC effect
Trees or permanent covers can provide shade along bicycle corridors. Such covers can block the direct solar radiation and protect from rain, and therefore contributing to cycling comfort.

Tropical climate
The high air temperatures and extreme level of humidity can make cycling a rather uncomfortable activity in Singapore. Recreational cycling is getting popular although there are not many designated bicycle lanes along the roads.

Urban planning
The location and orientation of the bicycle routes during planning are crucial to provide sufficient wind breeze and sun shade. An example is to locate bicycle lanes under wide infrastructure structures that provide sufficient shade length and protection from heavy rainfall.

State of the art
The location and orientation of bicycle lanes in relation to the sun-path can have a positive impact on the cyclist. A study investigated the effect of sunshields at red-light traffic stops and road intersections in relation to red-light running behaviours (Zhang and Wu 2013). It showed that the cyclists were about 1.4 times more likely to run through a red light when approaching the intersection without any sunshield. Another study suggested that the planning of streets include the shade rate along bicycle lanes (Zhao and Fang 2016). The shade rate is equal to the ratio of the shade length and the total length of the bike road.

REFERENCES

Ahmed, K.S. (2003). 'Comfort in urban spaces: defining the boundaries of outdoor thermal comfort for the tropical urban environments', Journal Energy and Buildings, 35(1): 103-110. doi: 10.1016/S0378-7788(02)00085-3.

Ali-Toudert, F., Mayer, H., (2007). 'Effects of asymmetry, galleries, overhanging façades and vegetation on thermal comfort in urban street canyons', Solar Energy, 81(6): 742-54. doi: 10.1016/j.solener.2006.10.007.

BBC. Materials and components: Smart and modern materials. Accessed on April 27, 2017. http://www.bbc.co.uk/schools/gcsebitesize/design/graphics/materialsandcomponentsrev4.shtml.

BCA - Building and Construction Authority (2008). Code for Environmental Sustainability of Buildings, 17.

BCA - Building and Construction Authority (2010). Building Planning and Massing: Green Buildings Platinum Series, 35-36.

Carmona, M. (2014). 'The Place-shaping Continuum: A Theory of Urban Design Process', Journal of Urban Design, 19(1): 2–36. doi: 10.1080/13574809.2013.854695.

dO|Su Studio. Project Bloom. Accessed April 27, 2017. http://dosu-arch.com/bloom.html.

Emmanuel, R., Rosenlund, H., Johansson, E. (2007). 'Urban shading - a design option for the tropics? A study in Colombo, Sri Lanka', International Journal of Climatology, 27(14): 1995–2004. doi: 10.1002/joc.1609.

Giguere, M. (2009). Literature Review of Urban Heat Island Mitigation Strategies, Quebec: Institut National de Sante Publique Quebec. 24-26.

Haase, M., Amato, A. (2009). 'An investigation of the potential for natural ventilation and building orientation to achieve thermal comfort in warm and humid climates', Journal Solar Energy, 83(3): 389–399. doi: 10.1016/j.solener.2008.08.015.

Hyde, R. (2000). Climate Responsive Design: A Study of Buildings in Moderate and Hot Humid Climates. London: Taylor & Francis.

IAAC - Institute for Advanced Architecture of Catalonia. Responsive Architecture. Accessed on April 22, 2017. http://www.bbc.co.uk/schools/gcsebitesize/design/graphics/materialsandcomponentsrev4.shtml.

Lin, T. (2016). 'Management of shading and public spaces', Urban climate challenges in the tropics: rethinking planning and design oportunities. London: Imperial College Press. 56-57.

Meteorological Service Singapore. Climate of Singapore. Accessed on July 5. 2017. http://www.weather.gov.sg/climate-climate-of-singapore/.

Oke, T.R. (1988). 'Street Design and Urban Canopy Layer Climate', Energy and Buildings 11(1-3): 103–113. doi: 10.1016/0378-7788(88)90026-6.

Ong, B.L., Hin, K., Ho, D. (2016). 'Green Plot Ratio - Past, Present & Future', presented at Conference iNTA2012 - Tropics 2050, Singapore.

Stack, A., Goulding J., Lewis, J.O. (2010). Shading Systems: Solar shading for the European climates. ENERGIE Programme of the European Commission, 1-2.

Seris. Façade Technology. Accessed on July 5, 2017. http://www.seris.nus.edu.sg/activities/façade-technologies.html.

Swaid, H. (1992). 'Intelligent Urban Forms (IUF): A new climate-concerned, urban planning strategy', Theoretical and Applied Climatology, 46(2): 179-191. doi: 10.1007/BF00866098.

Wong, N.H., Istiadji, A.D. (2003). 'Effects of external shading devices on daylighting and natural ventilation', presented at Eighth International IBPSA Conference, Eindhoven, 475–482.

Yeadon Space Agency. Projects Homeostatic Façade System. Accessed on April 27, 2017. http://www.yeadonspaceagency.com/projects/ .

Yang, F., Qian, F., Zhao, W. (2016). 'Towards a Climate-Responsive Vertical Pedestrian System: An Empirical Study on an Elevated Walkway in Shanghai China', Sustainability, 8(8): 744. doi: 10.3390/su8080744.

Zhang, Y., Wu, C. (2013). 'The effects of sunshields on red light running behavior of cyclists and electric bike riders', Accident Analysis and Prevention, 52: 210–218. doi: 10.1016/j.aap.2012.12.032.

Zhao, J., Fang, Z. (2016). 'Research on Campus Bike Path Planning Scheme Evaluation Based on TOPSIS Method: Wei'shui Campus Bike Path Planning as an Example', Procedia Engineering, 137: 858–866. doi: 10.1016/j.proeng.2016.01.326.

006
TRANSPORT

TRANSPORT

Provided that internal combustion engine vehicles have between 16-20 per cent efficiency, almost all of the rest of the energy contained in the fuel is transformed into heat, which inevitably increases the magnitude of the urban heat island (UHI) effect. Mitigation measures related to transport are typically applied on a city-scale rather than locally and coincide with standard congestion minimisation strategies from the field of transport. The amount of heat generated by a vehicle is directly proportional to the amount of consumed fuel, which is, in the urban case, roughly inversely proportional to the average speed of the vehicles. Therefore, all measures that reduce congestion in a transport system can be considered mitigation measures for reducing heat flux coming from vehicles.

Singapore's transport sector is responsible for 25 per cent of the total oil consumption of the country (Singapore energy statistics, 2014), thus making transport one of the biggest producers of heat on the island. The high level of infrastructural organisation and the technologically advanced state of the city allow it to adapt relatively easy to some highly effective strategies to mitigate UHI. Furthermore, transport is a highly critical system due to the tropical climate, which makes commuting via walking or biking not such a popular mode of transport.

This catalogue contains several general strategies in its first sub-category, which mostly deals with reducing the demand, more specifically the amount of vehicles on the road, but also includes solutions related to vehicle routing. The second sub-category deals with more technical solutions, which reduce the energy consumption and therefore the heat emission under already fixed general traffic conditions. The third sub-category deals with more specific low-level strategies to reduce the heat flux coming from vehicles and increase the thermal comfort of daily commuters.

Jordan Ivanchev
Cooling Singapore Researcher

TRAFFIC REDUCTION

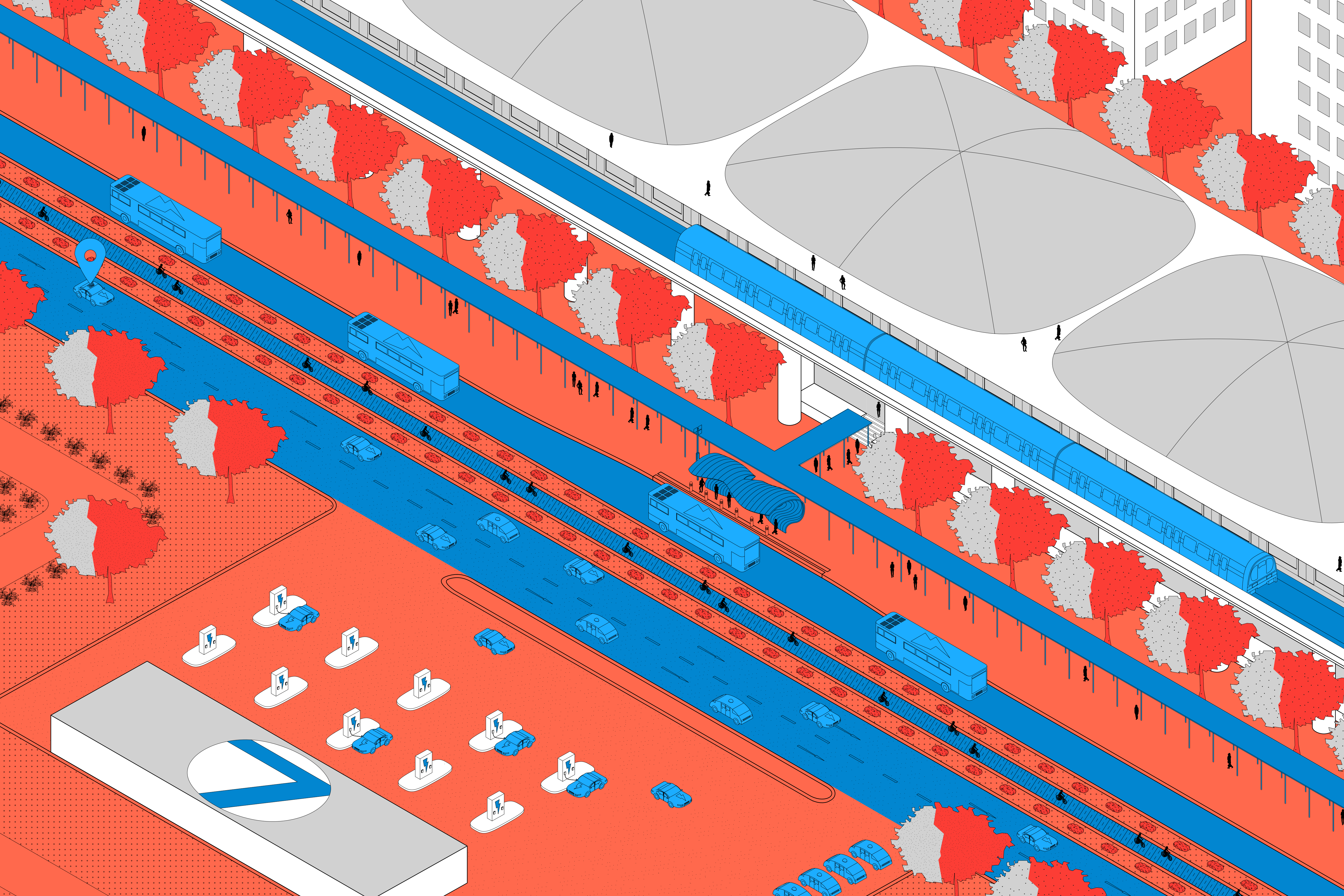
Vehicle population
Public transport
Centralised routing system
Active mobility

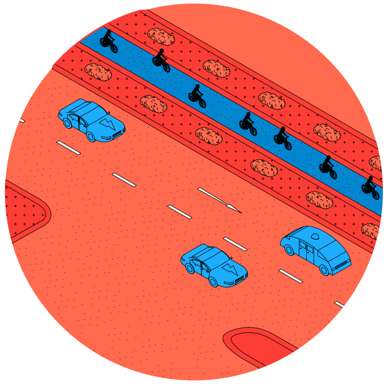
FUEL CONSUMPTION

Electric private vehicles
Electric public transport
Autonomous mobility

HEAT FLUX REDUCTION

Infrastructure of buses/bus stops
Types of road materials
Material and colour of cars





TRAFFIC REDUCTION
VEHICLE POPULATION

Reducing the number of vehicles is a straightforward approach to reducing heat production due to transport. The reduction of the number of vehicles in a system can be done by making it expensive to purchase, own and drive a private vehicle. This prompts more people to use public transport, and encourages or enforces ride sharing (Santi et al. 2014).

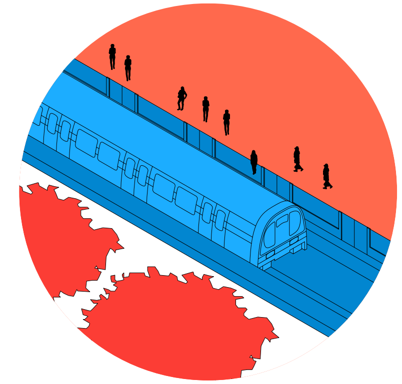
UHI & OTC effect
Provided traffic situation is constant if the vehicle size is reduced in half, the heat generated from the vehicle population would also be halved. Reducing the number of vehicles, however, also improves traffic conditions, which in turn reduces average fuel consumption and therefore further minimises heat generation. Fuel consumption and therefore heat generation grows exponentially with the number of vehicles. Therefore, removing a small number of vehicles from a congested system might have a much bigger relative impact on the reduction of generated heat, which has a positive impact on UHI. Furthermore, the OTC in close proximity to roads will be improved.

Tropical climate
Additional heat coming from vehicles is particularly important in tropical climate areas where a reduction of temperature typically means improvement of OTC.

Urban planning
Singapore has already made notable progress in minimising the number of vehicles on the road by making it expensive for commuters to own vehicles. The certificate of entitlement (COE) and a yearly vehicle quota make Singapore one of the countries with lowest cars to person ratio. Furthermore, the electronic road pricing (ERP) system makes it even more expensive to reach the busy parts of the city by car or taxi. Efforts are, however, still needed to make the public transport system even more appealing to the population and to educate commuters on the importance of ride sharing.

State of the art
It has been empirically shown that fuel consumption scales up in the same way as average travel time (Treiber et al. 2008) and that the average speed of traffic flow decreases nonlinearly with the number of vehicles in the transport system (Daganzo et al. 2008, Geroliminis et al. 2008).

TRAFFIC REDUCTION
PUBLIC TRANSPORT



In order to increase public transport usage, it is essential to generate incentives and improve the quality of transport services so that a larger portion of the population opts to use it.

UHI & OTC effect
Public transport is by far the most efficient means of people transportation. A car can transport people at a rate of 5 passengers per trip, bus at a rate of 130 while effectively taking the space of about 3 cars on the road. An MRT train can transport 1920 people, and contributes nothing to congestion. So convincing 130 people to use the bus instead of a private car effectively removes 127 vehicles from the road. This in turn reduces the amount of vehicle heat generated and is therefore a strong mitigator against the UHI effect. A reduction of heat generation would also improve the thermal comfort in close proximity to the road network.

Tropical climate
Increasing the use of public transport is relevant in tropical climate areas as the conditions typically do not predispose the population to walking medium distances. Therefore, it is important that the public transport presents itself as a viable choice with adequate air-conditioning, comfort and convenience levels.

Urban planning
More people opting for public transport can drastically reduce transport-generated heat emissions and thus the UHI effect. Urban planners have to therefore ensure that the public transport system can handle the additional amount of passengers. If such a transition is not planned carefully, the commuters could spend excess time waiting for buses or trains; this would reduce their thermal comfort to a level that might push them to go back to private transport.

State of the art
Apart from the apparent strategies for making public transport more comfortable and convenient, novel technologies would make it more flexible. A study (Spieser et al. 2014) showed that only one third of the vehicle population in Singapore would be enough to satisfy the mobility needs of the population if a shared mobility on-demand concept was adopted. This would remove a large amount of vehicles from the road and reduce heat emissions due to transport.

