Exploring the thermal benefits of plants in industrial areas with respect to the tropical climate

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ABSTRACT: The environment around the industrial buildings is considered to be relatively clean and neat in Singapore. However, the exposed factories with minimum planting are still the predominating image. The large areas of metal roofs absorb a lot of solar radiation and present high temperature which has been captured by a satellite image obtained above Singapore during the daytime.
Some concerns have been raised according to the current situation of industrial buildings. One is the negative thermal impact caused by industrial buildings towards the environment, especially the exaggerating of Urban Heat Island effect. Another one is the concern of energy consumption in the industrial area since the higher temperatures in the industrial areas will increase the cooling energy use in the buildings. The concern of thermal discomfort to the occupants of those buildings which are naturally ventilated and the concern of aggravating the air pollution problem due to the elevation of air temperatures have also been raised. Therefore a joint research project has been conducted by National University of Singapore and Jurong Town Corporation (JTC) to study the potential of introducing vegetation in the industrial buildings and to determine the impact on the environmental conditions as well as the energy performance of the industrial buildings. This paper will present some preliminary findings obtained from the filed measurements. The possible savings in terms of cooling energy will be discussed according to the quantitative data as well.

Keywords: Industrial buildings, plants, thermal impacts, UHI, energy consumption

1. INTRODUCTION

The familiar image of industrial estates to us is the massive chimneys and industrial buildings, with black smoke blocking out the light and covering streets with a blanket of dirty particulates. However, modern industry may be far different from this negative image. Jurong Town Corporation (JTC), as Singapore's leading provider of industrial land solutions, offers a wide spectrum of industrial facilities which can meet the requirements of all types of manufacturing and related operations. In general, around 7,000 hectares of industrial land and four million square meters of ready-built factories have been developed by JTC in Singapore over the past three decades. Among these industrial estates, there are not only traditional industrial clusters but also advanced business parks which are all well designed and organized in a clean and neat format.

However, the local factories with minimum plants are still the predominant impression. A recent study conducted by National University of Singapore (NUS) [1] indicates that, except for the Central Business District (CBD), the industrial areas exhibit higher ambient temperature and surface temperature. The higher ambient temperatures are primarily due to the higher release of stored heat in constructions and anthropogenic heat whereas the higher surface temperatures are the results of employing metal roofs.

Some concerns have been raised according to the current situation of industrial buildings. One is the negative thermal impact caused by industrial buildings towards the environment, especially the exaggerating of Urban Heat Island effect. Another one is the concern of energy consumption in the industrial area since the higher temperatures in the industrial areas will increase the cooling energy use in the buildings. The concern of thermal discomfort to the occupants of those buildings which are naturally ventilated and the concern of aggravating the air pollution problem due to the elevation of air temperatures are also considered to be the potential issues in industrial areas.

It is well known that planting of vegetation is one of the major strategies normally employed to mitigate the above negative issues since vegetation plays a significant role in regulating the urban climate [2 & 3]. In order to explore the potential of introducing vegetation in the industrial areas and to determine the impact on the environmental conditions, a joint research has been carried out by NUS and JTC.

2. RESULTS AND DISCUSSION

2.1 Macroscale measurements and simulation

Firstly, the measurements have been carried out at macro level in order to capture an overall image of the impact of the current landscape within the industrial areas. Two business parks with relatively extensive landscape have been chosen. They are Changi Business Park (CBP) and International Business Park (IBP). Since CBP is still under construction, it is possible to set up a reference point (green point) in the vacant area where more extensive greenery can be observed. Except for the measuring points within the boundary of CBP, another two measuring points had been placed in a traditional industrial area which is quite near to CBP. Overall there were 17 measurements points set up within IBP, CBP and nearby area (see Figure 1).

