THE INFLUENCE OF URBAN BUILT FORM ELEMENTS FOR OUTDOOR THERMAL COMFORT CONDITIONS

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Thesis/ Dissertation Submitted in partial fulfillment of the requirements for the degree
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DECLARATION

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CERTIFICATION

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ABSTRACT

Rapid urbanization lead built-up area expansion is one of the key challenges in present cities. Most of the cities in tropical countries, will be significantly affected by the urban heat which is caused by high-density built-form and exacerbated by climate change. This study discusses the impact of different built form elements to the outdoor thermal comfort of pedestrians/users with special reference to a given micro-climatic zone at Pettah in Colombo. The location for the case study was purposely selected which consists with highly urbanized and highly pedestrianized area in Colombo. For the Field measurements there were selected five different elements of built forms located under the same microclimatic condition. The first Location is an Urban Plaza, the second Location is a narrow, East-West canyon (i.e, Prince street), the third Location is a North – South Urban Canyon (i.e., 02nd cross street), the fourth Location is a wider, East-West Urban (i.e., Main Street) and the fifth Location is a Parking Precinct.

Field measurements of five weather parameters effects on the thermal comfort of pedestrians (i.e., Air temperature, Relative Humidity, Wind direction, Wind speed and the Surface temperature) were taken on the 27th March 2019 which is the time of the time of the year that usually records the highest temperature in the given micro –climatic zone.

Empirical data were analyzed and discussed the behavior of measured Air Temperature, Surface Temperature, Thermal Heat Index (THI) values and Thermal Heat Index Difference (THI Difference) of each Location. To study the influence of different urban forms and to explore the urban heat mitigation strategies in depth used the ENVI-met 4.1 computer simulation for selected five locations and Air temperature, Mean Radiant Temperature (MRT) and Predicted Mean Vote (PMV) data were analyzed.

As results the different built form elements indicates the different thermal comfort levels. Among all selected built forms, Urban canyons/ urban streets and Urban Plaza with More Green indicated sensible results according to the urban heat mitigation. Therefore, mainly highlighted the Urban Streets/ Urban Canyons which gives the urban shade and Urban Plaza comprises Trees with Larger Tree canopies are most considerable urban forms in city planning to mitigate the urban heat in an urban setting.

Key words: Different Built forms elements, Thermal heat Index (THI), Thermal heat Index Difference (THI Difference), Predicted Mean Vote (PMV), Outdoor thermal comfort.

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CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Large portion of the world population have been migrated from rural to urban areas due to the rapid growth of the Urbanization. Therefore, the Urban development has also increased to cater for the highly increased population in urban areas. These rapid un organized urban developments and the population growth caused for the Climate change.

As per the findings of researches done by Author Johansson' s and other authors in 2014 it was clearly identified the most of cities are getting increasingly hotter, which has mostly effects on the health and well-being of the people in urban areas. Further the Johansson was highlighted this scenario especially critical in tropical climates. The Outdoor thermal environment is more complex than the indoor thermal comfort considering the large temporal and spatial variations.

Recently, the climate change was the most discussed topic in the world in the context of global environmental impacts. The climate change is exacerbated by the increasing population, built structures and sealed surfaces in cities. Authors, Field et al in 2014 and Gao et al in 2015 were also highlighted regarding the climate change impacts such as increase in flooding, droughts, heat stress which were mostly threats to public health and safety.

Accordingly, integration of urban climatic knowledge into planning policies and development of mitigation technologies against to the impacts occurred due to the climate change is essential in recently as highlighted authors Oke in 2006, Roth in 2007, Ng in 2016, Rajagopalan in 2017 and Kotharkar in 2017.

1.2 Research Problem

The environmental degradation which impacts of climate change phenomenon is occurring in South Asian cities. The Urban Heat Island effect (UHI) is one of the most vulnerable impacts can be occurred due to the climate change in future. Tropical urbanization remains the largest and the most critical man- made environment issue in the world and almost 90% of global urbanization between now and the 2025 will occur in developing countries which located in tropical and sub-tropical region in the world. These statistics were indicated the urgency and the importance of the studying the human behavior of tropical urbanization (Emmanuel, 2005)

Although there were several studies on the urban heat impact on cities, the application of climate knowledge in urban planning in tropical cities is very rare. (Ng, 2016; Perera,2016). The Urban Heat Island (UHI) phenomenon is sparsely studied in the tropical areas (Emmanuel,2005).

There are very few studies referred to tropical urban climate, particularly, relevant to the different built forms (Roth,2007). There is need to understand how the built form characteristics effects on the thermal comfort and to assess effectiveness of alternative planning interventions in enhancing the thermal comfort.

1.3 The Significance of the Study

Urbanization process have a huge impact on the rise of urban heat in many cities. The Spatial quality and its special characteristics are important in regulating the anthropogenically- induced Urban Heat.

Outdoor spaces with the thermal comfort encourage the human movements in a city and its assist to improve the Public Health, Air quality and the Urban Life. Accordingly designing a better comfortable outdoor spaces with different built form elements is an essential to achieve the thermal comfortable urban environment on cities located in Tropical climate.

This simulation study assesses the effectiveness of a selected set of built form solutions in reducing urban heat which will subsequently guide planners to make decisions on improving the thermal comfort of cities.

1.4 Objectives and Aims.

This study is aimed to discuss and assess the impact of different built form elements over the thermal comfort of pedestrian on a selected microclimate.

Objectives:

- To measure the Outdoor Thermal Comfort conditions affected by different urban built form elements such as 1.) An Urban Plaza, 02.) East –West Urban Canyon, 03.) North-south Urban canyon, 04.) Urban Parking Precinct in a selected urban area.

and

- To explore;
    - a.) The impact of different Geometries (Low rise, Intermedium Rise, Medium rise and High rise) over the thermal comfort of pedestrian by comparing thermal comfort conditions in different scenarios, by computer simulation.
    - b.) The impact of different planned scenarios for the outdoor thermal comfort, by computer simulation.

1.5 The Method of Study.

1.5.1. Colombo as a Case Study

Colombo Metropolitan Region (CMR) is rapidly urbanization as 4.5 million in 1996 and it was increased in to 6.5 million in 2010 due to the growth of population and the generated workforce. The first ever comprehensive historical survey of the Urban Heat Island phenomenon in the Colombo Metropolitan Region (CMR) was completed only in 1999 and it is important to do more studies of the Urban Heat Island (UHI) phenomenon in Sri Lanka. (Emmanuel,2005)

The author Ranagalage *etal* in 2017 was emphasized Trend of urban Development of Colombo and the variation of land surface Temperature in Colombo as shown in the Figure 01 and the Figure 02 respectively.