TRAFFIC REDUCTION

CENTRALISED ROUTING SYSTEM

Traffic is typically spread heterogeneously on the road network. This means a small number of roads have extremely high demand while others remain underutilised. A centralised routing system would consist of a platform that takes in queries on trips from all users in the system and computes the optimal route for each of them.

UHI & OTC effect
In the presence of a centralised route planning system, the traffic demand on the network can be spread more evenly thus leading to a reduction of congestion, fuel consumption and heat generation, with consequent effects on UHI and OTC in proximity to the road network.

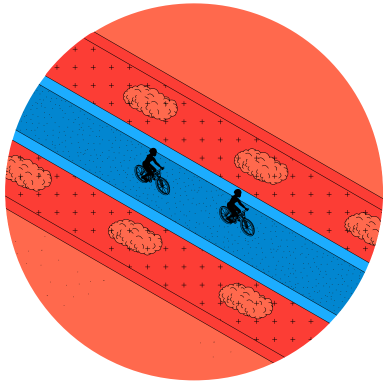
Tropical climate
In tropical climates, additional heat emissions due to high congestion levels are undesirable, thus making optimum routing a helpful tool for mitigating UHI effects and improving OTC.

Urban planning
The realisation of a centralised routing platform is largely in the hands of policy makers, who have to make the decision to inculcate the approach into the commuting habits of the population. The technology needed for the implementation of the system is already available, especially with the advances in the field of autonomous mobility. Therefore, the only step that needs to be taken is to educate the population and convince them to adopt this new approach.

State of the art
In the work of Roughgarden (2005), it is demonstrated that the degree of improvement of traffic conditions using such a system is unbounded, and grows with the level of congestion. Smart system routing algorithms such as BISOS (Ivanchev et al. 2016) have been shown to reduce fuel consumption and therefore heat production by as much as 15 per cent.

TRAFFIC REDUCTION

ACTIVE MOBILITY



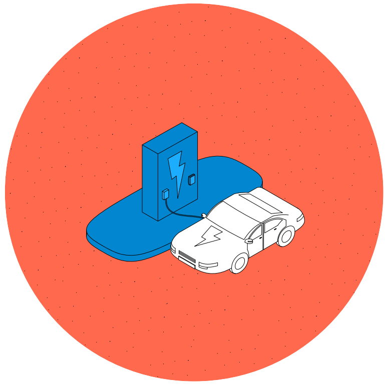
Walking, cycling or using electric scooters for short trips (or for the first and last mile of longer trips) is a viable option for reducing heat generation from the transport sector. Such modes of transport do not produce significant emissions.

UHI & OTC effect
Active mobility targets the same problem as the reduction in vehicle numbers and increased use of public transport: the reduction of the overall congestion. This measure, however, targets the first and last mile problems of typical trips. Ideally, this would result in less people using taxis, private vehicles or private vehicle transit services such as Uber and Grab. Singapore has 28,000 taxis (LTA statistics in brief, 2014), which during rush hours constitute 10-15 per cent of all vehicles, thus generating additional heat and increased congestion. A viable means of transport that combines public transport and a first/last mile solution would remove many private vehicles from the roads thus reducing heat production, with benefits to mitigating the UHI effect and improving OTC near roads.

Tropical climate
Active mobility includes commuting outside an enclosed space, thus commuters are subject to variations in weather conditions. Tropical areas are not ideal for exposed commuting due to the high temperatures and intense levels of rainfall.

Urban planning
Active mobility solutions are very sensitive to the type of population they are applied to. Urban planners need to undertake extensive surveys in order to understand the exact needs, comfort requirements, and decision-making logic of commuters that drive the take-up of active mobility solutions.

State of the art
Active mobility options such as utilising bike sharing platforms (Demaio et al., 2009), electric scooters (Shaheen et al., 2003) or walking all effectively reduce the number of vehicles and thus the heat generated from the transport sector.



FUEL CONSUMPTION

ELECTRIC PRIVATE VEHICLES

Replacement of conventional internal combustion engine (ICE) vehicles with electric vehicle (EV) transport.

UHI & OTC effect

The highest contributor (at more than 50 per cent according to Wagner et al., 2015) to heat from vehicles is exhaust, which is non-existent in an EV. The CO2 and other emissions also trap heat in the area, increasing the UHI effect (Chapman et al., 2007). The operating temperature of an ICE engine is 90-100˚C, which transfers significant heat to the environment. The operating temperature of an EV battery is 30-40˚C, which reduces the amount of heat exchange, especially in the case of Singapore, where the average atmospheric temperature is not far above this value. During braking in an EV, energy is harvested through regenerative braking and fed back to the battery, Constant acceleration and braking manoeuvres under congestion will thus have a smaller effect on energy consumption and heat generation from EVs. So less heat will be produced by transport, which will reduce the UHI effect and improve OTC close to road networks.

Tropical climate

As the operating temperature of an electric vehicle battery powering is very close to ambient temperature in tropical climates, the introduction of EVs would radiate almost no heat flux into the environment.

Urban planning

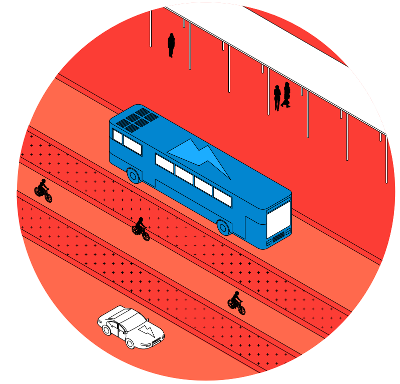
Large amount of planning is needed in order to shift users to using electric vehicles. The main challenge is building an efficient charging infrastructure, which will maximise efficiency and minimise the range anxiety of drivers. Furthermore, action and incentives must be implemented to convince early adopters within the population that electric vehicles have many positive effects apart from heat reduction.

State of the art

The average fuel efficiency of a modern car is 35.5 mpg (summary of fuel economy performance, 2011), which translates to about 1kWh per mile using ICE vehicle. The Tesla S vehicle uses around 0.3kWh per mile (Model S efficiency and range, 2012). This means that 70 per cent of the energy (which usually is transformed into heat) is saved by an electric vehicle.

FUEL CONSUMPTION

ELECTRIC PUBLIC TRANSPORT



Electrification of public transport is a natural step towards exploiting new technologies for the better of the commuting population and the environment.

UHI & OTC effect

Electrified public transport would be beneficial in terms of thermal comfort at bus stops, which is where the transport generated heat can often cause most discomfort. The lower running temperatures of EVs and the lack of exhaust would drastically reduce heat fluxes from buses. Furthermore, as buses are forced to make stops, which include many acceleration and deceleration manoeuvres, an electric bus would save significant energy and produce less heat due to regenerative braking technologies.

Tropical climate

Buses produce a higher amount of heat than smaller vehicles due to large engines; in tropical climates this means more heat flux is directed at passengers waiting at bus stops. In the case of electric buses there is almost no heat flux arising from the batteries.

Urban planning

Options for realising a charging infrastructure needed for battery electric buses (Rogge et al., 2015, Zhang et al., 2009, Beekman et al., 2016, You et al., 2016) are already available. Urban planners need to analyse the transport system and choose the most efficient and affordable option in order to ensure the smooth and consistent operation of the bus services.

State of the art

China launched its “Ten Cities, Thousand Vehicles Program”, which has put hundreds of battery powered electric buses on the roads since 2009. However, electric buses are still in development in most other parts of the world including the United States and Europe. One comparison between buses powered by alternative fuels and EV buses reveals the advantages of electric power in terms of fuel efficiency, emissions, noise pollution, speed of traffic and sense of comfort (Tzeng et al, 2005). There was a recent implementation of an electric bus service in Milton Keynes, UK (Miles and Potter, 2014).

FUEL CONSUMPTION
AUTONOMOUS MOBILITY

Autonomous mobility can severely increase the efficiency of a transport system via concepts such as platooning, optimum system routing, and virtual traffic lights. All these decrease fuel consumption and heat emissions.

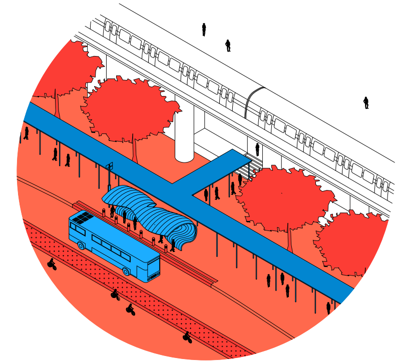
UHI & OTC effect
Platooning (convoys) of autonomous vehicles reduces the fuel consumption and increases the virtual capacity of roads, which in turn reduces congestion. This results in mitigation of UHI effects and increase in OTC close to roads. Furthermore, autonomous vehicles allow for automated routing using system optimum routing, which also reduces fuel consumption. The concept of virtual traffic lights can also be utilised for autonomous vehicles (AVs) (Ferreira et al., 2010). This concept allows cars to communicate with each other and coordinate passing through an intersection dynamically. This leads to less heat generation at intersections and better OTC at pedestrian lights. Virtual traffic lights are also shown to reduce CO_2 emissions by up to 18 per cent (Ferreira et al., 2012) thus cutting heat trapping in urban areas from transport related emissions.

Tropical climate
The first and last mile problems, which can be efficiently solved by autonomous mobility are critical in tropical climate environments as commuters are not inclined to undertake long walks to and from their home.

Urban planning
Although highly beneficial, autonomous vehicle technology is also disruptive for existing transport systems. Significant effort must be spent planning the integration of autonomous vehicles on the road to ensure safety while keeping comfort levels within acceptable norms. Fine-grained traffic simulation platforms are the primary support tool for this scenario; urban planners will need to rely heavily on them in order to choose the best measure.

State of the art
Platooning (Shladover et al., 2007), a group of cars travelling with small inter-vehicle distances in a single unit, is shown to reduce fuel consumption by up to 16 per cent (Davila et al., 2010) and to increase road capacity by up to 80 per cent (Segata, 2016). Virtual traffic lights minimise waiting time at intersections by increasing the vehicle flows by up to 60 per cent (Ferreira et al., 2010) thus reducing heat emissions at intersections.

HEAT FLUX REDUCTION
INFRASTRUCTURE OF BUSES/BUS STOPS



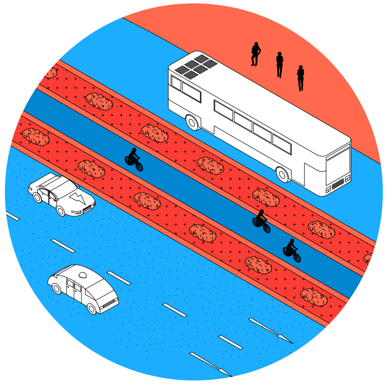
Bus stops are the locations where commuters are in closest proximity to the transport system. Redirecting heat fluxes coming from buses, increasing ventilation at the stop or shielding it from heat emissions can help increase the thermal comfort of commuters.

UHI & OTC effect
Singaporeans spend a total of 600,000 hours daily waiting at bus stops (LTA statistics in brief, 2014) while taking an average of 3.7 million bus trips per day. Therefore, comfort at bus stops is vital. Research indicates an almost immediate temperature increase of 3-4˚C when a bus pulls into a stop (Chung et al., 2015). This is an extremely unpleasant occurrence for commuters, thus reducing their OTC.

Tropical climate
This measure is highly climate specific. In tropical climates the outdoor thermal comfort challenges are almost exclusively related to mitigating heat sources. This is unlike four season locations where heat coming from a vehicle might even be comforting during winter.

Urban planning
Major sources of heat are the exhaust system and air-conditioning units of the bus. If those are routed to the road-facing side of the bus, the problem will be minimised. Furthermore, the bus stop or shelter can also be “shielded” against heat using some heat absorbing material or by turning the shelter 180 degrees around so that commuters are protected by the structure of the shelter. Alternatively, the bus stop can be elevated to avoid the direct heat flux from the bus. Additional aspects could include the shading of the bus stop and the provision of landscaping around the bus stop.

State of the art
The work of Zhang (2013) on bus stop urban design presents solutions that maximise the thermal and acoustic comfort at bus stops, together with shielding from environment, accessibility and vegetation.



HEAT FLUX REDUCTION

TYPES OF ROAD MATERIALS

Switching from asphalt roads to cement concrete ones can have positive effects on fuel consumption, heat generation, and on the albedo of the transport network.

UHI & OTC effect
Most roads in modern cities use hot mixture asphalt overlay material. Researchers are also investigating Portland cement concrete overlay. Concrete surfaces offer a smaller total energy cost and further reduce fuel consumption and therefore heat generation from heavy vehicles. In Singapore, trucks, buses and lorries constitute about 40 per cent of total vehicle population and 85 per cent of the annual mileage of the population. Heat production due to their drive cycle is therefore intensive (LTA statistics in brief, 2014). The temperature difference between asphalt and concrete is governed by their albedo; that of concrete is four times smaller than asphalt, so it absorbs less solar radiation (Guan et al., 2011, Gajda et al., 1997). Reducing the temperatures of the road, which in Singapore is around 9,000 lane kilometres, would reduce the transport-based UHI and improve OTC near roads.

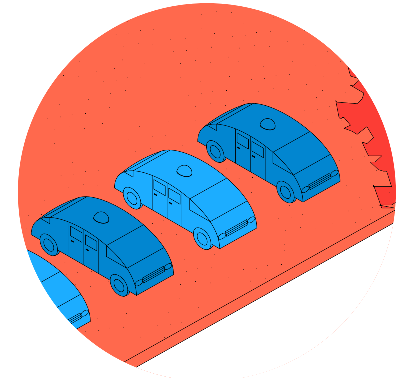
Tropical climate
The road system of a city is one of the main contributors to overall high albedo of the city's surface. While high albedo of the roads might be favoured in Nordic countries, where roads are often warmed to avoid ice formation, the opposite is true in a tropical climate where low albedo materials are preferred.

Urban planning
In terms of investment, concrete pavements require a higher initial cost but less investment overall. This is because of significantly smaller maintenance costs than asphalt (Gajda et al., 1997).

State of the art
Studies have shown that alternative materials can present less environmental burdens (Yu et al., 2012). Including lifecycle production, distribution, construction, usage and end of life options, the total energy cost of asphalt is twice that of concrete. Examining the effect of the pavement on the fuel consumption, Gajda et al., 1997 indicate that although conventional vehicles are not affected, trucks see lower fuel consumptions (between 10 per cent and 20 per cent) when travelling on concrete surfaces.

HEAT FLUX REDUCTION

MATERIAL AND COLOUR OF CAR PAINT



The paint colour chosen for the car chassis can have an impact on the in-car temperature and thus on the amount of energy used by the air-conditioning unit.

UHI & OTC effect
In a tropical location, using an air-conditioning unit in a car can be seen as a necessity. However research has shown that fuel consumption can rise by up to 22 per cent as a result of air-conditioning (Levinson et al., 2011). To reduce this energy expenditure, the interior heat level inside a car can be potentially lowered by choosing a more reflective paint colour. Also, the higher albedo of a white or silver paint colour effectively reduces the temperature of the chassis of the car, and the resulting heat flux from the vehicle.

Tropical climate
This measure is climate specific as it mitigates effects of continuous sun exposure on vehicles. Singapore is a good example of a location where this measure shows high efficiency due to the high intensity of solar radiation all year round.