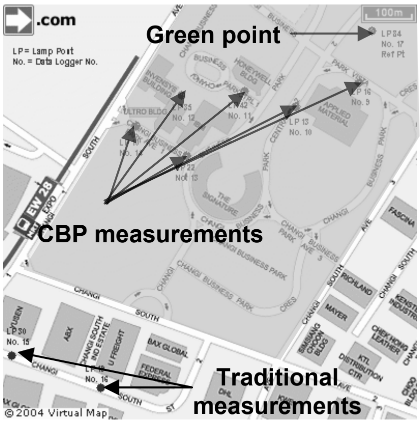
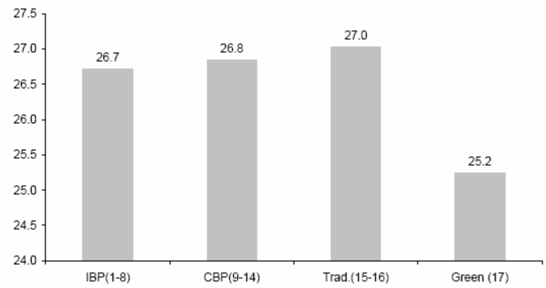


Figure 1: The measurements in CBP.

The average temperatures calculated at different locations over a period of 20 days were compared (see Figure 2). It can be seen that the average temperature obtained from the vacant area with relatively extensive greenery is significant lower, 1.5 – 1.8°C, than the other locations. Meanwhile, there is also around 0.2-0.3°C difference between business parks (IBP and CBP) and the traditional industrial area. The long term comparison actually shows the two extremes as the result of landscaping in industrial areas. With more extensive greenery, the ambient temperature tends to be lower whereas it can rise up to around 1.8°C higher with minimal planting. The local rule of thumb is that around 5% cooling energy can be saved with 1°C decrease of ambient air temperature.



	IBP(1-8)	CBP(9-14)	Trad.(15-16)	Green (17)
Ave T	26.7	26.8	27.0	25.2
SD	2.1	1.9	1.9	2.2

Figure 2: Comparison of average air temperatures (°C) obtained at different locations over a period of 20 days.

Another issue at this level is whether landscape should be integrated within industrial areas in concentrated or scattered form. In order to explore it, a simulation programme, Envi-met [4] was employed to simulate the two scenarios, one with concentrated landscape and the other with scattered one (see Figure 3). The premise is that the amount of greenery is the same in the two scenarios.

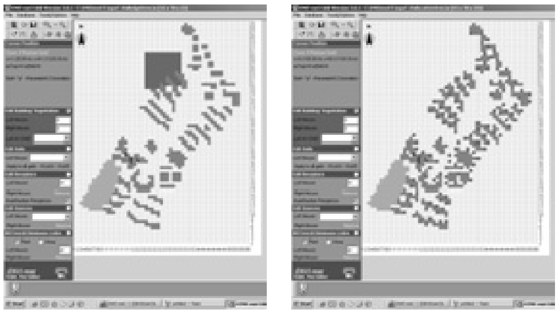


Figure 3: The two scenarios (left: concentrated landscape; right: scattered landscape).

It can be observed that the industrial area with concentrated landscape has better thermal condition (see Figure 4). The concentrated greenery can be treated as a huge cooling source. With the help of proper air movement, buildings near to the concentrated greenery do benefit from it. On the other hand, the impact of the scattered greenery is much localized. The small portion of greenery is not good enough to balance the negative impacts of the hash built environment, especially during the daytime when the incident solar radiation is strong.

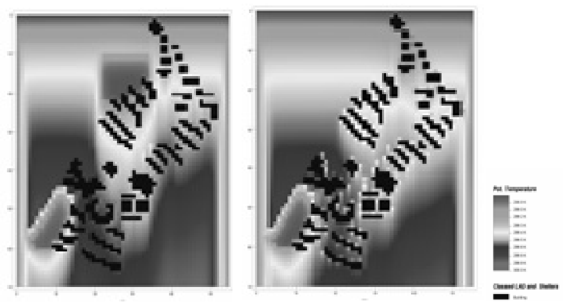


Figure 4: the simulation results at midnight (left: concentrated landscape; right: scattered landscape).