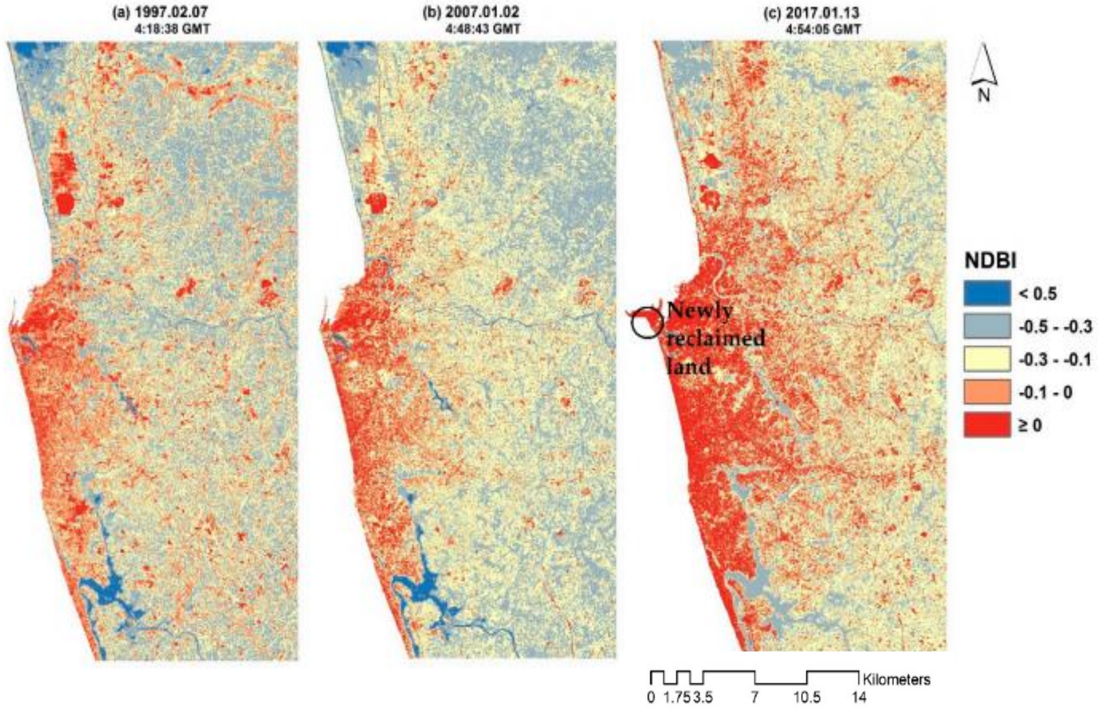

Figure 01: Normalized difference built-up index (NDBI) maps of the CMA in (a) 1997; (b) 2007; and (c) 2017 (Ranagalage M.etal, 2017)

As per the Figure 02, it was observed that a highly incensement of the land surface temperature in the Colombo region.

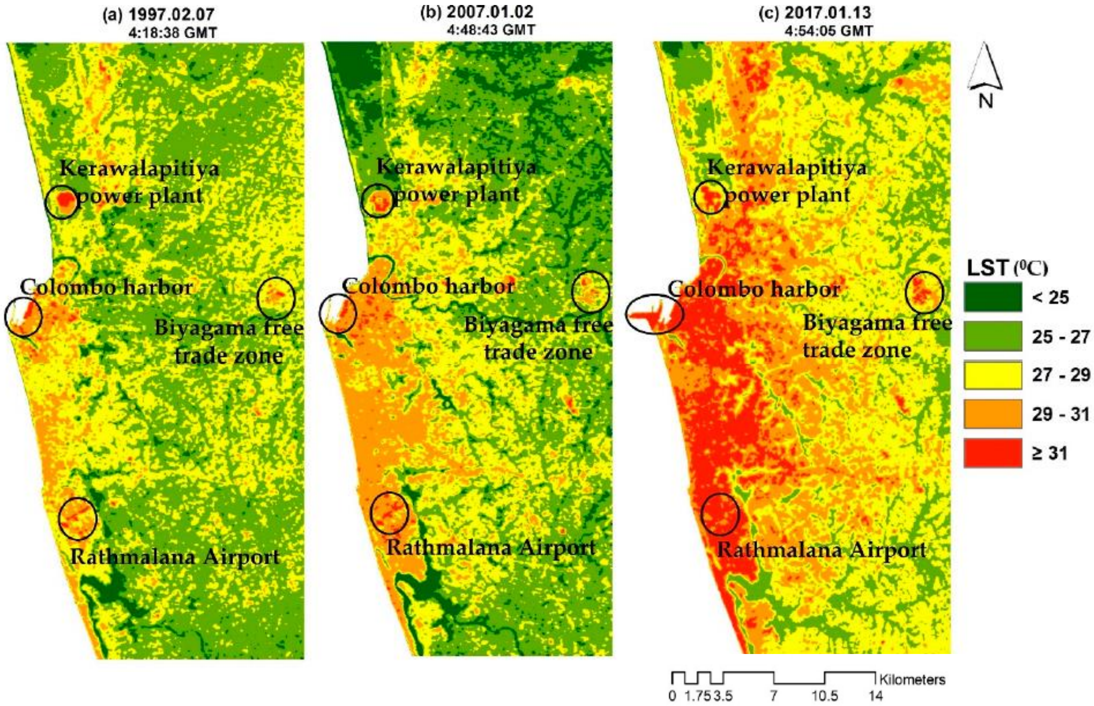

Figure 02 :Land surface temperature (LST) maps of the CMA in (a) 1997; (b) 2007; and (c) 2017 (Manjula Ranagalage, 2017)

According to the Land Surface Temperature maps analysed by the author Ranagalage *etal* in 2017 was highlighted the trend of urban heat in Colombo as shown in the Figure 02 and the Table 01.

Data	Time(GMT)	Minimum	Maximum	Mean	Standard Deviation
7-Feb-97	4:18:38	21.06	34.86	26.98	1.12
2-Jan-07	4:48:43	21.1	34.02	26.96	1.57
13-Jan-17	4:54:05	22.31	35.94	28.62	1.71

Table 01: Descriptive statistics of the retrieved LST values in CMA (°C).

Source: Manjula Ranagalage, 2017

Furthermore, the Colombo which was identified as the Commercial Capital of Sri Lanka. It includes to the low country wet zone of Sri Lanka. Rapid urban development and unorganized urban planning projects have transformed Colombo into a highly urbanized city in South Asian region. The Colombo having with resident population 752,993 in 2011 and a floating population of nearly 100,000 as per the census data.

As per the Climate data obtained from the Meteorological Department in Sri Lanka from March 2018 to March 2019, the Maximum Monthly Mean Air temperature indicated as the 32.2 C^0 in March 2019 and the Minimum Monthly Mean Air temperature indicated as 23.5 C^0 in January 2019.

	January	February	March	April	May	June	July	August	September	October	November	December
Min. Air Temperature (°C)	21.9	22	23.2	24.2	25.2	24.9	24.9	25	24.6	23.7	22.7	22.2
Max. Air Temperature (°C)	30.2	30.7	31.6	31.8	30.8	29.7	29.7	29.8	29.8	29.7	29.8	29.7
Average Air Temperature (°C)	26	26.5	27.4	28	28	27.3	27.3	27.4	27.2	26.7	26.2	25.9
Average Rainfall (mm)	74	73	136	246	360	208	134	103	180	358	317	159
Relative Humidity (%)	75	76	78	81	82	82	80	80	80	83	82	78

Table 02: Annual Average Air Temperature of Colombo (1982-2012)

Source: Climate data of Meteorological Department in Sri Lanka

According to the Climate data in the Table 02, it was clearly observed that the highest Average Air temperature is indicated as 31.8 C^0 in April and 31.6 C^0 in March respectively.

Furthermore, the variation in Annual Air Temperature is around 2.1 C^0.
Considering the previous outdoor thermal comfort, urban heat studies and Climate data, the Colombo city is getting hotter day by day with the rapid urban development and also have signs to create urban heat island effect and it will affect to the climate change.

In the Sri Lankan context, the city planners and urban designers are not studied deeply the impact of different urban form elements to the outdoor thermal comfort and very few explores the potential contribution of the urban development for the pedestrian's thermal comfort in depth. Further there are no create any policies or not including any guidelines for development guide plans to mitigate urban heat and to facilitate comfort environment for the pedestrians in urban areas yet.

Therefore, it is essential to explore with a gravity of the behavior of outdoor thermal comfort with rapid urban development special reference to the different built form elements and introducing mitigation options in Town planning will assist to create a most sustainable living environment.

1.5.2. Data collection methods

- Data collection regarding to the selected site by doing photographic survey, Historical data collection and climatic data (Air Temperature, Rainfall, Humidity and Wind) collection from Meteorological Department, in Colombo 07.
- Filed measurements will obtain and evaluates the existing thermal comfort behaviors on selected 05 Numbers of locations within a same hot day.
- All Air temperature measurements taken on the 1.2m level from the selected locations by using HOBO meter. Measured air temperature on a reference point also for the accuracy of Thermal Heat Index (THI) values.
- Discussed, the Air temperature, Surface Temperature, THI values and THI variations on selected locations with using empirical measurements.

- Explored, the impact of different built form elements for the outdoor thermal comfort by doing a computer simulation at the day of 27th March 2019 using from following different scenarios.