Urban planning
Carmakers are aware of the effects of vehicle colour and offer predominantly light-coloured vehicles in high sun exposure regions. Nonetheless, officials could invest effort into education on the effects of paint colour, so that buyers can make an informed choice about vehicle colour.

State of the art
It is shown in Levinson et al. (2011) that painting car bodywork in white or silver will save two per cent of fuel. By reducing fuel consumption, gas emissions can be also reduced by1.9 per cent for CO2 emissions and 0.67 per cent for hydrocarbon emissions (HC). Less fuel consumed also means that less heat is being produced and radiated into the environment.

REFERENCES

Beekman, R. van den Hoed, R. (2016). 'Operational demands as determining factor for electric bus charging infrastructure', presented at 6th Hybrid and Electric Vehicles Conference (HEVC 2016), London.

Chapman, L. (2007). 'Transport and climate change: a review', Journal of Transport Geography, 15(5): 354–367. doi: 10.1016/j.jtrangeo.2006.11.008.

Chung, D.H.J., Hien, W.N., Jusuf, S.K. (2015). 'Anthropogenic heat contribution to air temperature increase at pedestrian height in singapore's high density central business district (CBD)', presented at ICUC9 - 9th International Conference on Urban Climate jointly with 12th Symposium on the Urban Environment, Toulouse.

Daganzo, C.F., Geroliminis, N. (2008). 'An analytical approximation for the macroscopic fundamental diagram of urban traffic', Transportation Research Part B: Methodological, 42(9): 771–781. doi: 10.1016/j.trb.2008.06.008.

Dávila, A., Nombela, M. (2010). 'Sartre: Safe road trains for the environment', presented at Conference on Personal Rapid Transit PRT@ LHR, 3: 2–3.

DeMaio, P. (2009). 'Bike-sharing: History, impacts, models of provision, and future', Journal of Public Transportation, 12(4): 41-56. doi: 10.5038/2375-0901.12.4.3.

Energy Market Authority. Singapore energy statistics 2014, Accessed on 19/06/2017, https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/SES14/EMA_SES%202014%20A5%20Public.pdf.

Ferreira, M., Fernandes, R., Conceição, H., Viriyasitavat, W., Tonguz, O.K. (2010). 'Selforganized traffic control', presented at Proceedings of the Seventh ACM International Workshop on VehiculAr InterNETworking, 85–90. doi: 10.1145/1860058.1860077.

Ferreira, M., d'Orey, P.M. (2012). 'On the impact of virtual traffic lights on carbon emissions mitigation', IEEE Transactions on Intelligent Transportation Systems, 13(1): 284–295. doi: 10.1109/TITS.2011.2169791.

Gajda, J., Van Geem, M.G. (1997). 'A comparison of six environmental impacts of Portland cement concrete and asphalt cement concrete pavement', PCA R&D Serial, 2068.

Guan, K. (2011). 'Surface and ambient air temperatures associated with different ground material: a case study at the University of California, Berkeley,' Surface and Air Temperatures of Ground Material.

Geroliminis, N., Daganzo, C.F. (2008) 'Existence of urban-scale macroscopic fundamental diagrams: Some experimental findings', Transportation Research Part B: Methodological, 42(9): 759–770. doi: 10.1016/j.trb.2008.02.002.

Ivanchev, J., Zehe, D., Viswanathan, V., Nair, S., Knoll, A. (2016). 'Bisos: Backwards incremental system optimal search algorithm for fast socially optimal traffic assignment', presented at IEEE 19th International Conference on Intelligent Transportation Systems (ITSC). 2137–2142. doi: 10.1109/ITSC.2016.7795902.

Land Transport Authority (2014). Annual vehicle statistics 2014. Accessed on 19/06/2017, https://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/Statistics%20in%20Brief%202014.pdf.

Levinson, R., Pan, H., Ban-Weiss, G., Rosado, P., Paolini, R., Akbari, H. (2011). 'Potential benefits of solar reflective car shells: Cooler cabins, fuel savings and emission reductions', Applied Energy, 88(12): 4343–4357. doi: 10.1016/j.apenergy.2011.05.006.

Miles, J., Potter, S. (2014). 'Developing a viable electric bus service: the Milton Keynes demonstration project', Research in Transportation Economics, 48: 357-363. doi: 10.1016/j.retrec.2014.09.063.

Musk, E., Straubel, J. (2012). Model S efficiency and range. Accessed on April 30, 2017. https://www.tesla.com/blog/model-s-efficiency-and-range.

NHTSA - National Highway Traffic Safety Administration et al. (2014). Summary of fuel economy performance, US Department of Transportation. Accessed on 19/06/2017, https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/performance-summary-report-12152014-v2.pdf.

Rogge, M., Wollny, S., Sauer, D.U. (2015). 'Fast charging battery buses for the electrification of urban public transport—a feasibility study focusing on charging infrastructure and energy storage requirements', Energies, 8(5): 4587 4606. doi: 10.3390/en8054587.

Roughgarden, T. (2005). Selfish routing and the price of anarchy. Cambridge: MIT Press.

Santi, P., Resta, G., Szell, M., Sobolevsky, S., Strogatz, S.H., Ratti, C. (2014). 'Quantifying the benefits of vehicle pooling with shareability networks', Proceedings of the National Academy of Sciences, 111(37): 13290–13294. doi: 10.1073/pnas.1403657111.

Segata, M. (2016). Safe and efficient communication protocols for platooning control. Ph.D., University of Trento.

Shaheen, S.A., Finson, R. (2003). 'Bridging the last mile: a study of the behavioral, institutional, and economic potential of the segway human transporter', Transportation Research Board, 03(4470): 13.

Shladover, S.E. (2007). 'Path at 20—history and major milestones', IEEE Transactions on Intelligent Transportation Systems, 8(4): 584–592. doi: 10.1109/TITS.2007.903052.

Spieser, K., Treleaven, K., Zhang, R., Frazzoli, E., Morton, D., Pavone, M. (2014). 'Toward a systematic approach to the design and evaluation of automated mobility on-demand systems: A case study in singapore', Road Vehicle Automation. Berlin: Springer. 229–245. doi: 10.1007/978-3-319-05990-7_20.

Treiber, M., Kesting, A., Thiemann, C. (2008). 'How much does traffic congestion increase fuel consumption and emissions? Applying a fuel consumption model to the ngsim trajectory data', presented at 87th Annual Meeting of the Transportation Research Board, Washington, DC.

Tzeng, G.-H., Lin, C.-W., Opricovic, S. (2005). 'Multi-criteria analysis of alternative-fuel buses for public transportation', Energy Policy 33(11): 1373-1383. doi: 10.1016/j.enpol.2003.12.014.

Wagner, M., Viswanathan, V., Pelzer, D., Berger, M., Aydt, H. (2015). 'Cellular automatabased anthropogenic heat simulation', Procedia Computer Science, 51: 2107–2116, 2015. doi: 10.1016/j.procs.2015.05.480.

You, P., Yang, Z., Zhang, Y., Low, S.H., Sun, Y. (2016). 'Optimal charging schedule for a battery switching station serving electric buses', IEEE Transactions on Power Systems, 31(5): 3473–3483. doi: 10.1109/TPWRS.2015.2487273.

Yu, B., Lu, Q. (2012). 'Life cycle assessment of pavement: Methodology and case study', Transportation Research Part D: Transport and Environment, 17(5): 380–388. doi: 10.1016/j.trd.2012.03.004.

Zhang, W.L., Wu, B., Li, W.F., Lai, X.K. (2009). 'Discussion on development trend of battery electric vehicles in china and its energy supply mode', Power System Technology, 4: 1-5.

Zhang, K.J. (2013). Bus stop urban design. Ph.D., University of British Columbia.

007
ENERGY

ENERGY

The urban heat island (UHI) effect increases the temperature of the environment surrounding the urban buildings, which has an immediate effect on the energy consumption for cooling or heating these buildings depending on the season. In winter, when buildings need to be heated, the UHI effect decreases the energy consumed due to lower heating demands whereas in summer, the UHI effect increases the cooling demand for these buildings.

Singapore has a tropical climate where the space cooling of building is a necessity throughout the year and therefore the UHI has a negative effect on the energy consumed. Thus, any mitigation measure developed with the aim of reducing energy consumption has dual effects: one, the direct reduction in energy consumption; and the other, the indirect contribution of reduced UHI effect, which in turn impacts energy consumption.

This category provides UHI mitigation strategies from the perspective of reducing energy consumption that can be divided into three sub-chapters. The first sub-category of Energy Consumption deals with the mitigation strategies involved in decreasing energy consumption in various sectors. This includes ways of improving the energy efficiencies of various equipment used in residential, commercial and industrial sectors. The second sub-category deals with Building Systems and the technical advancements that can be employed to improve energy savings. This discusses the use of renewable energy, implementing heat recovery measures in the existing systems. Outdoor Systems, the third sub-category, covers the equipment used in outdoor spaces and the ways to decrease energy consumption through them.

Sreepathi Bhargava Krishna & Gloria Pignatta
Cooling Singapore Researchers

CONSUMPTION

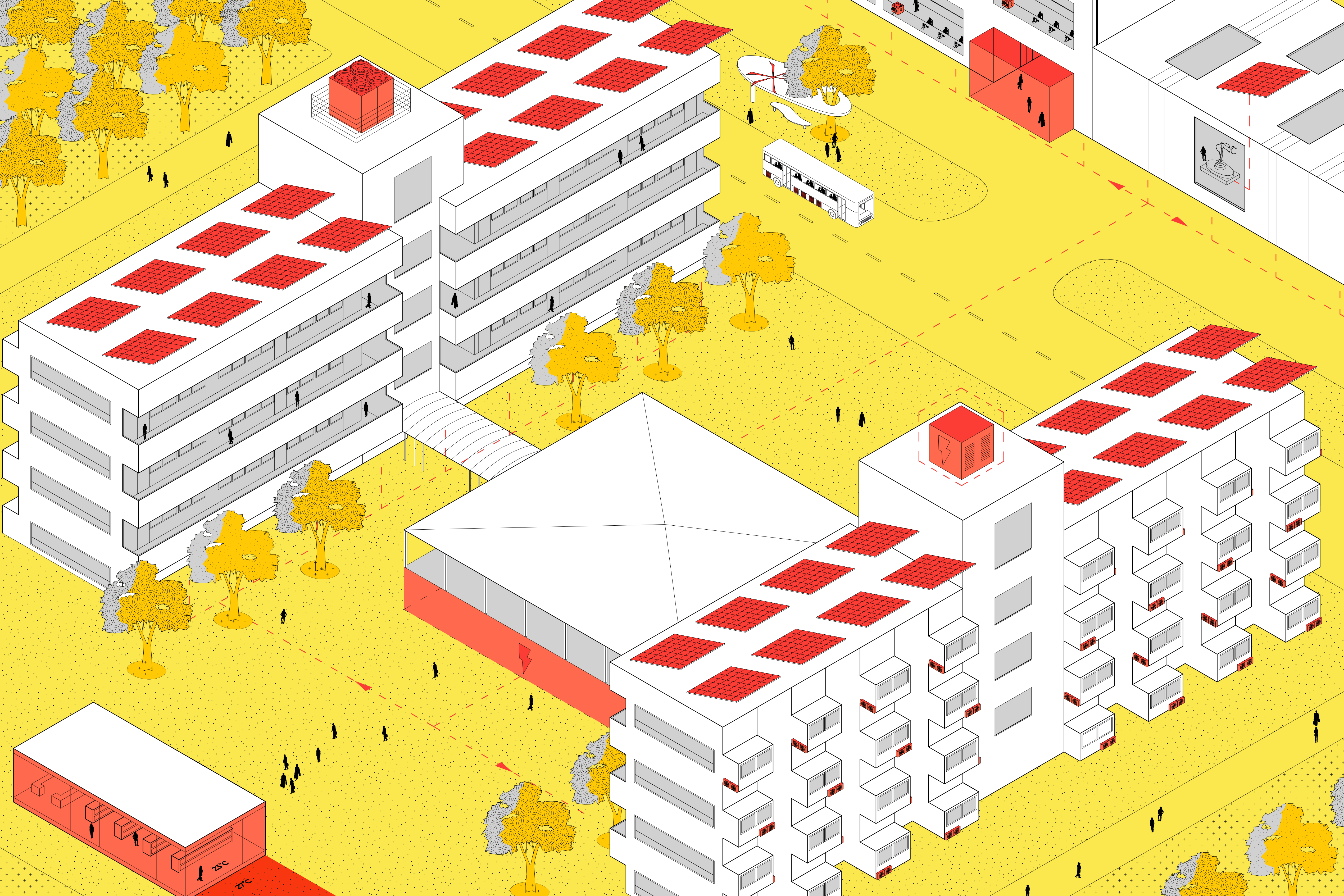
Heat losses in buildings
Energy efficiency of air-conditioning systems
Energy efficiency of household appliances and office equipment
Energy efficiency of industries
Cooling load of buses
Indoor temperature setting
Sizing of the energy plants
Ventilation for heat release of air-conditioning units
Window-to-wall ratio

BUILDING SYSTEMS

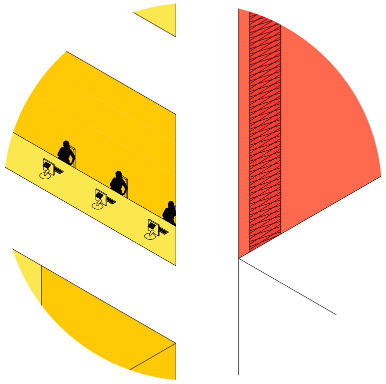
District Cooling
Renewable energy sources
Heat recovery systems
Mixed used neighbourhoods

OUTDOOR SYSTEMS

Buffer zones
Hybrid ventilation in outdoor spaces



23°C
27°C



CONSUMPTION

HEAT LOSSES IN BUILDINGS

Heat losses in buildings can be classified into three categories: transmission, ventilation and infiltration losses. Transmission losses include heat losses through walls, windows, ceilings and floors. Heat loss due to ventilation occurs when the air in the space is replaced with fresh air from outside. Heat loss due to infiltration occurs due to leakages present in buildings. The building management system (BMS) plays a major role in decreasing the heat losses in buildings. A careful and timely control of the systems such as heating, cooling and ventilation is vital in achieving satisfactory comfort levels, increased energy savings and reduced heat losses in buildings. The orientation and arrangement of the cooling system also helps in reducing heat losses in buildings.

UHI & OTC effect

Reducing heat losses in buildings and having airtight buildings decreases the energy consumption involved in space cooling. This decreases the heat release into the atmosphere and has a positive impact on UHI as well as the OTC near the building.

Tropical climate

The difference between indoor and outdoor temperatures in tropical climates is of high magnitude, thus the presence of any leaks in the buildings will increase the heat losses significantly.

Urban planning

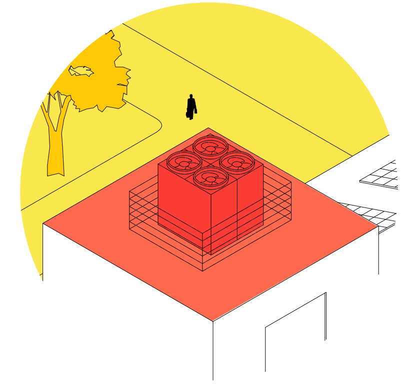
As buildings are recognised based on their energy performance, managing heat loss will provide an incentive for the implementation of good building automation practices. Heat losses are also accompanied by increased energy costs. A guideline of best practices for heat loss management needs to be provided based on the location to improve building performance. In Singapore, Green Mark labels incentivise buildings to save energy.