2.2 Mesoscale measurements

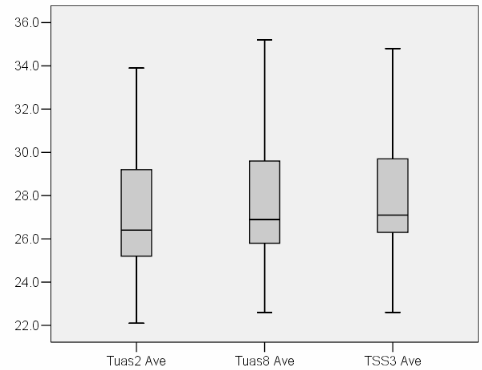
The measurements carried out at this level have been focused on the impact of road trees and large area of turfing.

The impact of road trees in industrial area was explored by measuring three streets in Tuas (see Figure 5). Tuas Avenue 2 and Tuas Avenue 8 are two parallel streets. Tuas Avenue 2 has very extensive trees planted along the roadsides. Trees planted along Tuas Avenue 8 are not as dense as those along Tuas Avenue 2. In addition, Tuas Avenue 2 and Tuas Avenue 8 are all streets with busy traffic during the daytime. Tuas South Street 3 is further away from Tuas Avenue 2 and 8 down to the southern part of Tuas. Compared with Tuas Avenue 2 and 8, Tuas South Street 3 is a narrow street with very young trees and minimal traffic.

All measuring points were evenly distributed in the three streets. There were 6 points in Tuas Avenue 2 and Tuas Avenue 8 respectively. Tuas South Street 3 had 5 points.

Figure 5: The three strees in Tuas industrial area (a) Tuas Ave 2 (b) Tuas Ave 8 (c) Tuas South Street 3.

It is interesting that the mean or the median values obtained from Tuas Avenue 2, Tuas Avenue 8 and Tuas South Street 3 over a long period follow exactly the sequence of the density of the planted road trees. Since it has many mature trees with big crowns, Tuas Ave. 2 had the lowest average mean temperature which was lower than those in Tuas Ave. 8 and TSS 3 by 0.5°C and 0.6°C respectively. It is noted that the difference between Tuas Avenue 8 and Tuas South Street 3 is not significant. The possible reason is that the heave traffic in Tuas Avenue 8 blurred the impacts of its road trees.



	Tuas 2 Ave	Tuas 8 Ave	TSS 3 Ave
Mean	27.3	27.8	27.9
Median	26.4	26.9	27.1
SD	2.6	2.7	2.4

Figure 6: Comparison of average ambient air temperatures measured on the three streets over a period of 26 days.

In order to explore the extreme condition, a clear day was chosen. The comparison of average temperatures measured in Tuas area is shown in Figure 7. A clear sequence was still observed among the three Tuas streets at the night time. Tuas Avenue 2, as expected, has lowest average temperature followed by those in Tuas Avenue 8 and Tuas South Street 3. During the daytime, especially from 1000 to 1730hr, higher temperatures were observed in Tuas Avenue 2 and 8. As mentioned earlier, it is probably due to the heavy traffic took place during this period.

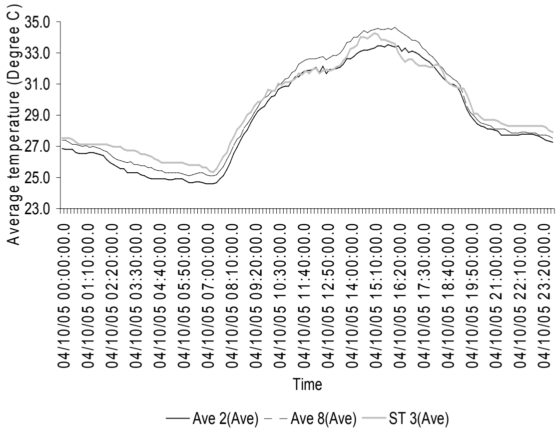


Figure 7: Comparison of average temperatures obtained at the three streets on a clear day.