  Scenario One – Base case - Existing situation
  Scenario Two - Increasing of Building heights.
  Scenario Three - Green Scenario
  Scenario Four – Create Open Spaces
  Scenario Five – Create Wind Corridors
  Scenario Six – Changing Surface Materials

To discuss the behavior of Simulated Air temperature, Simulated Mean Radiant Temperature (MRT) and discuss the thermal stress by using calculated Predicted Mean Vote (PMV) at the level of 1.5m for the Day time 13:00:00h and the Night Time 21:00:00h respectively by using a simulating software ENVI –met 4.1 and prepare relevant graphs by using the Leonardo 2014, of all different Five built forms. To discuss the PMV value use BIOMET V1.01 to obtain the calculated PMV values for each Locations and for each scenarios.

1.5.3. Urban Simulation Tools.

01: ENVI-met 4.1 – is the Main simulation software to explore the Simulated Air temperature, Mean Radiant Temperature and the Predicted Mean Vote.
02: BIOMET V1.01- also a PMV value calculation tool. This also including in the ENVI-met 4.1 software.
03. LEONARDO 2014 Beta (E.T.) Build 3.100.2 – also a tool in the ENVI-met 4.1 software and it use to prepare simulation maps and graphs.

1.6 Scope Limitations to the Study.

01. This research is limited to a selected study area of Colombo, Sri Lanka which has a warm humid climate and sea breeze will effect to the accuracy of measuring data. Further, this study is carrying out a selected urban area under the same microclimatic conditions. The study area is very limited. Therefore, the results will limit for the study area.
02. There are different measures for Thermal Comfort. But in this study it limited to Air temperature, Thermal Heat Index (THI), Thermal Heat Index Difference (THI Difference), Mean radiant temperature (MRT), Predicted Mean Vote (PMV), Humidity, Wind Speed and wind direction.
03. Several technical difficulties which occurred when carrying out the Simulations for the ENVI- met software. (Time period) It possible to occurs a worst scenario.
04. Due to ENVI- met 4.1 software have limitation for the modeling of the selected area have difficulties at some times to obtain real accurate data.

CHAPTER TWO: BACKGROUND / LITERATURE REVIEW.

2.1 Urban Development/ Urbanization and Climate Change

Rapid Urban development contributed as the main affected key to deteriorate the urban environment. Lack of the knowledge to control rapid urbanization in development control and their needs directly affected to the urban climate and the efficiency of to create a sustainable environment.

Urbanization is an extreme situation involving land cover / land use (LCLU). The human Local environmental influences have also affected urban environment changes in the atmospheric composition, the water cycle and changes in ecosystems.

As per the research done in 1982 by the author Oke, was stated that more than half of the whole world's population became as urban residents in 2009 considering the frequency of the increasing the urban population and also he highlighted that this number is projected to reach 66% by 2050.

Owing to this rapid urbanization have to continue the process of rapid economic growth and the industrial development in every city. It will definitely cause to create a general deterioration of urban environment. The urban Heat Island effect which creates under the climate change scenario is the one of the environment problems causes by human modification on cities. (Oke,1982)

High Temperature at the surrounding environment, Poor Air quality and strong wings can cause heatstroke, heat stress and types of rashes and injuries. Mitigation of the Urban heat/ Urban Heat stress is a huge challenge for cities which located in tropical climate such as Sri Lanka. (Emmanuel, 2005 and Perera,2013)

2.1.1. Urban Heat Island Scenario (UHI)

An Urban Heat Island is an urban area which is most warmer than the its surroundings and other rural areas, due to the rapid urbanization and its different human activities.

As Emmanuel said in 1997, the usually the temperature difference at the Night time is larger than the Day time when apparent winds are weak. Further, he highlighted the different modifications of the existing land surfaces in different ways by the urban development is mainly caused to create the Urban Heat Island.

Moreover, Emmanuel indicated that due to increasing number of population, the modifications for existing cities were increased and also parallel increased the average temperature at the surroundings. As a result of the creating Urban Heat Island scenario, monthly rainfall is about 28% greater between 20 to 40 miles downwind of cities, compared with upwind as Emmanuel stated in 1997.

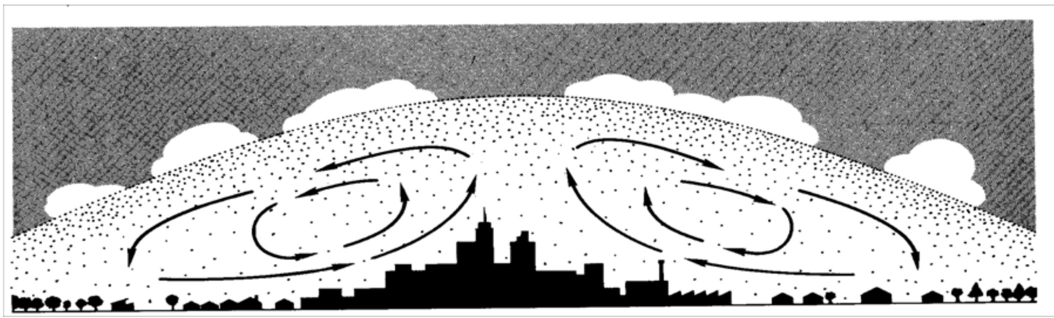

Figure 03: : The urban heat island is clearly apparent in many numerical studies of surface air temperatures over the years including Woolum, 1964 and in the illustrations below from Critchfield 1983

Source: William R. Lowry," The Climates of Cities", Scientific Amarican, August 1967

The main factors for the UHI that have been identified so far include catching the city in the heat of the city Geometry, alteration of urban thermodynamic properties, vegetation coverings and human change (Anthropological) heat input.

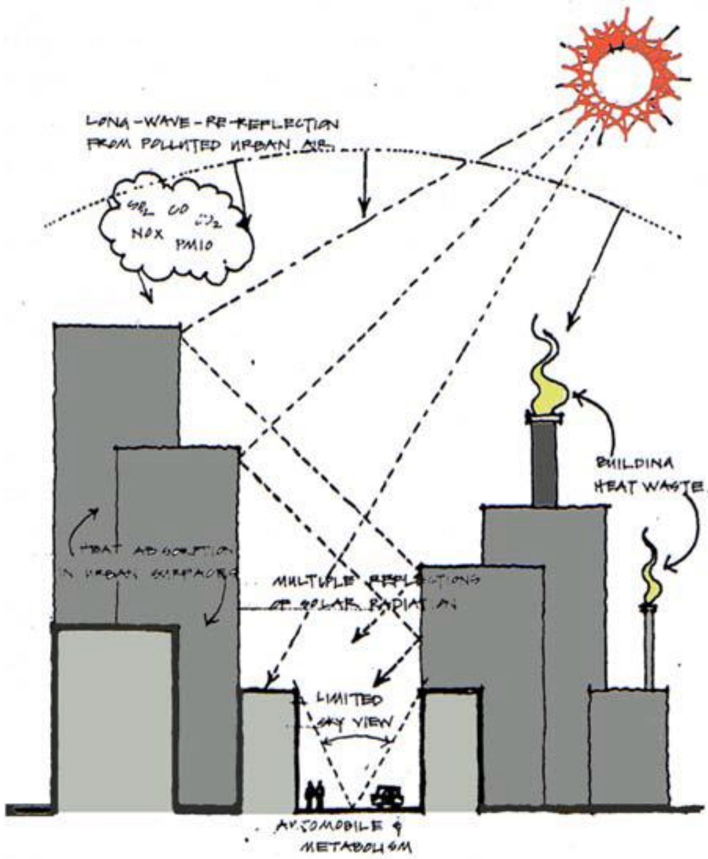

Figure 04 Causes for UHIs

Source: Emmanuel, 2005:25

An Urban Heat Island scenario is greatest visualized as a dome of stagnant warm cover which created over the deeply built-up areas of as shown in the Figure 04.

A Schematic View of Urban Air Temperature Profile is shown in the Figure 05.