State of the art

Decreasing heat losses in buildings depends on improving the energy efficiency using appropriate techniques that complement the local climate (Rattanongphisat and Rordprapat 2014). BMS studies show that a sustainably built environment can be developed by meeting the thermal comfort levels while simultaneously decreasing the heat losses incurred in buildings (Kumara et al. 2016). Smart buildings are becoming a construction trend that facilitates the intelligent control of buildings to effectively manage the indoor comfort levels, energy consumption, and attain a trade-off between them (Shaikh et al. 2016).

CONSUMPTION

ENERGY EFFICIENCY OF AIR-CONDITIONING SYSTEMS



Air-conditioning is an essential building service to meet the cooling demand of buildings. Air-conditioning systems circulate cool air through supply ducts and the cooled air becomes warmer as it circulates through the home, which then flows back through return ducts. As space cooling is a large proportion of energy demand in buildings, improvement in the efficiency of these systems leads to significant cost savings. Installation of a new energy efficient air-conditioner can achieve 20-30 per cent reduction in energy consumed compared to the same cooling provided by an air-conditioner that is 10 years old.

UHI & OTC effect

Making air-conditioning systems more energy efficient means less energy is consumed to provide the same cooling demand, thus it has a positive impact on the UHI effect. Energy efficient air-conditioning systems also decrease the carbon emissions, thus reducing the global warming impact.

Tropical climate

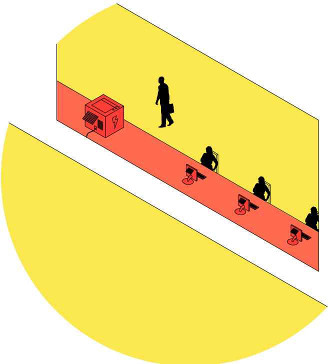
In tropical climates, there is a heavy duty on cooling technologies to remove both sensible and latent heat loads. Thus, installation and retrofit of energy efficient air-conditioning systems is important to decrease the energy consumption involved and the carbon emissions associated with it.

Urban planning

Though the benefits of energy efficient air-conditioning systems are evident, this does not overcome the initial roadblock of capital investment especially for retrofit scenarios. To aid this, there is a need to incentivise the installation or retrofit of air-conditioning systems to make them more energy efficient. This could be in terms of public recognition schemes. For example, Singapore provides certifications such as Green Mark Gold or Platinum rating when a building incorporates energy efficient technologies.

State of the art

Different studies have discussed the benefits of energy efficient air-conditioning systems, impact of new technologies and strategies on improving the efficiencies (Chua et al. 2013). Research on new air-conditioning systems is also being carried out to improve the energy efficiency (Yang et al. 2013). Research is also focused on developing materials that absorb water at variable levels of humidity, which goes a long way in developing energy efficient air-conditioning systems (Wade et al. 2013).



CONSUMPTION

ENERGY EFFICIENCY OF HOUSEHOLD APPLIANCES AND OFFICE EQUIPMENT

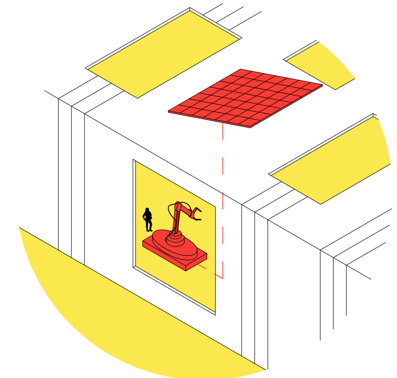
Household appliances such as air-conditioners, refrigerators, microwaves, kettles and blenders contribute to a significant amount of energy consumption within a residential building. To improve the energy efficiency of these appliances, it is good to choose the devices based on their energy rating. Devices of the same size but with different energy ratings consume different amounts of energy. Office equipment such as computers, printers and lighting also perform in a similar manner where devices of higher energy rating consume less energy compared to ones with lower energy rating. Apart from this, a behavioural change is also essential to make equipment energy efficient. For example, it is better to switch to a fan after running the air-conditioner for a short time.

UHI & OTC effect
Improving the energy efficiency of appliances decreases the overall energy consumption corresponding to the operation of these appliances. This indirectly has a positive impact on UHI. As the energy consumption is reduced, the carbon emissions corresponding to this are also reduced.

Tropical climate
In tropical climates, air-conditioners make the noticeable difference in energy consumption as the cooling loads are high compared to other climates.

Urban planning
A major part for the success of this mitigation measure depends on the involvement of people. To promote people participation, efforts need to be made to highlight the energy efficient practices and its impact. For office spaces, hiring a building manager could be made compulsory to take responsibility for implementing established energy management practices. Recognition schemes of buildings with the best energy-efficient practices also provide impetus for change to take place.

State of the art
Various studies have tried to uncover the impediments for implementing energy efficient practices in households. Contextual influences to change the behaviour of the residents to adopt energy efficient practices have been studied (Niemeyer 2010). Significant work has also been done in developing country-specific energy efficiency policy framework (Mills and Schleich 2012; Liu et al. 2013).



CONSUMPTION

ENERGY EFFICIENCY OF INDUSTRIES

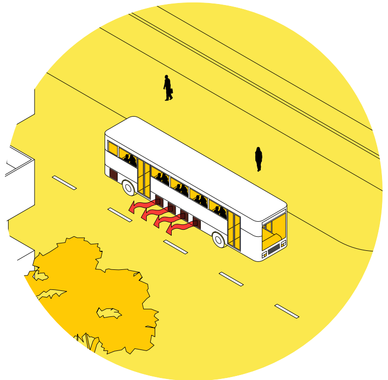
The industrial sector consumes more energy than any other end-use sector. Improving the efficiency of the energy consumed in industries will increase the revenue generated by industries. As improving the energy efficiency involves monetary benefits, industries are on the constant lookout for technological advances that are worth the retrofit costs. As the technological developments are rapid and often volatile, industries tend to go for ‘tried and tested’ retrofits.

UHI & OTC effect
Improving the energy efficiency of various processes involved in industries decreases the overall energy consumption and decreases the heat losses suffered during the processes. This indirectly decreases the UHI effect as the heat flux into the atmosphere is decreased. Reducing the energy consumption is directly linked to reducing the carbon emissions, which in turn improves the OTC in the long run.

Tropical climate
Making industries more energy efficient is profitable regardless of climatic conditions. This can be more prominent in the tropics, though, where the savings could further be invested in renewable energy sources like photovoltaic solar systems for power generation and decreasing the dependence on national grids.

Urban planning
Developing energy efficient systems is an incentive in itself as the savings in energy consumption can be quite significant. Regulations in the form of energy efficiency guidelines can further provide impetus in making industries more efficient.

State of the art
Various studies have established the benefits of improving the energy efficiency of industries. The adoption of advanced technologies could provide energy savings along with a reduction in carbon emissions (Smith et al. 2014). Heat recovery systems are extensively used in industries to utilise the waste heat available in the process streams (Sreepathi and Rangaiah 2014). Process industries are continuously updating their technologies to increase process efficiencies and decrease the energy losses (Rangaiah et al. 2015).



CONSUMPTION

COOLING LOAD OF BUSES

Internal environment in buses is important for the thermal comfort of the passengers. But often, the environment is maintained at much cooler temperatures to satisfy the peak occupation of the buses. As peak occupation occurs only at certain parts of the day, this incurs extra cooling load and causes further discomfort to the passengers. This raises the need to optimise cooling loads of buses based on the passenger occupancy and the surrounding climatic conditions.

UHI & OTC effect

Optimising the cooling load and thus decreasing the heat release to the environment directly impacts the UHI. As there is less heat flux, the UHI effect associated with this mode of transportation is decreased. Less heat release also improves the OTC as the exhaust streams have less waste heat and thus decreased amount of thermal pollution.

Tropical climate

As the climatic conditions are subject to rapid change in the tropics, it necessitates the development of a responsive control system instead of following a fixed cooling load in buses. In Singapore, where about 25 per cent of commuter journeys occur through buses, the savings in energy consumption achieved by optimising the cooling load of buses will be significant (Land Transport Authority Report, 2014).

Urban planning

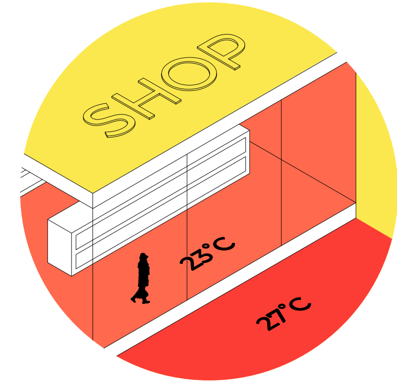
The provision of good public transport plays an important role in making a place sustainable. A set of guidelines needs to be developed and followed to optimise the cooling loads involved in buses. Efforts need to be made in improving the comfort levels of the passengers, which can be done by conducting surveys and getting feedback on the steps to be taken to improve travelling on buses.

State of the art

Various factors such as thermal transmittance and solar gain factor have been studied to optimise the energy performance of buses (De Lieto Vollaro et al. 2014). Different thermal comfort parameters such as the gradient of temperature and CO2 levels have been studied to evaluate the satisfaction of the passengers with the indoor environment (Patania et al. 2012).

CONSUMPTION

INDOOR TEMPERATURE SETTING



The setting of building indoor temperature needs to be optimised, keeping in mind the comfort levels of the residents of the building. Maintaining the indoor temperature – either lower than the comfort temperature or higher – has impact on the productivity of its residents. Having lower indoor temperature in tropical climates also increases the energy cost of the building.

UHI & OTC effect

Increasing the indoor temperatures and thus reducing the heat release to the environment has a positive effect on the UHI. This also relates to the decreased energy consumption, which further influences carbon emissions. Reduced heat release directly influences the OTC as there is less thermal pollution involved in cooling.

Tropical climate

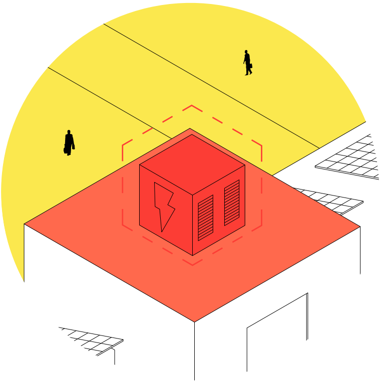
In tropical climate, space cooling accounts for a high proportion of the building energy requirements. An increase of 10°C of pre-set space cooling temperature can decrease the energy consumption up to 5 per cent without significantly impacting the thermal comfort of the residents.

Urban planning

As changes in the indoor environment influences the productivity and the comfort levels of the residents of building, it requires less persuasion for the implementation of this mitigation measure. A report detailing the ranges of optimal indoor temperatures based on building usage needs to be provided, which could serve to inform and even motivate the building managers in effective management of the indoor environment.

State of the art

Studies have shown that the variation in indoor temperature has significant impact on the productivity of the residents of the building (Jurelionis and Valančius 2013; Indraganti et al. 2013). In Singapore, the Nanyang Technological University (NTU) has achieved significant energy savings to date since 2011 by systematically managing and upgrading its air-conditioning systems through temperature set point management and chiller plant equipment upgrades.



CONSUMPTION

SIZING OF THE ENERGY PLANTS

Energy plants are generally sized based on the peak load experienced. This often leads to the operation of the plant at sub-optimal loads than what they were designed for, as the peak load only occurs at few instances. This can be countered by using multiple energy plants and controlling their operation to complement one another. This way, most of the time the energy plants are operated at their optimal performance levels and thus improves their efficiency.

UHI & OTC effect
The optimal sizing of energy plants improves its efficiency, thus decreasing the energy losses to the environment and has a direct positive impact on UHI. The decrease of energy losses also means reduced carbon emissions, which will improve the OTC in an indirect manner.

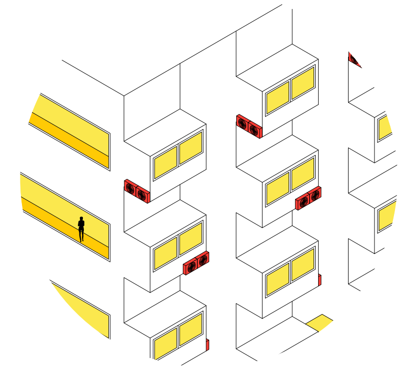
Tropical climate
In tropical climates, solar power, which is a renewable energy source, can be integrated along with a storage system to cater to the energy needs. As solar power is only available during daytime, a storage system is needed for the provision of electricity over longer periods. An effective control system along with the storage system will balance the load profile required by the consumers.

Urban planning
Regulations need to be enacted to diversify the sources of energy, which in turn will have impact on the sizing of the energy plants. Emphasis on the integration of multi-source energy plants along with a robust control system will eventually lead to optimal sizing of the energy plants.

State of the art
Building energy demands depend on the climate in which the building is located and on the characteristics of the building's envelope. Thus, the sizing of a multi-source energy plant is optimised based on the daily load profiles (Barbieri et al. 2014). Integration of renewable energy resources into power systems using storage systems provides the flexibility to balance the peak load and also forms a buffer for load variability (Hug and Kargarian 2016). Storage systems also counteract the intermittent nature of the renewable energy generation such as solar power (Doukas et al. 2012).

CONSUMPTION

VENTILATION FOR HEAT RELEASE OF AIR-CONDITIONING UNITS



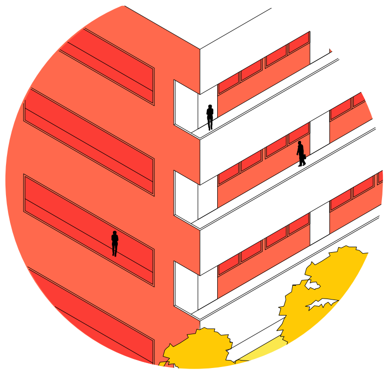
The heat released from the air-conditioning units not only influences the thermal environment around the building but also has profound impact on the energy consumption of the air-conditioner itself. Heat release into a well-ventilated area disperses this heat and decreases the immediate local impact. Leveraging the position of air-conditioner heat release along with the building construction that aims at using the wind flow to carry the heat released will reduce the impact of the issue.

UHI & OTC effect
Heat release into well ventilated areas will decrease the UHI effect as it reduces the concentration of heat into a small location and also influences the efficiency of the air-conditioner. This also has a positive impact on the OTC as the heat is now dispersed instead of being concentrated in the local atmosphere.

Tropical climate
In tropical climates, where the cooling demand is high, releasing heat into well ventilated areas will have far-reaching influence on the energy consumed. As the surrounding air is not heated up, the efficiency of the air-conditioning unit also improves.

Urban planning
Building design process needs to include the provision of well-ventilated areas for the heat release of air-conditioning units. Based on a case study in Singapore, it is found that stacking the exhaust of the air-conditioner in a high rise construction worsens both the performance of the air-conditioner and also the UHI effect (Bruelisauer et al. 2014).

State of the art
Recent studies have shown that the position of the heat release of the air-conditioner will lead to different energy consumption (Han and Chen 2017). Studies also show that the outdoor air-conditioning unit arrangement measure also influences the overall energy consumption (Duan et al. 2016). Field measurements also show that the temperatures in void spaces increased along the height of the building implying a stacking effect from the rejected heat, which is often neglected in the design process (Bruelisauer et al. 2014).