Measurements carried out for exploring the cooling impacts of the large turfing, such as Raffles Golf Course (RGC) and Tanah Merah Golf Course (TMGC), near to the industrial areas shown much localized results (see Figure 8). Even with a large area of turf, there is no clear cooling range formed at the leeward of the Golf Course and the detected cooling range is within 10m only.

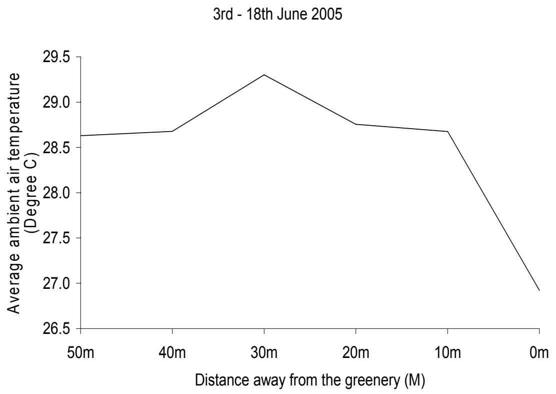


Figure 8: The average temperatures measured over 15 days on locations away from TMGC

2.3 Microscale measurement

In order to explore the impacts of introducing plants into individual buildings, some measurements have been carried out on eastern and western façades with tree-shading as well as metal roof with extensive rooftop garden system (see Figure 9).

A long term comparison of the surface temperature variations with and without tree-shading is shown in Figure 10. The outstanding shading effect of trees can be reflected by a narrow span of temperature variation. It can be observed that the reduction occurs mainly at the max-whisker which should be detected during daytime when incident solar radiation is strong. The trees can effectively intercept the solar radiation and generate lower surface temperatures behind them on the façade. On the other hand, there is no significant difference observed between the two min-whiskers. It indicates that the impacts caused by trees at night are not obvious. The mean surface temperature derived behind the trees is 28.7°C while that obtained from the exposed façade is 30.1°C.

Figure 9: Measurements on building facade and rooftop (Left: tree-shaded façade; Right: rooftop garden).

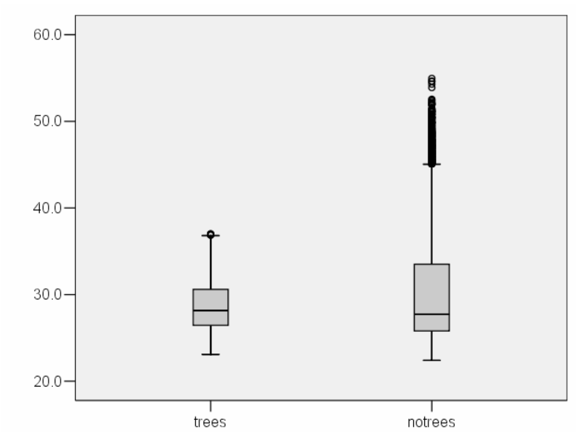


Figure 10: A comparison of the surface temperature variations with and without tree-shading on the western facade over a period of 50 days.

In order to have a close look of the performance of the trees on reducing the surface temperatures on the western orientation, two days have been selected. Figure 11 shows a comparison made on a relatively clear day. The shading effect caused by trees over the western orientation can be easily observed during the daytime. Due to the orientating effect, there is a time lag between the peak of solar radiation and the peak of external surface temperatures measured on the western facades. The maximum temperature difference can be up to 13.6°C at around 1530 hr. Figure 12 shows a comparison made on a relatively overcast day. Without much direct radiation, the shading effect of trees is mainly reflected on reducing the diffused radiation on the spot. A temperature difference of 7°C can still be observed at around 1550 hr. The findings highlight the impact of vertical shading on building facades not only during those clear days but also during the overcast conditions. On the other hand, the surface temperatures are inversely distributed at night compared with those observed during daytime. The difference is constantly around 2°C. Without the blockage of the foliages, the heat can be easily dissipated by the exposed façade to the surroundings. Compared with stunning reduction of surface temperature during daytime, the limitation occurs at night can be neglected.