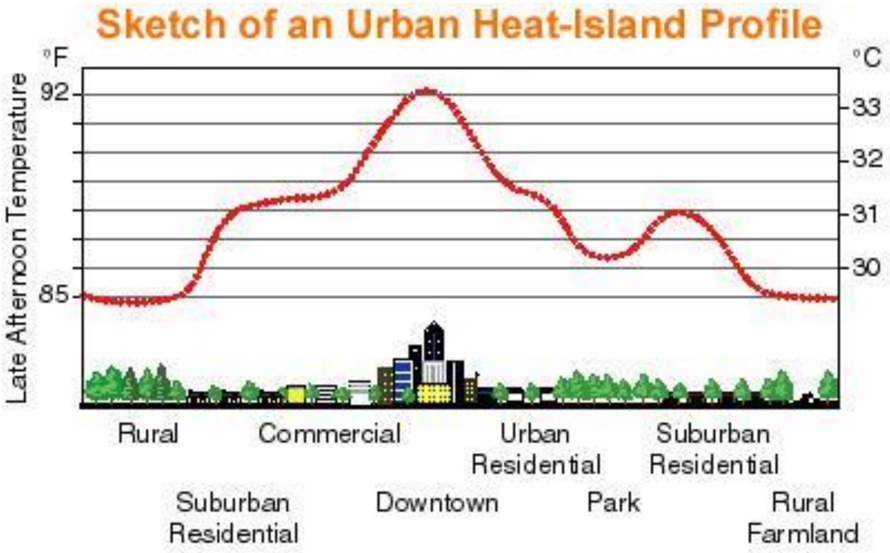

Figure 05: A Schematic View of Urban Air Temperature Profile

Source: A research Paper, The Urban Climate, Landsberg (1981)

2.1.2. Historical Studies relevant to the Urbanization and Climate

Changing of environment scenario due to the human activities is happening from many centuries.

A “Shilpa Shasthra” which is an ancient architectural manual translated by Acharya in 1979, created some rules for the setting of villages, towns and forts based on prevalent wind directions and solar orientation. When construct buildings also happened considering the solar orientation and the wind direction. When designing street layout, and massing, were arranged enhancing with street-level shade, air pollution dispersal, adding trees and storm-water drainage.

The author Morgan in 1960 also considered city layout and the environment conditions and it was clearly described on Vitruvius’(75-25BC) Book 1 of The Ten Books on Architecture.

The author, Boosselmann et al in 1995 was stated consideration of climate change and more concern with human health at the early stage.

The author, Cadwell in 1833 was suggested some heat mitigation options introduces as using of thick wall, using small windows and create courtyard houses with trees. And also he introduced open narrow streets and overhead balconies for hot humid cities.

2.1.3. Tropical Studies relevant to the Urbanization and Climate.

There were several completed researches regarding to the urbanization and climate change which relevant to the tropical countries. A few studies with major findings are shown in the Table 03.

Author/s	**City**	**Parameter/s studies**	**Major findings**
Nichol(1996a,1996b)	Singapore	Surface Temperature (Remotely sensed)	Due to high solar azimuth, horizontal surface temperatures are more representative of urban air temperatures in the tropical countries. Tropical cities do not have a single Urban Heat Island; rather a collection of small Urban Heat Islands separated by cooler areas.
Jauregui and Romales (1996)	Mexico City	Convective precipitation	Wet season rainfall, as well as the frequency of intense rainfall (>20mm/hr), appears to have increased over the city. The latter is related to daytime Urban Heat Island.
Jauregui and Tejeda (1997)	Mexico City	Specific humidity	City is drier during the day and wetter during the night than rural areas. The city-rural differences also depend on the season (smaller during dry season and larger during wet season).

Author/s	**City**	**Parameter/s studies**	**Major findings**
Jauregui (1997)	Mexico City	Air Temperature	Nocturnal heat island was more frequent (75 percent of the time) than daytime heat island (25 percent). Day time heat island may have been caused by differences in evaporative cooling from wet surfaces during the wet season.
Jauregui et al (1997)	Mexico City	Air Temperature and Relative Humidity	The heat-island effect reduces the "cold" and "cool" nights to "comfortable" bio climate (as measured by effective temperature ET).
Barr-Kumara-kulasingha (1997)	16 cities in South India and Sri Lanka.	Air Temperature	Negligible temperature trends were seen in all but one city (Colombo, Sri Lanka)
Deosthan (1999)	Pune, India	Wet and Dry bulb temperature	Rising trends in annuel and monthly thermal comfort (THI), particularly during the day. The presence of a"moisture island" detected.
Oke et al (1999)	Mexico City	Net radiation, sensible and latent heat fluxes	During day time, the heat uptake by buildings is so large that convective heating is severely suppressed in the central city with massive stone walled buildings. The heat release at

			night is equal to or larger than net radiation.
Wienert and Kuttler (2001)	Several cities	Air Temperature difference between city and rural areas	UHI magnitude is linked to latitude (low latitudes have smaller UHI), but this correlation is largely explained by differences in anthropogenic heat and radiation balance.
Emmanuel (2003)	Colombo, Sri lanka	Air temperature and relative humidity	Thermal comfort patterns(THI) are strongly correlated to hard land cover changes, particularly in the suburban areas.

Table 03: Recent tropical UHI studies

Source: Emmanuel,2005:30

Furthermore, South Asian literature in past reviews regarding to the Urban climate and the Urban Heat Island studies is shown in the Table 04.

Study	**Objectives**	**Selection criteria**	**Total studies cited**	**South Asian studies reviewed**
Some aspects of the urban climates in India (Padmanabhamurty, 1984)	Reviews existing knowledge in the field.	Urban climate studies in India	21	11

Study	Objectives	Selection criteria	Total studies cited	South Asian studies reviewed
Two Decades Of Urban Climate Research: A Review Of Turbulence, Exchanges Of Energy And Water, And The Urban Heat Island (Arnfield, 2003)	Assesses advances in select urban climate processes; explores literature on the urban temperature field.	Studies published in International Journal of Climatology	530	
Review of urban climate research in (sub)tropical regions (Roth, 2007)	Improves scientific understanding of urban climates in (sub)tropical areas; Provides data and guidance for climate responsive urban design in cities of the developing world.	Only examples of key studies to summarize Urban climate processes in these regions	250	25
A review on the generation, determination and mitigation of Urban Heat Island (Memon et al., 2008)	Reviews available literature on the generation, determination and mitigation of UHI.	Aimed at summarizing valuable findings, discussing potential research areas.	70	Nil

Study	Objectives	Selection criteria	Total studies cited	South Asian studies reviewed
A systematic review and scientific critique of methodology in modern urban heat island literature (Stewart, 2011)	Uses nine criteria of experimental design and communication to critically assess methodological quality.	Observational heat island studies published between 1950 and 2007.	190	Around 8% of studies reviewed. (approximately 15)
Study of the different approaches used to estimate the urban heat island effect in India (More et al., 2014)	Analyzes the transformation undergone in the process of using different tools to assess the formation of UHI in India.	Only studies from India	14	14
Three decades of urban heat islands and mitigation technologies research (Akbari and Kolokotsa, 2016)	Analyzes the evolution of the urban climate change as well as its mitigation technologies; particularly summertime UHI	Studies on heat island mitigation technologies published in the last three decades	56	Nil

Table 04: South Asian literature in past reviews.