CONSUMPTION

WINDOW-TO-WALL RATIO

The Window-to-Wall Ratio (WWR) is the ratio of the total glazed surface to the total external wall surface of the building façade. This is an important parameter affecting the energy performance of a building and in particular, the energy consumption for heating, cooling and lighting. WWR is also affected by the access to daylight, ventilation and views.

UHI & OTC effect
The window surfaces play a significant role in shaping the overall energy demand in buildings (Li 2010), which contributes to the UHI phenomenon.

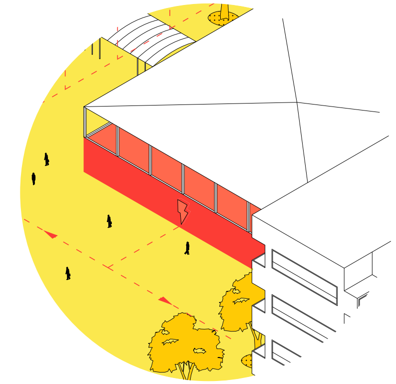
Tropical climate
In tropical climates, a high percentage of WWR in buildings is caused by excessive sunlight and heat infiltration. This means that a high value of WWR contributes to high-energy consumption for cooling for a fixed type of glazing (Yang et al. 2015). When the WWR is above 50 per cent, high performing glazing and/or shading systems are preferable (BCA 2010), especially in Singapore.

Urban planning
Building design process needs to define this parameter according to the maximum value suggested by the local code and building regulations. In some cases, a higher percentage of WWR can be chosen when high performance glazing systems are used. This way, a reduction of the unwanted solar gain through the window area can be still guaranteed and simultaneous natural daylight is able to enter within the indoor ambient. The preferred range of WWR to achieve both thermal and daylight performance is approximately 30 per cent (Rizki et al. 2016).

State of the art
In the design phase, contradictions often occur when trying to maximise daylight penetration and view (typically with large windows) while trying to minimise energy consumption (by applying small windows) (Rizki et al. 2016). In tropical climates, the cooling energy consumption is a major concern and the natural ventilation in buildings can contribute to minimising this energy demand (Aflaki et al. 2015) when the optimal WWR is defined. A study in Malaysia analysed the WWR and its impact on overall ventilation through measurements and simulations. It is found that with every 10 per cent increase in WWR, the cooling load increases by 1.3 per cent (Al-Tamimi and Fadzil 2012).

BUILDING SYSTEMS

DISTRICT COOLING



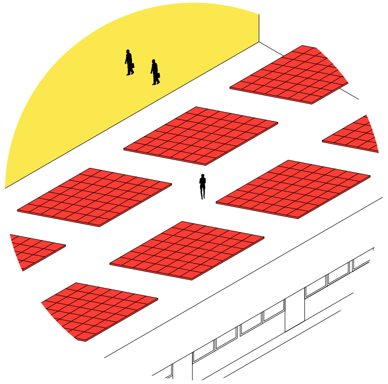
District Cooling is a system used for distributing chilled water generated in a centralised location to satisfy the cooling requirements of buildings (both residential and commercial). District Cooling provides higher efficiencies compared to multiple localised chillers and also helps in reducing the carbon emissions.

UHI & OTC effect
District Cooling indirectly affects UHI and OTC as it decreases the use of a number of local chillers for cooling. This affects the heat emitted into the environment by the buildings and thus decreasing the UHI effect. District Cooling improves OTC as cooling units can be placed in a strategic location to avoid their impact on the local air temperature.

Tropical climate
In the tropics, space cooling has high requirement both in commercial and residential use. District cooling provides a good alternative for the existing system of air-conditioners. District Cooling has higher efficiencies and consumes less energy for the same cooling load. It also helps in reducing the carbon emissions and thus helps in achieving the levels agreed in the COP21 Agreement.

Urban planning
Developing a District Cooling network involves high investment costs and as such its implementation needs to be incorporated in city planning. Countries need to formulate regulations to either facilitate the implementation of District Cooling or provide subsidies for buildings that use District Cooling. For example, Singapore has enacted The District Cooling Act favouring the implementation of District Cooling.

State of the art
Different studies have proven both the economic and environmental benefits of District Cooling systems (Werner 2017). District Cooling coupled with the use of seawater for condenser cooling brings in higher efficiency and this has been depicted in a Hong Kong case study (Chow et al. 2004). Singapore is operating one of the world's largest district cooling network in the Marina Bay district. The operator Singapore Power claims that the energy saved by implementing District Cooling can power up to 24,000 three-room Housing and Development Board apartment units.



RENEWABLE ENERGY SOURCES

Renewable energy is energy generated from natural sources that are continuously replenished. This includes sunlight, wind, geothermal, water, tides and various forms of biomass. The life cycle carbon emissions of the renewable energy sources compared to the traditional fossil fuels is significantly lower. As such, incorporating renewables within energy systems helps in meeting the COP21 standards.

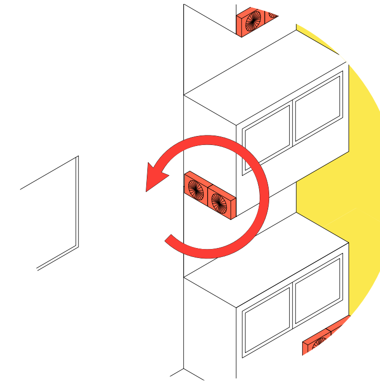
UHI & OTC effect
The use of renewable energy sources regulate the anthropogenic inducers of the UHI effect, thus increasing the share of renewables would directly help in decreasing the UHI impact. This also reduces the carbon emissions, thus reducing the global warming potential and indirectly effecting the OTC.

Tropical climate
The tropical climate enjoys good solar irradiance over the span of a year, thus making solar power a viable renewable energy option. Biomass production is an option but it depends on the availability of feedstock. If there is potential, wind and water (in the form of hydropower and tidal energy) are two of the cleanest energy sources.

Urban planning
Many countries are subsidising the technologies used for renewable energy sources and thus promoting to improve the share of renewables within the energy mix. For example, Singapore plans to increase the share of solar power by up to five per cent of the peak electric demand by the year 2020. Such targeted regulations will aid in improving the use of renewables. In addition, there is a need to build awareness of energy conservation to promote social acceptance and adoption of the use of renewables.

State of the art
Many countries are providing tax incentives to promote the use of renewable energy sources and thus making them more profitable to the user (Cansino et al. 2011). The major drawback of renewable energy sources such as solar panels currently is their cost and the efficiency. Given that the global trend shows decreasing costs and increasing efficiencies with respect to solar systems over the years, the future looks rosy for solar power adoption (Raugei and Frankl 2009).

HEAT RECOVERY SYSTEMS



Heat recovery systems recover waste heat available in the exhaust streams. For example, a heat recovery ventilator employs a cross flow between the fresh air coming into the building and the outbound air to reduce the cooling requirements in an air-conditioned space. The benefits of heat recovery systems span from directly improving process efficiencies to indirectly reducing the pollution levels.

UHI & OTC effect
Heat recovery systems reduce the heat of the exhaust streams released into the atmosphere, thus directly decreasing the thermal pollution caused by these streams and decreasing the UHI effect. This also goes a long way in improving the OTC, as the local air temperature is now less influenced by the recovered exhaust streams.

Tropical climate
In tropical climates, a significant amount of energy is used to produce for space cooling. The exhaust stream from space cooling contains waste heat, which can be used to preheat domestic hot water and thus increasing the efficiency of the overall process and decreasing the energy consumption.

Urban planning
Heat recovery can play a major role in industrial sector where there are numerous sources of waste heat. Implementing heat recovery systems though involves high capital investment; however, the cost savings obtained in reducing energy consumption makes it very beneficial. For the residential sector, which is another source of waste heat, the benefits are not very apparent in the utility savings as the scale is small. Thus, to counter this hesitation, incentives need to be provided either in the form of subsidies or recognition.

State of the art
Studies have discussed the benefits of heat recovery systems in the context of buildings, industries and transportation. A detailed review of the heat recovery systems and their application to buildings are available (Cuce and Riffat 2015). This also includes the environmental impact of these technologies. In transportation, multiple promising technologies like thermoelectric generators (TEGs), kinetic energy recovery systems (KERS) and heat pipes are being implemented (Guizzi et al. 2014; Orr et al. 2016). Formula One cars use KERS to improve the efficiency of the cars and promote the use of environmentally friendly options.

BUILDING SYSTEMS
MIXED USED NEIGHBOURHOODS

Energy consumption patterns seem to differ significantly based on the building type - residential and commercial. Differences exist even in residential building types, whether they are apartment buildings, terraced houses or detached houses. A commercial building consumes more energy during the daytime when there is socio-economic activity whereas a residential building consumes more energy at night as people return from work or school. The performance of a mixed-use neighbourhood designed with consideration to the clear differences in the patterns of energy consumption would present a clear advantage over single use neighbourhoods.

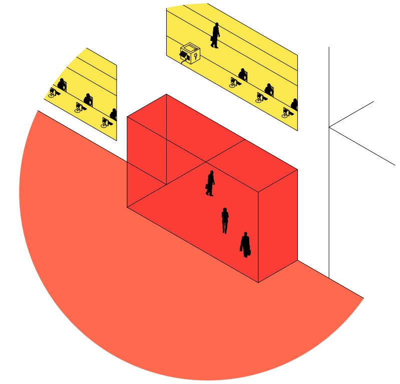
UHI & OTC effect
A mixed-use neighbourhood designed to strike a balance between various peaks of energy consumption tend to have a positive effect on the UHI. This is because of decreased energy consumption and reduced cases of equipment oversizing, which further improves the efficiency of the process. As neighbourhoods become more energy efficient, the carbon emissions decrease and this has an indirect positive impact on OTC.

Tropical climate
Mixed use neighbourhood work well in the tropics where the demand for space cooling is equally important in both residential and commercial spaces.

Urban planning
The demand side management emphasises on encouraging the consumers to optimise their energy use. Regulations need to incentivise the use of energy during non-peak hours compared to peak hours. These regulations, when made dependent on the use of a building, will help in further optimising the energy consumption. By making the energy consumption costly for residential buildings during the office hours compared to non-office hours and vice-versa for commercial buildings, the consumption behaviour can be influenced.

State of the art
Different studies explored the energy performance of a mixed use community coupled with the use of solar power (Hachem-Vermette et al. 2016). Most energy consuming tasks of households need not be performed at a specific time, studies revealed, but instead could be performed during preferred timings. If these tasks were to be coordinated among the neighbourhood to take place at preferred timings, the peak demand and the energy cost of residences could be reduced (Zhang et al. 2013; Yaqub et al. 2016).

OUTDOOR SYSTEMS
BUFFER ZONES



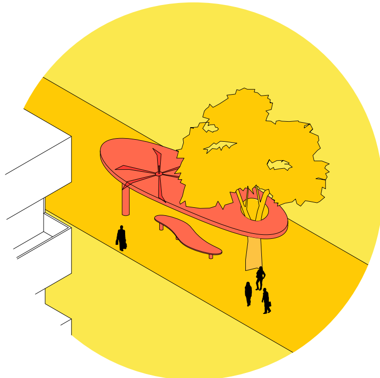
This measure concerns spaces that cannot be easily classified as being indoors or outdoors, but can still influence the thermal comfort of pedestrians who encounter tunnels, enclosed footbridges, partially roofed courtyards, foyers, lobbies, and more. It is important for such spaces to be designed to ensure there is a comfortable temperature transition from indoors to outdoors, and vice versa.

UHI & OTC effect
Modified comfort limits in transition spaces of buildings can be responsible for potential energy savings and reduction of energy losses. In particular, a study dedicated to transitional spaces has shown that these spaces could help save energy if they were well designed and developed according to their climatic needs (Chun et al. 2004).

Tropical climate
In tropical climates characterised by high thermal variation between the outdoor and the indoor, these transitional areas are important to reduce the thermal shock for pedestrians moving in and out. Step magnitudes lower than 3°C are proposed as acceptable for transitional spaces in hot-humid climates (Zhang et al. 2017), while the most efficient architectural shape of these spaces cannot be easily determined since it depends on the regional climatic condition (Chun et al. 2004).

Urban planning
Transitional spaces connecting the indoor and outdoor spaces of a buildings account for 10-40 per cent of the total area in various buildings (Pitts and Saleh 2007). These spaces have an important role in controlling air circulation and impacting the senses and perceptions of occupants. They should thus be designed to provide environmental conditions somewhere between internal and external thermal conditions. A well-designed transitional space would reduce thermal shock. To this aim, Rohinton (2016) suggested that building standards be elaborated to address the differences between indoor and outdoor conditions.

State of the art
There is lack of information on response to conditions in transitional spaces. A study involving 103 pedestrians in an urban area aimed to define the transitional space and provide the evidence for their existence and their use (Kray et al. 2013). In Europe and Asia, shopping malls are characterised by indoor spaces connected by large openings to the outdoor environment. These spaces are characterised by dynamic, variable, unstable, and fluctuating conditions.



HYBRID VENTILATION IN OUTDOOR SPACES

This measure concerns systems that are able to ventilate the outdoor spaces in a controlled mode, combining the advantages of both natural and mechanical ventilation systems and minimising the energy consumption.

UHI & OTC effect
The use of ventilation systems in outdoor spaces of urban areas helps to increase pedestrians' thermal comfort, since the airflow generated by natural ventilation may not be enough to maintain the thermal comfort and cannot be controlled. Additionally, these hybrid systems are preferable with respect to mechanical ventilation systems when necessary for use in the public outdoor areas. This is because their energy consumption is lower and therefore could contribute to minimising the UHI effect when compared to more energy intensive mechanical systems.

Tropical climate
The excess of heat and humidity in the outdoor and public areas of tropical climate can be partially removed by using hybrid ventilation systems. Therefore, these systems can be considered a valid solution to guarantee a good level of thermal comfort in tropical outdoor areas.

Urban planning
Only a minor percentage of hybrid ventilation for outdoor spaces exists, but they are a solution to meet the thermal comfort level with low and non-continuous loads.

State of the art
Several research studies have been done on hybrid ventilation systems for indoor application (Menassa et al. 2013, Niachou et al. 2008). On the contrary, it is not easy to find in literature studies performed on the same systems for outdoor spaces. Some applications of hybrid ventilation system can be seen in some public outdoor areas in Singapore. An example is the Clarke Quay's green ventilation system, which uses heat differential to move air around, thus cooling the semi-enclosed shopping area, bars, restaurants and walkways.

REFERENCES

Aflaki, A., Mahyuddin, N., Mahmoud, Z.A.-C., Baharum, M.R. (2015). 'A review on natural ventilation applications through building façade components and ventilation openings in tropical climates', Energy and Buildings, 101: 153-162. doi:10.1016/j.enbuild.2015.04.033.

Al-Tamimi, N., Fadzil, S.F.S. (2012). 'Energy-efficient envelope design for high-rise residential buildings in Malaysia', Architectural Science Review, 55(2): 119-127. doi:10.1080/00038628.2012.667938.

Barbieri, E.S., Dai, Y.J., Morini, M., et al. (2014). 'Optimal sizing of a multi-source energy plant for power heat and cooling generation', Applied Thermal Engineering, 71(2): 736–750. doi: 10.1016/j.applthermaleng.2013.11.022.