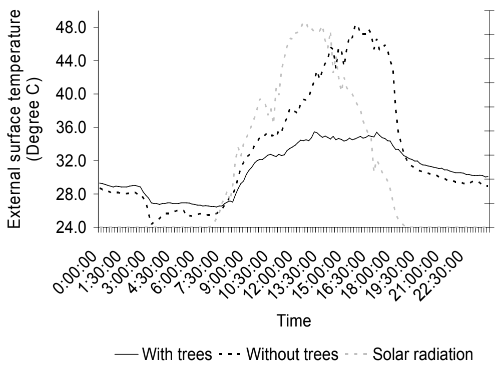


Figure 11: A comparison of solar radiation and the surface temperatures measured with and without tree-shading on the western facade on a clear day.

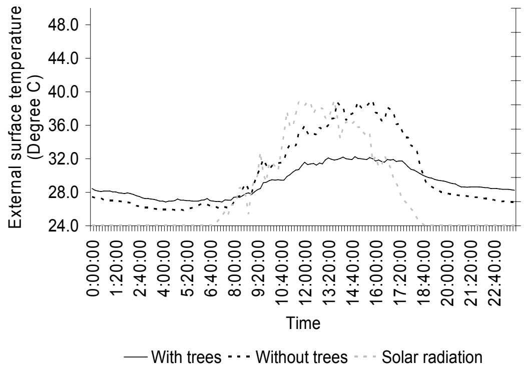
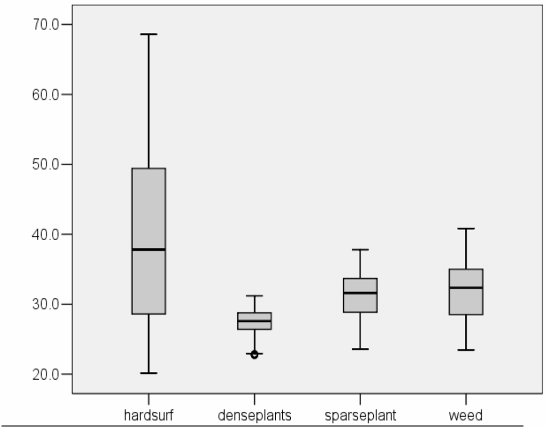


Figure 12: A comparison of solar radiation and the surface temperatures measured with and without tree-shading on the western facade on a cloudy day.

The data obtained on the green metal roof has also been analyzed over a relatively long period of time (see Figure 13). Some remarkable findings are summarized as follows:

- The effect of Leaf Area Index (LAI) values, which is the ratio of the total area of all leaves on a plant to the area of ground covered by the plant, on the surface temperature fluctuating can be clearly noted from the variations observed from dense plants, sparse plants and weed. The mean surface temperatures ranged from 27.5°C to 32.0°C and the Standard Deviations ranged from 1.6 to 4;
- The benefits of reducing the surface temperature by greenery can be observed from mean surface temperature differences between the hard metal surface and those below the plants. They are 12.1°C, 8.4°C and 7.6°C with the presence of the dense plants, the sparse plants and the weed respectively;
- The benefits of greenery has also been reflected in controlling the fluctuation of surface temperature. Without plants, the metal surface can fluctuate from 20°C up to 70°C. Even the 50% observations are distributed between 29°C to 50°C during the daytime. With plants, the maximum surface

temperature observed below the dense plants is around 40°C while the lower limit is around 24°C.