Source: (Rajashree Kotharkar, Urban Heat Island studies in South Asia: A critical review, 2017)

An equatorial UHI study was recently concluded by Emmanuel (1999a). Figure 2.4 shows the trends for 30-year ambient air temperature in the Colombo Metropolitan Region, the capital city region of Sri Lanka. Since the UHI phenomenon is best seen in the night-time records rather in the day time, the graph depicts the daily (diurnal) variation in temperature. A diminishing diurnal temperature variation would indicate a growing UHI problem. (Emmanuel R. , An Urban Approach To Climate Sensitive Design, 2005)

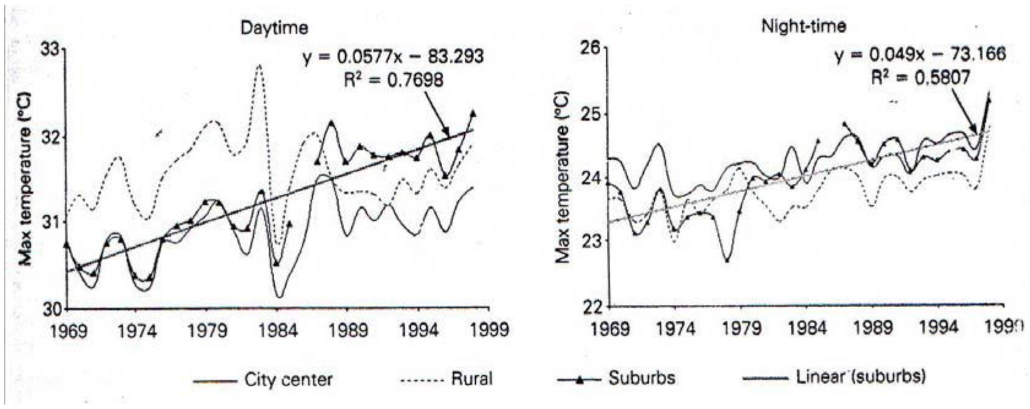

Figure 06: Historic air temperature trends in the CMR

Source: Emmanuel,2005:33

The Author Emmanuel in 2005 was highlighted the historic air temperature trends in Colombo Metropolitan region having with smallest diurnal variation. This was happened due to the increase in the daily minimum temperature, which in turn leads to smaller amount of variation in daily temperature. Daily maximum temperature remains unaffected by the urbanization.

The annual trends in diurnal variations in the CMR are minimal. If one looks at the temperature records alone, there is no indication that the problem is growing, even though the presence of a UHI is confirmed. However, this is true only if air temperature records are considered in isolation. The picture is different if thermal comfort trends, instead of air temperature, are compared for CMR. (Emmanuel R. , An Urban Approach To Climate Sensitive Design, 2005)

The Figure 07, shows the daytime thermal comfort trends in the region during the past 30 years (average annual trends and the trends during the hottest month- April respectively). The thermal comfort trends are measured in terms of a combined comfort index called the temperature- humidity index (THI). (Emmanuel R. , An Urban Approach To Climate Sensitive Design, 2005)

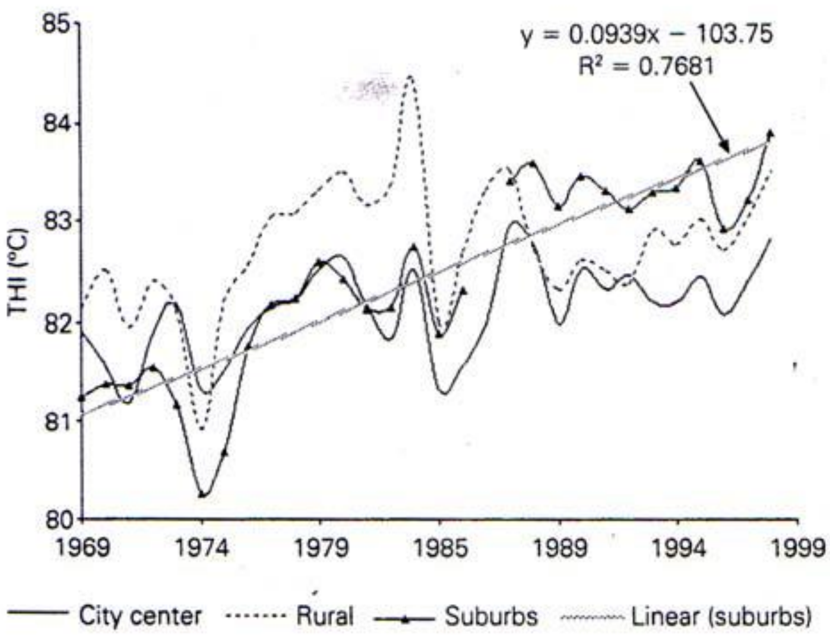

Figure 07: Day time thermal comfort trends in the hottest month in Colombo

Source: Emmanuel,2005:34

The author, Emmanuel in 2005 was concluded as the Air Temperature regime, thermal comfort in the city is better than in the rural surroundings during the day time and the recent climate of the Colombo Metropolitan Region is beyond the limits of thermal comfort. The lowest Thermal Heat Index (THI) in the region (28.3 C^0) is in above the lower limit of thermal discomfort levels. (said as 26 C^0). This is shown in the Figure 07.

Further, the Figure 08 shows the night-time thermal comfort variation in the Colombo Metropolitan Region. Here, too, the variation of an Urban Heat Island is clear.

The THI values are higher than those of the suburbs than other areas as shown in the Figure 08.

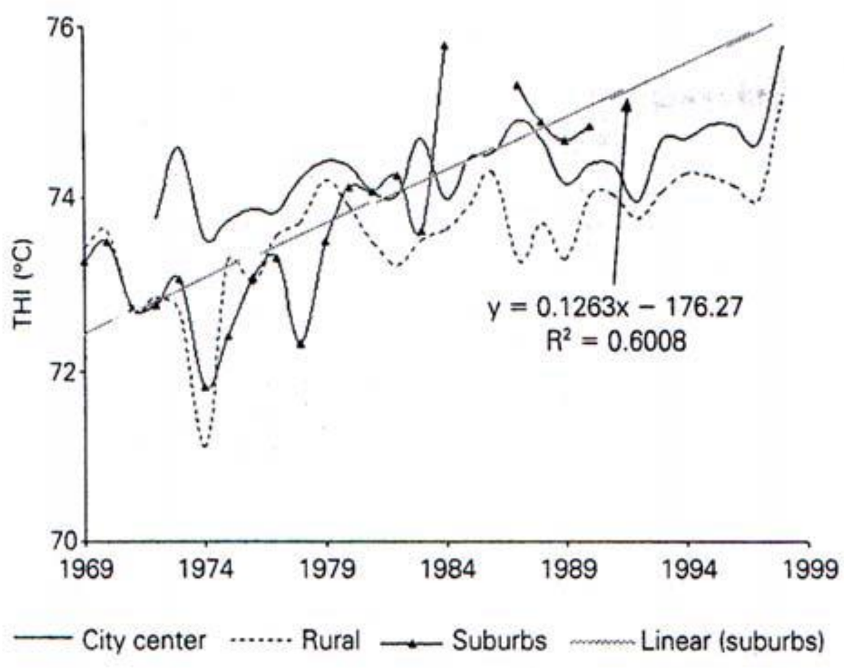

Figure 08: Night time thermal comfort trends in the hottest month

Source: Emmanuel,2005:35

Figure 07 and Figure 08 shows a thermal comfort comparison for Colombo city under “typical” climate. Typical climate data was taken from the period 1920 to 1979.“Recent” climate is assumed to be from 1994 to 1998. (Emmanuel R. , An Urban Approach To Climate Sensitive Design, 2005)

It was indicated that the Day time typical climate was barely tolerable during the year. Further, the day time typical climate was barely tolerable during most of the year in Colombo as shown in the Figure 09. As per the Figure 10, it was observed that the night-time, the typical climate was within the 100 percent comfort limit throughout the whole year, while the urban changes have resulted in approximately 6 months (mid-march to late September) having only a 50 percent comfort level.