BCA - Building and Construction Authority (2010). Building Planning and Massing: Green Buildings Platinum Series, 42-43.

Bruelisauer, M., Meggers, F., Saber, E., et al. (2014). 'Stuck in a stack—Temperature measurements of the microclimate around split type condensing units in a high rise building in Singapore', Energy and Buildings, 71: 28–37. doi: 10.1016/j.enbuild.2013.11.056.

Cansino, J.M., Pablo-Romero, M., Román, R., Yñiguez, R. (2011). 'Promoting renewable energy sources for heating and cooling in EU-27 countries', Energy Policy, 39(6): 3803–3812. doi: 10.1016/j.enpol.2011.04.010.

Chow, T., Au, W., Yau, R., et al. (2004). 'Applying district-cooling technology in Hong Kong', Applied Energy, 79(3): 275–289. doi: 10.1016/j.apenergy.2004.01.002.

Chua, K.J., Chou, S.K., Yang, W.M., Yan, J. (2013). 'Achieving better energy-efficient air conditioning – A review of technologies and strategies', Applied Energy, 104: 87–104. doi: 10.1016/j.apenergy.2012.10.037.

Chun, C., Kwok, C., Tamura, A. (2004). 'Thermal comfort in transitional spaces-basic concepts: literature review and trial measurement', Building and Environment, 39(10): 1187-1192. doi:10.1016/j.buildenv.2004.02.003.

Cuce, P.M., Riffat, S. (2015). 'A comprehensive review of heat recovery systems for building applications', Renewable and Sustainable Energy Reviews, 47: 665–682. doi: 10.1016/j.rser.2015.03.087.

De Lieto Vollaro, R., Evangelisti, L., Battista, G., et al. (2014). 'Bus for urban public transport: Energy performance optimization', Energy Procedia. 45: 731–738. doi: 10.1016/j.egypro.2014.01.078.

Doukas, D.I., Papastergiou, K., Bakas, P., Marinopoulos, A. (2012). 'Energy storage sizing for large scale PV power plants base-load operation - comparative study & results', presented at 2012 38th IEEE Photovoltaic Specialists Conference - IEEE, Austin. doi: 10.1109/PVSC.2012.6317678.

Duan, R., Wang, X., Song, Y., Liu, J. (2016). ‘Influence of Air-conditioning Outdoor Unit Arrangement Strategy on Energy Consumption’, Procedia Engineering, 146: 350–358. doi: 10.1016/j.proeng.2016.06.409.

Guizzi, G.L., Manno, M., Manzi, G., et al. (2014). ‘Preliminary study on a kinetic energy recovery system for sailing yachts’, Renewable Energy, 62: 216–225. doi: 10.1016/j.renene.2013.06.051.

Hachem-Vermette, C., Cubi, E., Bergerson, J. (2016). ‘Energy performance of a solar mixed-use community’, Sustainable Cities and Society, 27: 145–151. doi: 10.1016/j.scs.2015.08.002.

Han, M., Chen, H. (2017). ‘Effect of external air-conditioner units’ heat release modes and positions on energy consumption in large public buildings’, Building and Environment, 111: 47–60. doi: 10.1016/j.buildenv.2016.10.014.

Hug, G., Kargarian, A. (2016). ‘Optimal sizing of energy storage systems: a combination of hourly and intra-hour time perspectives’, IET Generation, Transmission & Distribution, 10(3): 594–600. doi: 10.1049/iet-gtd.2015.0031.

Indraganti, M., Ooka, R., Rijal, H.B. (2013). ‘Thermal comfort in offices in summer: Findings from a field study under the “setsuden” conditions in Tokyo, Japan’, Building and Environment, 61: 114–132. doi: 10.1016/j.buildenv.2012.12.008.

Jurelionis, A., Valančius, R. (2013). ‘Influence of indoor air temperature variation on office work performance’, Journal of Environmental Engineering and Landscape Management, 21(1): 19–25. doi: 10.3846/16486897.2012.721371.

Kray, C., Fritze, H., Fechner, T., Schwering, A., Li, R., Anacta, V.J. (2013). ‘Transitional Spaces: Between Indoor and Outdoor Spaces’, Spatial Information Theory. Berlin: Springer. 14-32. doi: 10.1007/978-3-319-01790-7_2.

Kumara, W.H.C., Waidyasekara, K.G.A.S, Weerasinghe, R.P.N.P. (2016). ‘Building management system for sustainable built environment in Sri Lanka’, Built Environment Project and Asset Management, 6(3): 302–316. doi: 10.1108/BEPAM-02-2015-0004.

Li, D.H.W. (2010). ‘A review of daylight illuminance determinations and energy implications’, Applied Energy 87(7): 2109-2118. doi:10.1016/j.apenergy.2010.03.004.

Liu, W., Spaargaren, G., Heerink, N., et al. (2013). ‘Energy consumption practices of rural households in north China: Basic characteristics and potential for low carbon development’, Energy Policy, 55: 128–138. doi: 10.1016/j.enpol.2012.11.031.

LTA - Land Transport Authority (2014). Passenger Transport Mode Shares in World Cities. Accessed on June 17, 2017. https://www.lta.gov.sg/ltaacademy/doc/J11Nov-p60PassengerTransportModeShares.pdf.

Menassa, C.C., Taylor, N., Nelson, J. (2013). ‘Optimizing hybrid ventilation in public spaces of complex buildings – A case study of the Wisconsin Institutes for Discovery’, Building and Environment, 61: 57-68. doi:10.1016/j.buildenv.2012.12.009.

Mills, B., Schleich, J. (2012). ‘Residential energy-efficient technology adoption, energy conservation, knowledge, and attitudes: An analysis of European countries’, Energy Policy 49: 616–628. doi: 10.1016/j.enpol.2012.07.008.

Ministry of Communications and Information. TODAY Online - World’s biggest underground district cooling network now at Marina Bay. Accessed on June 17, 2017. https://www.gov.sg/news/content/today-online-worlds-biggest-underground-district-cooling-network-now-at-marina-bay.

Niemeyer, S. (2010). ‘Consumer voices: adoption of residential energy-efficient practices’, International Journal of Consumer Studies, 34(2): 140–145. doi: 10.1111/j.1470-6431.2009.00841.x.

Niachou, K., Hassid, S., Santamouris, M., Livada, I. (2008). ‘Experimental performance investigation of natural, mechanical and hybrid ventilation in urban environment’, Building and Environment, 43(8): 1373-1382. doi:10.1016/j.buildenv.2007.01.046.

Orr, B., Akbarzadeh, A., Mochizuki, M., Singh, R. (2016). ‘A review of car waste heat recovery systems utilising thermoelectric generators and heat pipes’, Applied Thermal Engineering, 101: 490–495. doi: 10.1016/j.applthermaleng.2015.10.081.

Patania, F., Gagliano, A., Nocera, F., Galesi, A. (2012). ‘Thermal comfort analysis of public transport passengers in Catania’, WIT Transactions on Ecology and the Environment, 157: 327–338. doi: 10.2495/AIR120291.

Pitts, A., Saleh, J.B. (2007). ‘Potential for energy saving in building transition spaces’, Energy and Buildings. 39: 815-822. doi:10.1016/j.enbuild.2007.02.006.

Rangaiah, G., Sharma, S., Sreepathi, B.K. (2015). ‘Multi-objective optimization for the design and operation of energy efficient chemical processes and power generation’, Current Opinion in Chemical Engineering, 10: 49–62. doi: 10.1016/j.coche.2015.08.006.

Rattanongphisat, W., Rordprapat, W. (2014). ‘Strategy for energy efficient buildings in tropical climate’, Energy Procedia, 10–17. doi: 10.1016/j.egypro.2014.07.049.

Raugei, M., Frankl, P. (2009). ‘Life cycle impacts and costs of photovoltaic systems: Current state of the art and future outlooks’, Energy, 34: 392–399. doi: 10.1016/j.energy.2009.01.001.

Rizki, A.M., Mardliyahtur, R., Anindya, D.A. (2016). ‘Design optimisation for window size, orientation, and wall reflectance with regard to various daylight metrics and lighting energy demand: A case study of buildings in the tropics’, Applied Energy, 164: 211-219 doi:10.1016/j.apenergy.2015.11.046.

Rohinton, E. (2016). ‘Achieving thermal pleasure in tropical urban outdoors’. Urban climate challenges in the tropics: Rethinking planning and design oportunities. London: Imperial College Press. 40-41.

Shaikh, P.H., Nor, N.B.M., Nallagownden, P., Elamvazuthi, I. (2016). ‘Intelligent Multi-objective Optimization for Building Energy and Comfort Management’, Journal of King Saud University - Engineering Sciences. doi: 10.1016/j.jksues.2016.03.001.

Smith, R., Zhang, N., Perry, S., et al. (2014). ‘EFENIS: Efficient Energy Integrated Solutions for Manufacturing Industries. European Context', Computer Aided Chemical Engineering, 33: 1789–1794. doi: 10.1016/B978-0-444-63455-9.50133-1.

Sreepathi, B.K., Rangaiah, G.P. (2014). 'Review of heat exchanger network retrofitting methodologies and their applications', Industrial & Engineering Chemistry Research, 53(8): 11205–11220.

Wade, C.R., Corrales-Sanchez, T., Narayan, T.C., et al. (2013). 'Postsynthetic tuning of hydrophilicity in pyrazolate MOFs to modulate water adsorption properties', Energy & Environmental Science, 6(7): 2172. doi: 10.1039/c3ee40876k.

Werner, S. (2017). 'International review of district heating and cooling', Energy. doi: 10.1016/j.energy.2017.04.045.

Yang, C.M., Chen, C.C., Chen, S.L. (2013). 'Energy-efficient air conditioning system with combination of radiant cooling and periodic total heat exchanger', Energy, 59: 467–477. doi: 10.1016/j.energy.2013.07.015.

Yang, Q., Liu, M., Shu, C., Zhan, X. (2015). 'Impact Analysis of Window-Wall Ratio on Heating and Cooling Energy Consumption of Residential Buildings in Hot Summer and Cold Winter Zone in China', Journal of Engineering, 17. doi:10.1155/2015/538254.

Yaqub, R., Ahmad, S., Ahmad, A., Amin, M. (2016). 'Smart energy-consumption management system considering consumers' spending goals (SEMS-CCSG)', International Transactions on Electrical Energy Systems, 26(7): 1570–1584. doi: 10.1002/etep.2167.

Zhang, Z., Zhang, Y., Ding, E. (2017). 'Acceptable temperature steps for transitional spaces in the hot-humid area of China', Building and Environment, 121: 190-199. doi:10.1016/j.buildenv.2017.05.026.

Zhang, D., Shah, N., Papageorgiou, L.G. (2013). 'Efficient energy consumption and operation management in a smart building with microgrid', Energy Conversion and Management, 74: 209–222. doi: 10.1016/j.enconman.2013.04.038.


PR-PG TC

GLOSSARY

A

Active Mobility	Walking, biking or the use of electric scooters for commuting.	p 129
Air temperature (Tair)	This is a thermodynamic property expressed as degree Celsius (˚C) or Fahrenheit (˚F) or Kelvin (K). It is an intensive variable expressing how hot or cold the volume of air is at a point in time.	p 129
Albedo	Refers to a dimensionless parameter that ranges between 0 (low reflectance – black body that absorbs all incident radiation) and 1 (high reflectance – white body that reflects all incident radiation). It is defined as the ratio of radiation reflected to the radiation incident on a surface. *Henderson-Sellers, A., Wilson, M. F. (1983). 'Albedo observations of the Earth's surface for climate research', Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences. 309(1508), The Study of the Ocean and the Land Surface from Satellites, 285–294.*	p 10, 14, 28, 86, 89, 92, 133, 135
Ambient temperature	The temperature of the surrounding atmospheric air. Ambient air temperature can affect the operation of process equipment, instruments, and control. It is sometimes referred to as room temperature. *Schaschke, C. (2014). 'Ambient Temperature', Dictionary of Chemical Engineering, Oxford University Press. Accessed on June 19, 2017. http://www.oxfordreference.com.libproxy1.nus.edu.sg/view/10.1093/acref/9780199651450.001.0001/acref-9780199651450-e-92.*	p 58, 89, 92, 114, 130
Anthropogenic heat	The heat produced by all types of human activity. It alters the earth surface energy balance producing and increase in temperature especially in the nearby surface temperature. *Iamarino, M., Beevers, S., Grimmond, C. S. B. (2012). 'High-resolution (space, time) anthropogenic heat emissions', International Journal of Climatology, 32(11): 1754–1767. doi: 10.1002/joc.2390.* *Kikegawa, Y., Genchi, Y., Kondo, H., Hanaki, K. (2006). 'Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning', Applied Energy, 83(6): 649–668. doi: 10.1016/j.apenergy.2005.06.001.*	
Aspect ratio (H/W)	It is the most important geometrical characteristic of a street canyon and is defined as the ratio of the canyon height (H) to the canyon width (W). It is usually calculated by dividing the mean height of buildings by the width of the street.	p 40, 41, 56, 106
Asymmetrical thermal environment	Refers to the development of the urban area considering the different areas with different uses with respect to their thermal comfort. In tropical areas, it is assumed that thermal comfort is difficult to achieve, thus, the emphasis is on improving certain areas assuming others will not attain a comfortable thermal situation.Refers to the development of the urban area considering the different areas with different uses with respect to their thermal comfort. In tropical areas, it is assumed that thermal comfort is difficult to achieve, thus, the emphasis is on improving certain areas assuming others will not attain a comfortable thermal situation.	p 21, 29
Autonomous mobility	This involves concepts such as platooning, system optimum routing, and virtual traffic lights, therefore decreasing fuel consumption and heat emission.	p 128, 132

B

Backwards Incremental System OptVimum Search (BISOS)	This algorithm redistributes traffic volumes homogeneously around the city and converges significantly faster than existing methods for system optimum computation in current literature. *Ivanchev, J., Zehe, D., Viswanathan, V., Nair , S., Knoll, A. (2016). 'BISOS: Backwards Incremental System Optimum Search algorithm for fast socially optimal traffic assignment,' presented at IEEE 19th International Conference on Intelligent Transportation Systems (ITSC), Rio de Janeiro, 2137-2142.*	p 128
Bioclimatic thermal stress	Refers to thermal stress that is caused on humans in natural outdoor environments due to climate.	p 45
Brise-soleils/ sun baffles	An architectural feature of a building that reduces heat gain within that building by deflecting sunlight, often outside the windows or extending over the entire surface of a building's façade. *Encyclopedia Britannica. 'Brise-soleil'. Accessed on June 15, 2017. https://www.britannica.com/technology/brise-soleil.*	p 111
Building envelope	The physical separator between the interior and exterior of a building. Components of the envelope are typically: walls, floors, roofs, fenestrations and doors. *Autodesk Sustainbility Workshop. 'Building Design'. Accessed on June 15, 2017. https://sustainabilityworkshop.autodesk.com/buildings/building-envelope.*	p 19, 54, 82, 91, 93, 96, 98, 99, 111, 152
Building porosity/ permeability	This can be achieved by generating adequate openings or gaps in buildings, either in horizontal or vertical direction.	p 48, 49, 53, 54

C

Canopy cover	The proportion of the forest covered by the vertical projection of the tree crowns. *Eurostat (2016). 'Glossary: Canopy cover'. Accessed on June 15, 2017. http://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Canopy_cover.*	p 25, 57
Certificate of Entitlement (COE)	Anyone who wishes to register a new vehicle in Singapore must first obtain a Certificate of Entitlement (COE) in the appropriate vehicle category. A COE represents a right to vehicle ownership	p 126

and use of the limited road space for 10 years.