	Hard surface	Dense plants	Sparse plants	Weed
Mean	39.6°C	27.5°C	31.2°C	32.0°C
Standard Deviation	11.9	1.6	3.1	4.0

Figure 13: A long term analysis of the surface temperatures measured on the green metal roof (excluding night-time) from 0700 to 1900 hr.

Subsequently the observation has been zoomed into a clear day when the performance of plants can be easily found (see Figure 14). It can be observed that the surface temperatures of the exposed mental roof are very sensitive towards the solar radiation. They more or less followed the profile of solar radiation during the daytime. The peak value is around 60°C which is observed at 1230 hr when the solar radiation also reaches its peak. The maximum difference between the surface temperatures of the exposed metal roof and below the dense plants is 35.1°C during the daytime. At night, the inverse situation occurred and the surface temperatures of the exposed metal roof dropped dramatically. They are lower than all the temperatures measured below the rooftop greenery. The maximum surface temperature difference between the exposed metal roof and the dense plants is 4.74°C at night. Meanwhile, a clear sequence can be observed under different plants according to their density during daytime.

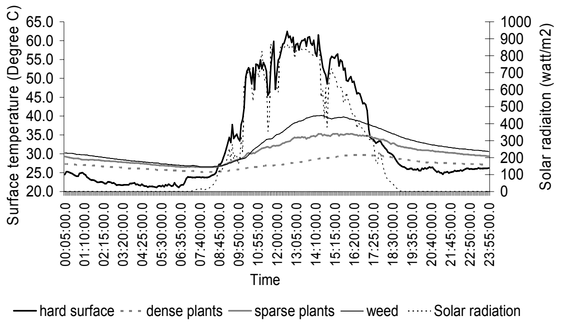


Figure 14: A comparison of surface temperatures measured on the green metal roof on a clear day

2.4 Energy and simple cost analysis

The preliminary field measurements show plants do benefit the industrial area at both the macro and micro levels. The issue is how much plants can contribute to cooling energy consumption in these industrial buildings. In order to answer the question, a TAS [5] simulation has been carried out. A common stand-alone one-storey-building was built in the simulation (see Figure 15). Some assumptions had been made as follows:

- The factory building is fully air-conditioning;
- The indoor temperature is set to be 24°C;
- The working hour is set from 0700 to 1900hr;
- No internal heat source (avoiding possible interference from internal environment).

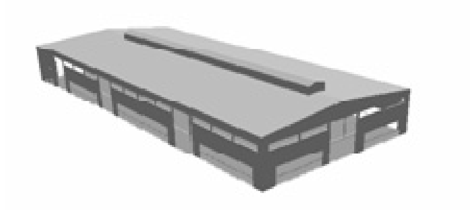


Figure 15: TAS model –one-storey-factory.

There are five scenarios assumed in the programme. They are bare factory (case 1), factory with eastern and western tree-shading (case 2), factory with a extensive green roof(case 3), factory with both tree-shading and green roof (case 4), and factory with both tree-shading and green roof in a environment with very extensive road trees (case 5). The boundary conditions employed in the simulations are derived from the field measurements.

Figure 16 shows the result of the cooling energy consumption in the factory building under the five scenarios. With tree-shading on the unfavoured orientations (East and West), 10% energy can be saved. Another 18% energy can be saved with an extensive rooftop greenery system on the metal roof. The combined strategic introduction of plants on not only unfavoured facades but also metal roof can cause altogether 28% energy saving. Finally, with additional help from extensive trees at macro-level, overall 48% energy can be saved. It is encouraging that nearly half of the cooling energy can be saved with the help of plants at both the micro and the macro levels.

Based on the above energy analysis, a simple cost analysis has been done (see Table 1). It is evidenced that strategic tree planting around industrial buildings is a good and cheap solution. Most local industrial developments are low-rise buildings. They are vulnerable to excessive solar heat gain at the unfavoured orientations and the metal roofs. Trees can easily protect the facades and part of roof area as long as they are planted near to a low-rise factory. Meanwhile, the initial cost for tree planting and necessary maintenance is cheap. It can be observed that the payback time for a factory is less than a year. Compared with trees, the extensive rooftop system is costly. The payback time can be up to 15.4 years. The reason is due to the costly installation and maintenance. It is believe such cost can be reduced when more mature technology are employed. It is worth to mention that the payback time can be reduced to 8.7 years when both tree planting and extensive rooftop system are employed in a factory.