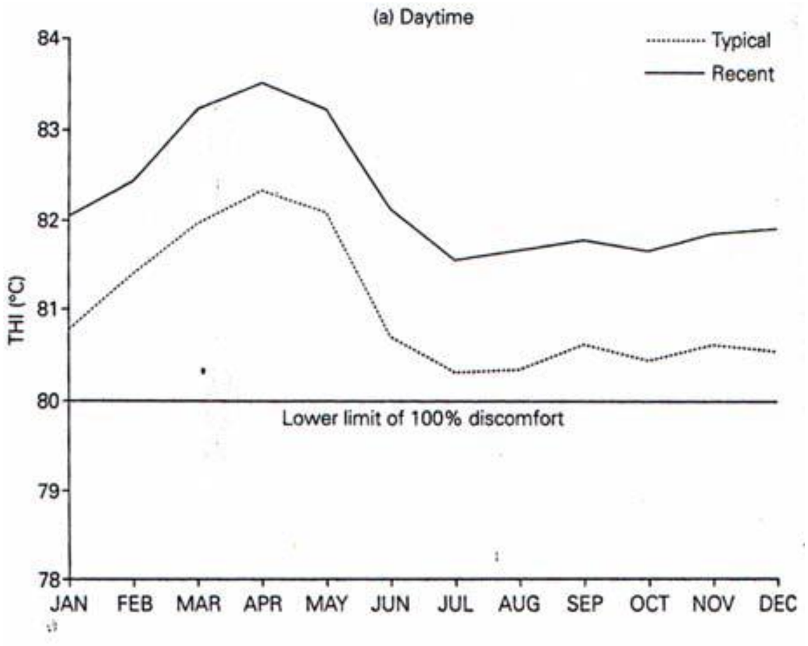

Figure 09: Typical” vs. “recent” a climate in Colombo city- Day Time

Source: Emmanuel,2005:36

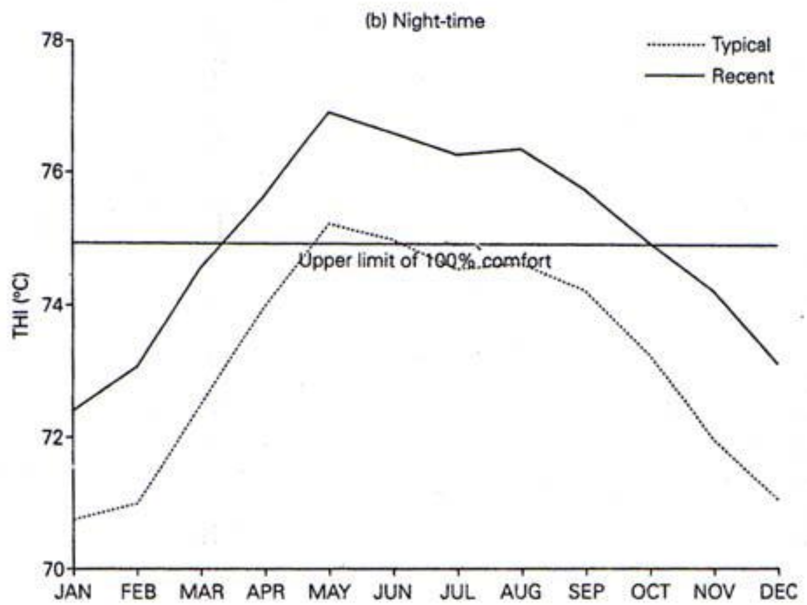

Figure 10: “Typical” vs. “recent” climate in Colombo city- Night Time

Source: Emmanuel,2005:36

2.2 Outdoor Climate and Comfort.

When considering the Outdoor Climate, Thermal comfort is most significant feature to deliberate.

Understanding and getting knowledge in thermal comfort is essential to designing of buildings in cities to create a sustainable environment.

Thermal Comfort

As per the ISO 7730 in 2005 description, Thermal comfort is defined as "the condition of mind which express the more satisfaction with the environment."

Further, the author Emmanuel in 2016 defined the Thermal comfort as "subjective thing which never can be achieved by all people." The Thermal comfort is different for every individual. Furthermore, the author stated that the thermal comfort is maintained when the heat produced by the human metabolism, allowed to waste at a rate that sustains thermal equilibrium in the human body. Any heat gains or heat loss elsewhere this produces substantial discomfort. To maintain the Thermal comfort, it is essential to heat generated must be equal to heat lost.

As stated by many authors, the Thermal comfort refers to the general personal insights about the Air Temperature, Air Humidity, wind speed and Mean Radiant Temperature under the general conditions of clothing and metabolism of people. The Thermal comfort is carefully linked to local climate, as well as the user's preferences, expectations, personal habits, perceived control and their cultural background, which are generally called as thermal adaptation. (McIntyre, 1980; Paciuk, 1990; Malama et al. 1998; Karyono,2000; Brager et al., 2004; Feriadi and Wong, 2004; Hwang and Lin, 2007; Lin and Matzarakis,2008) (Emmanuel R. , 2016)

2.2.1. Outdoor thermal Comfort in Tropics.

Outdoor activities are adjusted from the indoor activities. Comfort conditions also change according to the activities they are involved in. When people play in open areas without shading they feel less uncomfortable than waiting for a bus without shading.

Thermal comfort effect of land use categories

Land-use category	*Thermal comfort conditions (in TCI)*			
	Morning	*Early afternoon*	*Late afternoon*	*Night*
Low-density residential	4.8	8.0	1.3	0.6
Medium-density residential	1.8	4.8	3.4	1.3
Shopping area	3.6	6.8	5.8	−4.6
Central Business District	2.5	7.1	2.2	−4.7
Office complex	1.0	3.4	2.6	0.8
Heavy industrial	3.6	6.6	−1.9	−1.1
Park	1.0	3.4	2.1	0.8
Open grassland	5.8	6.3	3.6	−5.7
Open asphalt	5.8	11.7	4.9	−5.7

Source: Morgan and Baskett (1974)

Note: Thermal comfort is measured in "thermal comfort index" (TCI): +10 = unpleasantly hot; 5 = pleasant warm; 0 = neutral; −5 = pleasantly cool; −10 = unpleasantly cold

Figure 11: Thermal comfort effect of land use categories

Source: Emmanuel, 2005:82

This is understandable considering the great complexity of issues involved in the urban environment: spatial and temporal different type of environmental conditions, various of happenings, clothing patterns and complex effects of buildings and vegetation on shading and ventilation. (Emmanuel R. , 2005)

Nevertheless, there are numerous reasons why the indoor model is not conceptually suitable for outdoor thermal comfort. Hoppe (2002) identified three elementary reasons for that difference. There are;

- Psychological Reasons
- Thermo-physiological Reasons
- Heat balance differences Reasons.

2.2.1.1. Psychological Reasons

The Psychological Reasons for the difference between indoor and outdoor comfort perceptions have to do with expectation. The author Emmanuel in 2005 stated that the People bear a larger difference in climatic conditions at the outdoors than the indoors. Outdoor environment has possibilities to provide for adaptive behavior and, more importantly, affords suitable sociable spaces. This can be seen in beach resorts, urban parks and street canyons where people did not mind warmer-than-usual conditions, as long as sociable spaces are reachable. Further the author mentioned that urban gathering for sports, carnivals and for many reasons are happening during the day time which is the hot part of the day in tropical cities. Then the people incline to ignore the extreme thermal stress on their accounts of ambience created by the different activities.

Outdoor spaces present few constraints. People use them of their own fee choice: to soak in the sun, to get some fresh air, or to see and to be seen. Unlike the indoors, environmental stimulation is crucial to outdoor comfort. People want to “charge up” with warmth and fresh air, especially when considered in combination with their immediate thermal history (where they come from). This enables them to tolerate larger variation in the outdoor climate than the indoor. (Emmanuel R. , 2005, p. 82)

Figure 12: Environmental inspiration is essential to gain Outdoor comfort.

2.2.1.2. Thermo-physiological Differences

Thermo-physiological differences between indoor comfort and outdoor comfort will vary from differences in their clothing, activity levels and exposures times of the activity. In warm climates, people willing to wear less clothing, do very simple activities and also like to face for the natural environmental conditions longer in the indoors than outdoors.

Figure 13: Indoor and outdoor comforts varydue to the differences of clothing, activity levels and exposures times of the people.

Thermal adaptation of the body to warm conditions is much faster than for cold conditions. Since the human body is constantly attempting to lose heat, it is able to adapt to hot conditions much faster. (Emmanuel R. , 2005)

Even in warm conditions, the physiological processes associated with the outdoors are vastly different from those of the indoors, particularly if outdoor conditions are more complex. For an example, a person walking through a street canyon with a complex mix of shaded and sunny areas. (Hoppe, 2002:663-664)

Since the human body is relatively large, there is a lag effect which may lead to a mismatch between thermal comforts and the shade/sunny patterns in the outdoors, compounding the quantification of outdoor thermal comfort. For example, the thermal sensation of a person walking through a sunny urban area and then resting in a shaded urban pocket for a few minutes may not exactly correspond with his/her activities, clothing, or even the micro-environmental conditions on account of the lag effect. (Emmanuel R. , 2005)

2.2.1.3. Heat balance differences

Thermal stress is manifested in several physiological and sensory responses which reflect the strain imposed on the body to maintain thermal balance under stress conditions, or are affected by the discrepancy between the rates of heat production and heat loss.