Land Transport Authority (2017). 'Certificate of Entitilement (COE)'. Accessed on June 15, 2017. https://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/owning-a-vehicle/vehicle-quota-system/certificate-of-entitlement-coe.html.

Chassis — The base frame of a car, carriage or other wheeled vehicle. p 135

Oxford Living Dictionaries. 'Chassis'. Accessed on June 15, 2017. https://en.oxforddictionaries.com/definition/chassis.

Chromogenic systems — A chromogenic material is one that changes colour in response to electrical, optical (light intensity) or thermal changes (temperature change). p 114

Smart Materials. 'Chromogenic systmes'. Accessed on June 15, 2017. https://sites.google.com/site/smartmaterialsjordanbullen/home/introduction/chromogenic-systems.

Convective cooling — There are two types of convectional cooling, namely the natural convection cooling and the forced air convection cooling. p 58

Sunpower (2014). 'Convection cooling'. Accessed on June 15, 2017. http://www.sunpower-uk.com/glossary/what-is-convection-cooling/.

D

Diurnal variation — Fluctuations that occur during each day. p 71, 72, 93

Double skin façade — Double-skin façade is a special type of envelope, where a second 'skin', usually a transparent glazing, is placed in front of a regular building façade. p 95

Safer, N., Woloszyn, M., Roux, J. J. (2005). 'Three-dimensional simulation with a CFD tool of the airflow phenomena in single floor double-skin façade equipped with a venetian blind.' Solar Energy, 79(2): 193-203.

Downwash wind — Downwash occurs when the plume released from a stack is brought downward by the flow of air. Depending on the stack location relative to the upstream building, ground level concentrations could be significantly higher in the presence of the building. p 44, 46

Gupta, A., Stathopoulos, T., Saathoff, P. (2012). 'Wind tunnel investigation of the downwash effect of a rooftop structure on plume dispersion', Atmospheric Environment, 46: 496-507. doi: 10.1016/j.atmosenv.2011.08.039.

E

Ecosystem services — Ecosystem services are the benefits humankind derives from the workings of the natural world. These include most obviously the supply of food, fuels and materials, but also more basic processes such as the formation of soils and the control and purification of water, and intangible ones such as amenity, recreation and aesthetics. p 71

Harrison, R. M., Hester, R. E. (2010). 'Ecosystem services'. Cambridge: Royal Society of Chemistry.

Eggcrate — Eggcrate shading devices are mainly for east and west windows in hot climates and for the additional southeast and southwest orientations in very hot climates. It is a combination of horizontal overhangs (louvers) and vertical fins. p 111

Lechner, N. (1991). '9.14 Design Guidelines for Egg Crate Shading Devices', Heating, Cooling, Lighting: Sustainable Design Methods for Architects. Hoboken: John Wiley & Sons, 259.

Electronic Road Pricing (ERP) — ERP is used in Singapore in managing road congestion. Based on a pay-as-you-use principle, motorists are charged when they use priced roads during peak hours. p 126

Land Transport Authority (2017). 'Electronic Road Pricing (ERP)'. Accessed on June 16, 2017. https://www.lta.gov.sg/content/ltaweb/en/roads-and-motoring/managing-traffic-and-congestion/electronic-road-pricing-erp.html.

Evapotranspiration — The sum of evaporation and transpiration from plants. Some definitions include evaporation from surface-water bodies, even the oceans. p 71

U.S. Geological Survey (2016). 'Evapotranspiration - The Water Cycle'. Accessed on June 20, 2017. https://water.usgs.gov/edu/watercycleevapotranspiration.html.

F

Foliage density — Foliage density is the total leaf surface area per unit volume of space. p 25

Jain, M., et. al. (2010) 'Evaluation of methods to estimate foliage density in the understorey of a tropical evergreen forest.'

G

Gallery — Any covered passage that is open at one side, such as a portico or a colonnade. p 44

'Gallery'. In Encyclopedia Britannica. Accessed on June 15 2017. https://www.britannica.com/technology/gallery.

Green cool islands — Refers to the vegetated areas inside the city that due to their thermal characteristics remain colder in comparison to the surrounding non-vegetated urban area. p 30, 54

Green Mark — The Building & Construcution Authority (BCA)'s Green Mark is a green building rating system to evaluate a building for its environmental impact and performance. p 57, 147

Building & Construction Authority (2017). 'About BCA Green Mark Scheme'. Accessed on June 15, 2017. https://www.bca.gov.sg/greenmark/green_mark_buildings.html.

Green Mark Gold — A Green Mark Rating with a score of 75 to <85. p 147

	Building & Construction Authority (2017). 'BCA Green Mark Criteria and Online Application'. Accessed on June 15, 2017. https://www.bca.gov.sg/greenmark/green_mark_criteria.html.	
Green Mark Platinum	A Green Mark Rating with a score of 90 and above. *Building & Construction Authority (2017). 'BCA Green Mark Criteria and Online Application'. Accessed on June 15, 2017. https://www.bca.gov.sg/greenmark/green_mark_criteria.html.*	p 147
Greenhouse gas	A gas that traps heat in the atmosphere. Carbon dioxide and chlorofluorocarbons are examples of greenhouse gases. *United States Environmental Protection Agency (2017). 'Greenhouse Gas Emissions - Overview of Greenhouse Gases.' Accessed on June 16, 2017. https://www.epa.gov/ghgemissions/overview-greenhouse-gases.*	p 72, 87
Gross Floor Area (GFA)	All covered floor areas of a building, except otherwise exempted, and uncovered areas for commercial uses are deemed the gross floor area of the building for purposes of plot ratio control and development charge. The gross floor area is the total area of the covered floor space measured between the centre line of party walls, including the thickness of external walls but excluding voids. *Urban Redevelopment Authority (2017). 'Handbook on Gross Floor Area'. Accessed on June 14, 2017. https://www.ura.gov.sg/uol/publications/technical/dc-handbooks/handbook-on-gross-floor-area.*	p 56

H

Heat capacity	The ratio of heat absorbed by a material to the temperature change. It is usually expressed as calories per degree in terms of the actual amount of material being considered, most commonly a mole (the molecular weight in grams). *Encyclopedia Britannica. 'Heat capacity'. Accessed on June 15, 2017. https://www.britannica.com/science/heat-capacity.*	p 70, 73, 74, 76

I

Internal Combustion Engine (ICE) vehicles	ICE is where fuel is combusted with the system boundary to activate pistons and is the dominant prime mover in our society. *Arcoumanis, C. (1988). Internal combustion engines, San Diego and London: Academic Press.*	p 130

K

Kinetic energy recovery system	A system for motor vehicles using a flywheel or battery to store excess energy when braking and thereafter releasing it when extra power is needed for high acceleration. *Atkins, A. G. (2013). A dictionary of mechanical engineering: Kinetic-energy recovery system. Oxford: Oxford University Press.*	p 137

L

Leaf Area Index (LAI)	LAI represents the amount of leaf material in an ecosystem and is geometrically defined as the total one-sided area of photosynthetic tissue per unit ground surface area. *Gobron, N., Verstraete, M. M. (2009). 'Leaf Area Index (LAI)', Global Terrestrial Observing System. Accessed on June 16, 2017. http://www.fao.org/gtos/doc/ECVs/T11/T11.pdf.*	p 57
Littoral zone	LAI represents the amount of leaf material in an ecosystem and is geometrically defined as the total one-sided area of photosynthetic tissue per unit ground surface area. *Allaby, M. (2013). A dictionary of geology and earth sciences: Littoral zone. Oxford: Oxford University Press.*	p 47, 70
Local climate zone (LCZ)	Regions of uniform surface cover, structure, material, and human activity that span hundreds of meters to several kilometers in horizontal scale. The name is appropriate because the classes are local in scale, climatic in nature, and zonal in representation. *Stewart, I. D., Oke, T. R. (2012). 'Local climate zones for urban temperature studies', Bulletin of the American Meteorological Society, 93(12): 1879–1900. doi: 10.1175/BAMS-D-11-00019.1.*	p 55, 56
Louvers	Each of a set of angled slats fixed or hung at regular intervals in a door, shutter, or screen to allow air or light to pass through.	p 111

M

Magnetocaloric materials	Magnetocaloric materials (MCM) are the 'heart' of every magnetic refrigeration or heat-pump application. Apart from having a crucial role in the heat-regeneration process, they also exhibit a special and vital phenomenon for magnetic refrigeration called the magnetocaloric effect. *Kitanovski, A., Tušek, J., Tomc, U., Plaznik, U., Ožbolt, M., Poredoš, A. (2015). 'Magnetocaloric energy conversion: From theory to applications, Green Energy and Technology, Cham: Springer International Publishing. doi:10.1007/978-3-319-08741-2.*	p 114
Mass Rapid Transit (MRT)	The Mass Rapid Transit, or MRT, is a rapid transit system forming the major component of the railway system in Singapore, spanning the entire city-state. *Land Transport Authority (2017). 'MRT & LRT Trains'. Accessed on June 16, 2017. https://www.lta.gov.sg/content/ltaweb/en/public-transport/mrt-and-lrt-trains.html.*	p 127
Mean radiant temperature	The uniform temperature of an imaginary enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual non-uniform enclosure. It is simply the area weighted mean temperature of all the objects surrounding the body. *Acero, J. A., Herranz-Pascual, K. (2015). 'A comparison of thermal comfort conditions in four urban spaces by means of measurements and modelling techniques', Building and Environment, 93: 45–257. doi: 10.1016/j.buildenv.2015.06.028.*	

Lee, H., Mayer, H. (2016). 'Validation of the mean radiant temperature simulated by the RayMan software in urban environments', International Journal of Biometeorology. 60(11): 1775–1785. doi: 10.1007/s00484-016-1166-3.

Measures

The purpose of mitigation measures is to avoid, reduce or minimise unwanted impacts and enhance beneficial impacts.

Mircoclimate — p 30, 58, 92, 96

The climate of a small space with dimensions 2–10 m horizontally and within 10 m of the Earth's surface. The timescale of measurements for investigation of the microclimate is usually less than 24 hours.

Giles, B. (2014). 'Microclimate', Encyclopedia of environmental change, 3: 696-696. Thousand Oaks: SAGE Publications Ltd. doi: 10.4135/9781446247501.n2467.

O

Outdoor Thermal Comfort (OTC)

Refers to that condition of mind expressing satisfaction with the thermal environmental. It ranges from very uncomfortable to very comfortable. It depends not only on the thermal environment and physiological parameters, but also adaptation and expectation factor, and the recent thermal exposure/situation.

Blazejczyk, K., Epstein, Y., Jendritzky, G., Staiger, H., Tinz, B. (2012). 'Comparison of UTCI to selected thermal indices', International Journal of Biometeorology, 56(3): 515–535. doi: 10.1007/s00484-011-0453-2.

Höppe, P. (1999). T'he physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment', International Journal of Biometeorology, 43: 1–75. doi: 10.1007/s004840050118.

Oxidation — p 88

Specifically, a reaction in which oxygen combines with, or hydrogen is removed from, a substance. More generally, any reaction in which an atom loses electrons.

Allaby, M. (2013). 'Oxidation', A Dictionary of Geology and Earth Sciences, Oxford: Oxford University Press.

P

Passive cooling systems — p 54, 82, 96

In general, the flow of energy in a passive design is based on natural means such as radiation, convection or conduction.

Al-Obaidi, K. M., Ismail, M., Abdul Rahman, A. M. (2014). 'Passive cooling techniques through reflective and radiative roofs in tropical houses in Southeast Asia: A literature review', Frontiers of Architectural Research, 3(3): 283-297. doi: 10.1016/j.foar.2014.06.002.

Passive design techniques — p 41

The use of ambient energy sources instead of purchased energy like electricity or natural gas. These strategies include daylighting, natural ventilation, and solar energy.

Autodesk Sustainbility Workshop. 'Passive Design Strategies'. Accessed on June 15, 2017. https://sustainabilityworkshop.autodesk.com/buildings/building-envelope.

Passive survivability — p 54

A building's ability to maintain critical life-support conditions in the event of extended loss of power or water; or in the event of extraordinary heat spells, storms, or other extreme events.

State University of New Jersey Green Building Manual (2011). 'Passive Survivability'. Accessed on June 16, 2017. http://greenmanual.rutgers.edu/newcommercial/strategies/survivability.pdf.

Peak cooling load — p 111

The amount of heat that must be removed in an hour to maintain a comfortable room temperature.

Smith, B. (2011). 'HVAC Peak Load Calculation Methods – History and Comparisons'. Accessed on June 15, 2017. http://www.elitesoft.com/web/newsroom/loadcalcs.html.

Photocatalytic agents — p 88, 91

Defined as "acceleration by the presence of a catalyst". This definition includes photosensitization, a process by which a photochemical alteration occurs in one molecular entity as a result of initial absorption of radiation by another molecular entity called the photosensitized.

Abolinco (2015). 'What is Photocatalyst?' Accessed on June 16, 2017. http://www.abolinco.com/downloads/downloads/What_is_Photocatalyst.pdf.

Photochromic powder — p 114

Photochromic powders are photochromic microcapsules in a powder pigment form. Photochromic powders are colourless in their inactivated state and become coloured when exposed to an ultraviolet light source. They will respond to natural sunlight as well as artificial sources of 365nm 'black light'.

LCR Hallcrest (2017). 'Photochromic Powder Technical Data'. Accessed on June 16, 2017. https://www.hallcrest.com/DesktopModules/Bring2mind/DMX/Download.aspx?entryid=610&command=core_download&language=en-US&PortalId=0&TabId=185.

Platooning — p 132

The coordinated movement of a group of vehicles to reduce the inter-vehicle distance considerably compared to what is considered advisable during manual driving. This is achieved by partly or fully automating the driving tasks.

Axelsson, J. (2017). 'Safety in vehicle platooning: A systematic literature review', IEEE Transactions on Intelligent Transportation Systems, 18(5): 1033-1045. doi: 10.1109/TITS.2016.2598873.

Polyurethane insulation panels — p 97

These are made by reacting an isocyanate and typically installed as insulation on the roofs, walls, floors and ceilings of new and retrofit buildings. It is also used to insulate appliances, pipes and a variety of other products.

Huntsman (n.d.). 'Polyurethane insulation for energy efficient, green buildings'. Accessed on June 17, 2017. http://www.huntsman.com/polyurethanes/Media%20Library/a_MC1CD1F5AB7BB1738E040EBCD2B6B01F1/Products_MC1CD1F5AB8081738E040EBCD2B6B01F1/Insulation_ME4E93A022E848990E040EBCD2C6B1951/files/huntsman-polyurethane-insulation-for-energy-efficient-green-buildings.pdf.