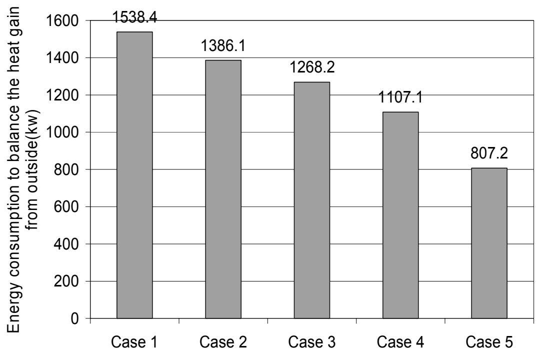


Figure 16 : Energy consumption analysis of a factory building.

Table 1: Simple cost analysis according to the simulation results (the question mark is due to the lack of data currently).

Item	With trees	With rooftop greenery	With both trees and rooftop greenery
Cost and installation	460/tree x 30 = -13,800	90/m² x 3024 = -272,160	-285,960
Maintenance cost per year	?	0.25/m² month x 3024 x 12 = -9027	0.25/m² month x 3024 x 12 = -9027
Energy savings per year	15,059	26,695	41,994
Total savings over 5 years	61,496	-184,045	-122,548
Total savings over 20 years	287,384	80,301	367,686
Payback	0.9ys	15.4ys	8.7ys

3. CONCLUSION

Both the field measurements and the simulations carried out in the local industrial areas indicate that plants can benefit the industrial buildings in the tropical climate. The results are summarized in Table 2. Based on the results, some general guidelines have been generated:

- It is believed that concentrated greenery has remarkable cooling impacts on surroundings. In the landscape design of the industrial developments, it is suggested that groups of concentrated greenery should be designed to replace sparsely distributed greenery to achieve the maximum cooling impact.
- Turfing, even it is large in terms of size, does not have significant cooling impact on surroundings and the effect tends to be localized. To achieve remarkable cooling impact, it should be built near the buildings in order to reduce the possible reflected radiation from surrounding hard surfaces.
- The cooling impact of trees is very much governed by their Leaf Area Index (LAI). Therefore, trees with dense foliage will help to cool the environment effectively. It is suggested that dense trees should be transplanted to the industrial area in stead of cultivating young trees on site. In order to achieve that best performance, heights of trees as well distance from buildings should be considered.
- Compared with extensive rooftop greenery, tree-planting is more applicable currently for local low-rise industrial buildings.

Table 2: Summary of results generated from the filed measurements and the simulations.

Marco level:

	Extensive plants	Current landscape in CBP	Road Trees	Large Golf Course
Cooling impact	Up to 1.4 to 1.8° C Lower (average temperature) than traditional industrial area	0.2° C Lower (average temperature) than traditional industrial area	0.6° C Lower than street with very young trees	Very localized

Meso level:

	Ambient temperature	Energy savings
Yong trees	25.2 to 34.9° C 27.9° C (ave.)	0%
Trees and heavy traffic	24.4 to 36.1° C 27.8° C (ave.)	1%
Extensive trees	23.2 to 34.0° C 27.3° C (ave.)	11%
Very extensive trees	23.2 to 32.5° C 26.7° C (ave.)	38%

Micro level:

	Surface temperature reduction (Degree C)	Energy savings
Eastern wall shaded by trees (light colour)	Max: 7.9 Ave: 2.5	10%
Western wall shaded by trees (dark colour)	Max: 13.6 Ave: 1.4	15%
Extensive rooftop system	Max: 35.1 Ave: 4.7	18-26%

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