While steady state conditions are possible in the indoors, they are hardly possible in urban situations. Primary reasons for the difference between the indoor comfort and the outdoor comfort is the energetic differences in between these two. There are different expectations from the two environments. People use the outdoors based on their perception of environmental variables (air temperatures, shade/sunny patterns, wind patterns, etc.), but once, they have decided to come outdoors their expectations are different-from that of the indoors. (Emmanuel R. , 2005)

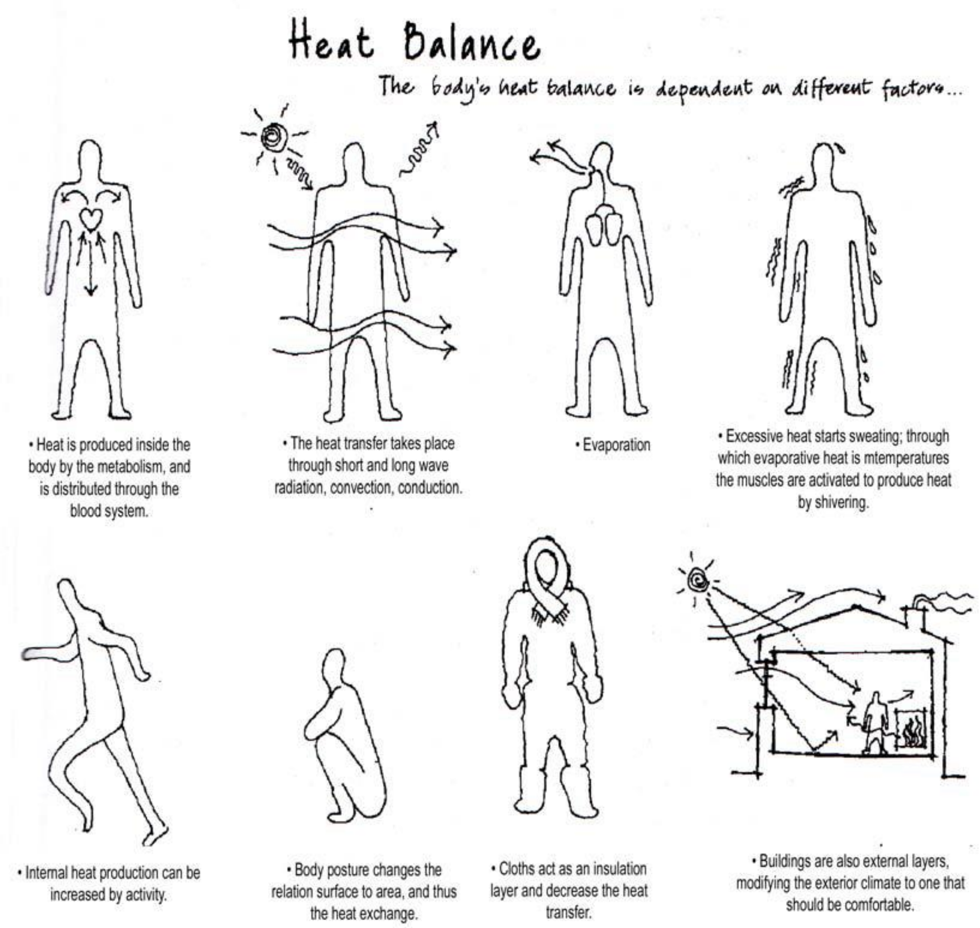

Figure 14: Human energy balance: steady –stat condition.

Source: Emmanuel, 2005:65

As long as surfaces surrounding a person are within comfortable ranges the environment may even be asymmetric about radiant temperature (i.e. More heat coming from one direction than the others). (Plumley ,1975: 153). It therefore seems clear that the alternative approach for thermal comfort in the equatorial tropics could be an effort to reduce radiant heating of the environment. (Emmanuel, 1993: 28)

2.2.2. Factors Influencing Thermal comfort in Tropical Climates.

In addition to the aesthetically pleasing environment, the human environment must provide light, air and heat. The satisfaction with the heat environment is a complicated, highly interactive variant for many interactive variables. Different Variables that heat the heat transfer process to the environment are the key to the effects of Thermal Comfort.

The author Emmanuel in 2016 highlighted from his studies that the independent environmental variables mostly affect the outdoor thermal comfort are Air Temperature, Mean radiant Temperature (Tmrt), Humidity and the wind speed.

2.2.2.1. Air Temperature

Air Temperature is a commonly measured weather parameter to identify the hot Air or the cold Air which is on the atmosphere on selected area. The author Emmanuel in 2016 was highlighted the tropical climates are considered normally they have high temperatures throughout the year and the Day time temperature variations are usually less than 10 ^{0}C as shown in the Figure 15.

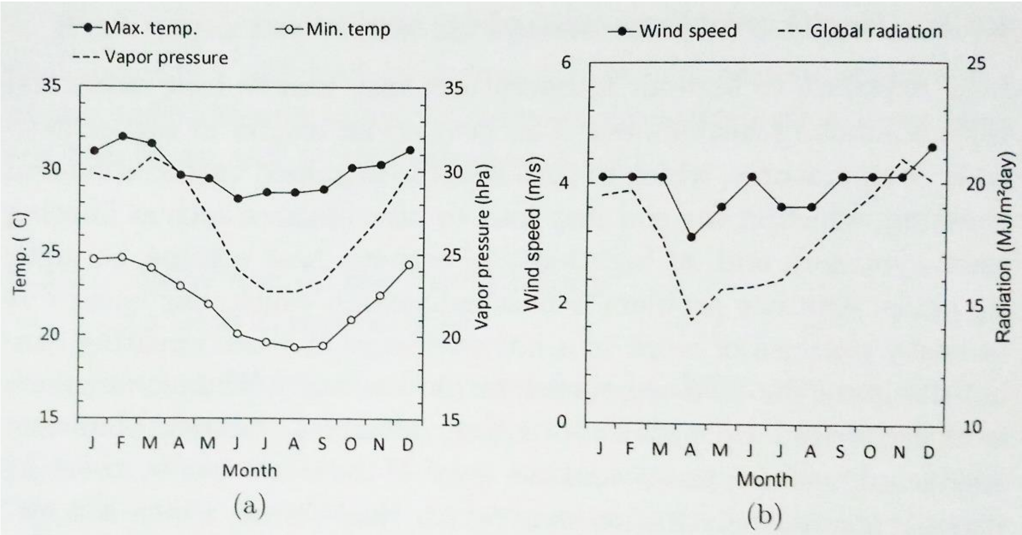

Figure 15: The climatic date of Dar es Salaam, Tanzania. (a) Mean maximum and minimum air temperature and vapor pressure, (b) mean daily wind speed and mean daily global solar radiation.

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016,p168

2.2.2.2. Mean Radiant Temperature (Tmrt)

The Mean Radiant Temperature is an essential parameter which affects for the both indoor and outdoor thermal comforts.

Generally, solar radiation is very strong in tropical countries. Owing to the large amount of clouds in the sky will help to diffuse the solar radiation. However, the high amount of clouds cover with the clear sky can be seen during the rainy days also.

The author Emmanuel in 2016 also highlighted that the solar radiation and he stated that direction of the different radiation beams was depends on the position of the sun, diffuse radiation comes from dome from the sky. The Figure 16 shows the solar radiation in Dar es Salaam, Tanzania as a result of the research done by the Emmanuel in 2016.