Psychological Equivalent Temperature (PET)	The equivalent air temperature to reproduce in a standardised indoor setting and for a standardised person the core and skin temperatures that are observed under the conditions being assessed. It is based on the Munich energy balance model for individual (MEMI), a thermo-physiological heat balance model. *Höppe, P. (1999). 'The physiological equivalent temperature - a universal index for the biometeorological assessment of the thermal environment', International Journal of Biometeorology, 43: 71–75. doi: 10.1007/s004840050118.*	p 111

R

Regenerative breaking	In a regenerative braking system, the mechanical energy from the vehicle's momentum is used to run the motor backwards. Once the motor has been reversed, the electricity generated by the motor is fed back into the batteries, where it can be used to accelerate the car again after it stops. *Lamption (n.d.). 'How Regenerative Breaking Works'. Accessed on June 16, 2017. http://auto.howstuffworks.com/auto-parts/brakes/brake-types/regenerative-braking1.htm.*	p 130
Relative humidity (RH)	It is a ratio, expressed in per cent, of the amount of atmospheric moisture present relative to the amount that would be present if the air was saturated. *National Oceanic and Atmospheric Administration (2009). 'National Weather Service - Glossary: Relative Humidity'. Accessed on June 16, 2017. http://w1.weather.gov/glossary/index.php?word=relative+humidity.*	p 22
Roof overhang	The part of a roof that extends over the side wall or end wall of a building. *Dictionary of Construction (n.d.). 'Roof Overhang'. Accessed on June 20, 2017. http://www.dictionaryofconstruction.com/definition/roof-overhang.html.*	p 111

S

Sky View Factor (SVF)	The ratio of the radiation received (or emitted) by a planar surface from the sky to the radiation emitted (or received) from the entire hemispheric radiating environment. *Watson I. D., Johnson, G. T. (1987). 'Graphical estimation of sky viewfactors in urban environments', International Journal of Climatology, 7(2): 193–197. doi: 10.1002/joc.3370070210.*	p 40, 41, 113
Solar gain factor (W/m^2)	The solar heat gain through a sunlit double strength sheet glass at any specified orientation and any daylight hour. *Chan, L. S. A. (2008). 'Solar Gain Through Building'. Accessed on June 16, 2017. http://personal.cityu.edu.hk/~bsapplec/solar3.htm.*	p 150
Solar irradiance	The amount of light energy from one thing hitting a square metre of another each second. *National Aeronautics and Space Administration (NASA) (2008). 'Solar Irradiance'. Accessed on June 16, 2017. https://www.nasa.gov/mission_pages/sdo/science/solar-irradiance.html.*	p 156
Solar reflectance/ reflectivity	The ability of a material to reflect solar energy from its surface back into the atmosphere. The fraction of incident sunlight reflected. *Sleiman, M., Ban-Weiss, G., Gilbert, H. E., François, D., Berdahl, P., Kirchstetter, T. W., Destaillats, H., Levinson, R. (2011). 'Soiling of building envelope surfaces and its effect on solar reflectance - Part I: Analysis of roofing product databases', Solar Energy Materials and Solar Cells, 95(12): 3385-3399. doi:10.1016/j.solmat.2011.08.002.*	p 86, 88, 89, 90, 91, 92, 96
Spectral reflectance	In vision, the proportion of photons at different wavelengths in the visible spectrum which are reflected by a given object in the visual field. Spectral reflectance is the inverse of spectral absorption. *Binder, M. D., Hirokawa, N., Windhorst, U. (2009). Encyclopedia of Neuroscience, Berlin: Springer.*	p 96
Stack effect	It is a natural ventillation strategy that utilises buoyancy as the driving force for ventilation when the air inside the building is warmer than the ambient. *Yang, D., Li, B., Du, T. (2012). 'Analytical models for evaluating buoyancy-driven ventilation due to stack effect in a shaft considering heat transfer from shaft interior boundaries', Journal of Central South University, 19(3): 651-656. doi: 10.1007/s11771-012-1052-z.*	p 53
Strategies	The systematic application of multiple measures in order to achieve a certain goal.	
Street/urban canyons	The space above the street and between the buildings, as the basic urban unit. *MIT Urban Nature and City Design (2012). 'Urban Street Canyon'. Accessed on June 16, 2017. http://web.mit.edu/nature/archive/student_projects/2009/jcalamia/Frame/03_urbastreetcanyon.html.*	p 40, 41, 45, 48, 49, 51, 86, 90, 110, 113
Surface runoff	The flow across the land surface of water that accumulates on the surface when the rainfall rate exceeds the infiltration capacity of the soil. *Allaby, M. (2013). 'Surface runoff', A Dictionary of Geology and Earth Sciences. Oxford: Oxford University Press. Accessed on June 15, 2017. from http://www.oxfordreference.com.libproxy1.nus.edu.sg/view/10.1093/acref/9780199653065.001.0001/acref-9780199653065-e-8270.*	p 87
Surface temperature (T_{sur})	Is a thermodynamic property expressed as degree Celsius (˚C) or Fahrenheit (˚F) or Kelvin (K). It is an intensive variable expressing how much an area of surface is hot or cold. *Picon-Feliciano, A. J., Vasquez, R., Gonzalez, J. E., Rickman, D. (2009). 'Use of remote sensing observations to study the urban climate on tropical coastal cities', Revista Umbral, 1: 218-232.*	

T

Temperature responsive polymers	A class of "smart" materials that have the ability to respond to a change in temperature. They exhibit a volume phase transition at a certain temperature, which causes a sudden change in the solvation state. *Gandhi, A., Paul, A., Sen, S. O., Sen, K. K. (2015). 'Studies on thermoresponsive polymers: Phase behaviour, drug delivery and biomedical applications', Asian Journal of Pharmaceutical Sciences, 10(2): 99-107. doi: 10.1016/j.ajps.2014.08.010.*	p 114
Terrace podium	A distinctive type of raised substructure that must be negotiated to enter a surrounding building or superstructure. A terraced podium design is adopted to direct downward airflow, which can help air movement at the pedestrian level. *Ng, E. (2009). Designing high-density cities for social and environmental sustainability, London: Routledge.* *Potts, C. R. (2015). Religious Architecture in Latium and Etruria, c. 900-500 BC. Oxford: Oxford University Press.*	p 44, 46
Thermal adaptation	The need to maintain constant the internal temperature of the body: adaptation to environmental conditions (thermal balance). *Havenith, G. (2005). 'Temperature regulation, heat balance and climatic stress'. Extreme Weather Events and Public Health Responses, 69–80. doi:10.1007/3-540-28862-7_7.*	p 115
Thermal emissivity/ emittance	It refers to thermal properties of the materials. It is the ratio of the thermal radiation emitted by the surface at one specific temperature to the radiation emitted by an ideal black surface (blackbody) at the same temperature. It varies between 0 (low emissivity) and 1 (high emissivity - blackbody). *ASTM International (2013). 'Standard Test Method for Total Hemispherical Emittance of Surfaces up to 1400°C'. Accessed on June 20, 2017. https://www.astm.org/Standards/C835.htm.*	p 86, 89, 90, 92
Thermal sensation	Refers to sensations of people regarding the climate environment ranging from very cold to vey hot. It can also be called thermal perception. *Nakamura, M., Yoda, T., Crawshaw, L. I., Yasuhara, S., Saito, Y., Kasuga, M., Nagashima, K., Kanosue, K. (2008). 'Regional differences in temperature sensation and thermal comfort in humans', Journal of Applied Physiology, 105(6): 1897–1906. doi: 10.1152/japplphysiol.90466.2008.*	
Thermal transmittance (U-value)	The rate of heat flow in watts, through 1 m² of an element, when there is a temperature difference across the element of 1°C (or K). Measured in W/m²K. *Gorse, C., Johnston, D., Pritchard, M. (2012). 'Thermal transmittance', A Dictionary of Construction, Surveying and Civil Engineering. Oxford: Oxford University Press.*	p 150
Thermobimetal	A smart material that curls when heated, can automatically animate a building's surface to shade, ventilate, self-assemble, strengthen, and change shape. Besides altering the molecular makeup of the laminated metal, its behaviour can be optimised, enhanced, and even negated depending on its shape. *Sung, D. (2016). 'Smart geometries for smart materials: Taming thermobimetals to behave', Journal of Architectural Education, 70(1): 96-106. doi: 10.1080/10464883.2016.1122479.*	p 114
Thermochromic/ selective materials	Materials that transform from insulating state into metallic state with increase in temperature or from metallic state into insulating state with increase in temperature and the typical one is alkaline-earth doped manganese oxide. Combination of these two kinds of thermochromic materials might result in more efficient rectification of heat transfer. *Huang, J., Li, Q., Zheng, Z., Xuan, Y. (2013). 'Thermal rectification based on thermochromic materials', International Journal of Heat and Mass Transfer, 67: 575-580. doi: 10.1016/j.ijheatmasstransfer.2013.08.057.*	p 96
Thermoelectric generators	Solid state heat engines that generate electricity from heat sources. *Baranowski, L. L., Snyder, G., Toberer, E. S. (2012). 'Concentrated solar thermoelectric generators', Energy & Environmental Science, 5(10): 9055-9067. doi: 10.1039/c2ee22248e.*	p 157
Thermoelectric materials	Materials that enable the direct conversion between thermal and electrical energy, thus providing an alternative for power generation and refrigeration. *Zhang, X., Zhao, L. (2015). 'Thermoelectric materials: Energy conversion between heat and electricity', Journal of Materiomics, 1(2): 92-105. doi: 10.1016/j.jmat.2015.01.001.*	p 114
Topography	The examination of the Earth's surface and its salient physical and cultural features. The shape of the Earth's surface is usually detailed through contour lines, with features such as rivers, roads, and different kinds of buildings along with place names, a scale, and legend. *Castree, N., Kitchin, R., Rogers, A.(2013). 'Topography', A Dictionary of Human Geography. Oxford: Oxford University Press.*	p 114
Transmissivity	The portion of radiant energy falling on a surface that is transmitted through the body. *Schaschke, C. (2014). 'Transmissivity', A Dictionary of Chemical Engineering. Oxford: Oxford University Press.*	p 42, 150

U

Urban canopy layer	The layer of air in the urban canopy beneath the mean height of the buildings and trees. Its climate is dominated by microscale processes due to the complex array of surfaces. *American Meteorological Society Glossary of Meteorology (2012). 'Urban canopy layer'. Accessed on June 16. 2017. http://glossary.ametsoc.org/wiki/Urban_canopy_layer.*	p 48

Urban climate

Refers to climatic conditions in an urban area that differ from neighbouring rural areas, and are attributable to urban development. The effect is produced by the whole urban area. The science that studies this issue is called urban climatology. Generally, this concept will be referring to the mesoscale but it could refer to the microscale, since variables have a high spatial variation (mainly air temperature, relative humidity, wind speed, radiation). Also air pollution is frequently included in the concept of 'urban climate'.

Kuttler, W. (2008). 'The Urban Climate - Basic and Applied Aspects', Urban Ecology: An International Perspective on the Interaction Between Humans and Nature, Boston, MA: Springer, 233–248. doi: 10.1007/978-0-387-73412-5_13.

Urban Heat Island (UHI)

Refers to the urban area that is significantly warmer than its surrounding rural areas due to development and urban activities occurring inside the urban area. The main cause is the modification of land surfaces. Urban surface accumulates heat and thus air temperature tends to increase in the urban area.

Chow, W. T. L., Roth, M. (2006). 'Temporal dynamics of the urban heat island of Singapore', International Journal of Climatology, 26(26): 2243–2260. doi: 10.1002/joc.1364.

Urban morphology

The study of the physical form of cities. p 56

Oliveira, V. (2016). Urban morphology: An introduction to the study of the physical form of cities. Cham: Springer International Publishing.

U-shaped vortices

The head of young turbulence spot and eventually breaks down to small pieces. p 48

Singer, B., Joslin, R. (1994). 'Metamorphosis of a hairpin vortex into a young turbulent spot', Physics of Fluids, 6(11): 3724. doi: 10.1063/1.868363.

V

Verandahway

Paved pedestrian walkways, five feet in width, projecting from the ground floor of a building into the road. This feature can be found in many shophouses (and buildings of similar structural design) in Singapore. p 115

Lim, J. S. H. (1993). 'The Shophouse Rafflesia': An Outline of its Malaysian Pedigree and its Subsequent Diffusion in Asia', Journal of the Malaysian Branch of the Royal Asiatic Society, 66(1): 47-66.

Void deck

The open spaces on the ground floor of Housing Development Board housing blocks in Singapore. Architecturally speaking, they are defined by the structural columns that support the housing block above, the largely unadorned walls of the lift and stair core, the smooth concrete or tiled surface of the floor, and the grooves, lips and gutters that run around its perimeter guiding away the rainwater run-off from the surrounding landscape or car parking areas. p 44, 45, 48, 53

Cairns, S., Jacobs, J. M., Yingying, J., Padawangi, R., Siddique, S., Tan, E. (2013). 'Singapore's void decks', Public Space in Urban Asia. doi: 10.1142/9789814578332_0005.

Void space dynamic insulation (VDSI)

Thick layers of conventional superinsulation is a new type of superinsulation that can deliver even lower envelope heat losses, use less thick conventional (low cost) insulation materials and offer near-zero risk of interstitial condensation. p 99

Imbabi, M. S. (2012). 'A passive–active dynamic insulation system for all climates', International Journal of Sustainable Built Environment, 1(2): 247-258. doi: 10.1016/j.ijsbe.2013.03.002.

W

Wake

The area of low pressure turbulent flow behind a moving body that causes the body to experience resistance to its forward motion. p 48

The Gale Encyclopedia of Science (2008). 'Fluid Dynamics', Accessed on June 21, 2017. http://www.encyclopedia.com/science/encyclopedias-almanacs-transcripts-and-maps/fluid-dynamics-0.

Water catchment

The area from which a surface watercourse or a groundwater system derives its water. Catchments are separated by divides. p 72

Allaby, M. (2013). 'Catchment', A Dictionary of Geology and Earth Sciences. Oxford: Oxford University Press.

Wetlands

Wetlands are lands that are significantly influenced by the presence of water. p 72

McGraw, M. (2010). 'Wetlands', Encyclopedia of Geography, Thousand Oaks, CA: SAGE Publications Ltd, 3093-3094. doi: 10.4135/9781412939591.n1239.

Wind velocity vectors

They indicate direction and intensity of the wind. The vectors point in the direction to which the wind is blowing and the intensity of the wind is conveyed through the size of the vector. p 46

Department of Atmospheric Sciences (DAS) at the University of Illinois at Urbana-Champaign (2010). 'Wind Vectors'. Accessed on June 20, 2017. http://ww2010.atmos.uiuc.edu/(Gl)/guides/mtr/cyc/upa/wndvct.rxml.

Wing walls

Is an architectural element for natural ventilation to direct the external air flow into the building by projecting portions of the walls vertically from the openings. p 48

Nejat, P., Calautit, J. K., Majid, M. Z. A., Hughes, B. R., Zeynali, I., Jomehzadeh, F. (2016). 'Evaluation of a two-sided windcatcher integrated with wing wall (as a new design) and comparison with a conventional windcatcher', Energy and Buildings, 126: 287-300. doi: 10.1016/j.enbuild.2016.05.025.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Published in 2017 by Cooling Singapore
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Printing
Goh Bros E-Print

The catalogue contains 86 strategies and measures for mitigating the Urban Heat Island (UHI) effect and/or for improving Outdoor Thermal Comfort (OTC). These are grouped into seven clusters: vegetation, urban geometry, water features and bodies, materials and surfaces, shading, transport, and energy. Each measure describes its impact towards the UHI effect and OTC, its applicability in the tropical context of Singapore, its integration into urban planning, and its current research status. While many of the items in the catalogue may also be applicable to non-tropical cities, mitigation strategies and measures that are not applicable to tropical cities have been excluded.

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