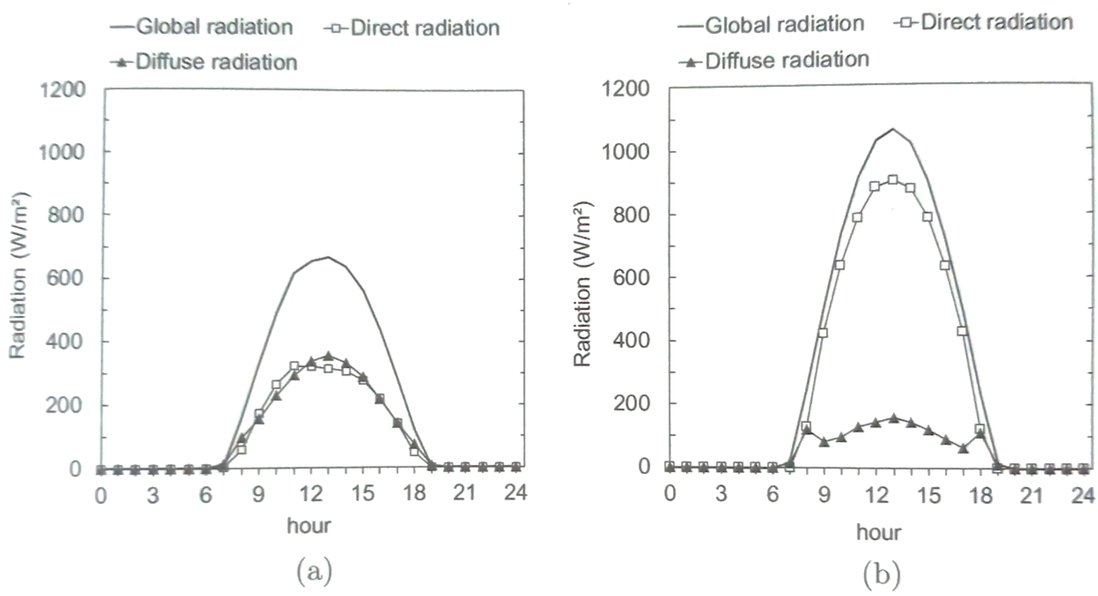

Figure 16 : Impact of Solar Radiation in Dar es Salaam, Tanzania. (a) Yearly average, (b) a clear day

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016,p169

As per the Figure 16 (a) , a person is exposed to the high levels of radiation in an urban area from the waves occurred from sun (short –wave radiation) and waves occurred from the heated surfaces (Long-wave radiation).

Different surfaces consist with different radiant temperatures. For example, walls, a street, a window has their different radiant temperatures.

As per the Figure 16 (b) observed that the Mean Radiant Temperature is lower than the body surface temperature. For an Example in the outdoors open areas at night, leads to a net heat loss and at the day time it leads to the heat gain. (Emmanuel R. , 2016, p. 169).

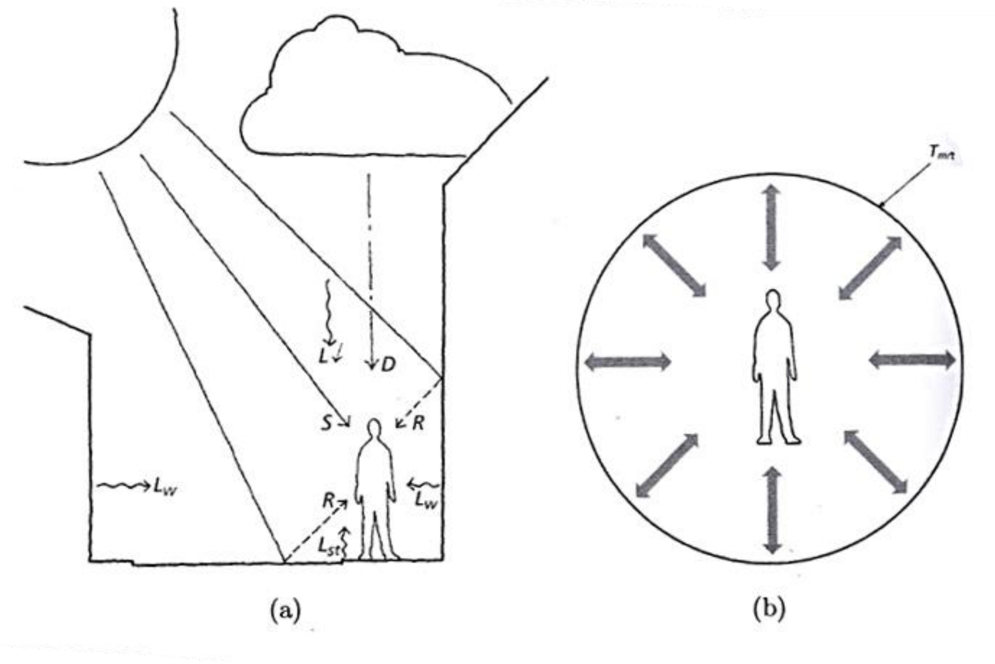

Figure 17: : (a) Directly exposed a person in a street canyon (S), diffuse (D) and reflected (R) short- wave radiation as well as long-wave radiation from the sky (L), (b) Concept of the Mean Radiant Temperature

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016, p170

The author Emmanuel in 2016 stated that the degree of the Mean Radiant temperature is toughly connected to the exposure to solar radiation. Mean radiant Temperature almost twice as compared to the overcast conditions at the clear sky conditions. The Figure 18, indicated the Mean Radiant Temperature may vary with the changes of weather conditions.

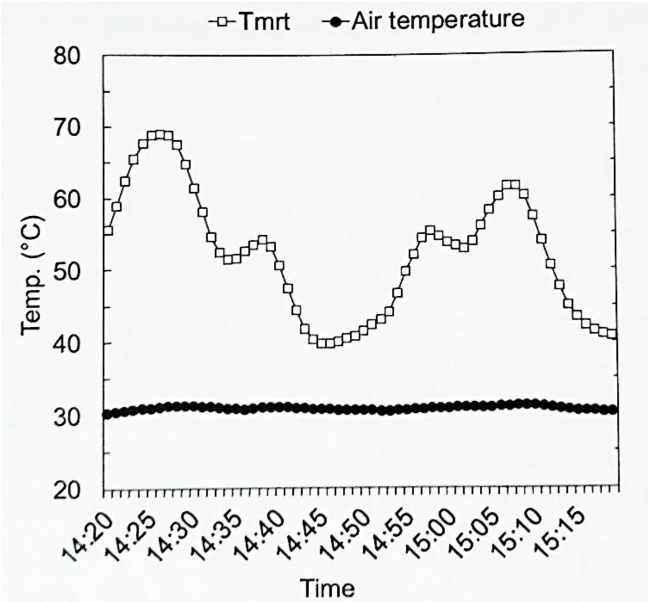

Figure 18: Variation of Mean Radiant Temperature against to the cloud cover at Ecuador as per the measurement taken on the date of 31st March 2010.

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016, p171

2.2.2.3. Humidity

As per the Emmanuel and Johansson stated in 2006, the Warm- humid climates are characterized by both normally in high levels of air temperature and high levels of relative humidity and this results in high values of absolute humidity, specific humidity and vapor pressure.

Further, they highlighted that the variation of vapor pressure in day time at the urban areas to be fairly steady and there is normally the vapor pressure reduce the Night time and its increase in the late morning.

As per the indicated in ASHRAE in 2001 was stated the mixture of the high temperature and the humidity is experienced as discomfort due to the restriction of cooling of the body through the evaporation. Further it was indicated that the higher humidity level assist to skin wittedness, which help to increase the uncomfortable owing to the feeling of moisture and also help to increase the friction in between the skin and the clothes worn.

The author Givoni in 1998 was suggested and the author Emmanuel in 2016 was highlighted that as the upper vapor pressure comfort limit is 27hPa which is for people adapted to warm –humid conditions.

2.2.2.4. Wind Speed

The wind speed has optimistic effect on thermal comfort in warm climates since it increases the convective heat loss. The author Emmanuel in 2016 was highlighted that tropical areas are regularly characterized by low wind speeds. They are affected by the intertropical convergence zone (ITCZ). This zone, also called as the doldrums, which is where the trade winds come together, moves around the equator depending on the season. As the author sated the outside the ITCZ, trade winds, monsoon winds and tropical cyclones may occurs. Urban areas are especially problematic since wind speeds may be only 25-50% of the wind speed in the surrounding rural areas.

Further there are Several formulas to calculate the cooling effect of wind speed have been developed. The Figure 19 shows the effect depends on the humidity of the air; the higher the relative humidity and the lower the cooling effect.

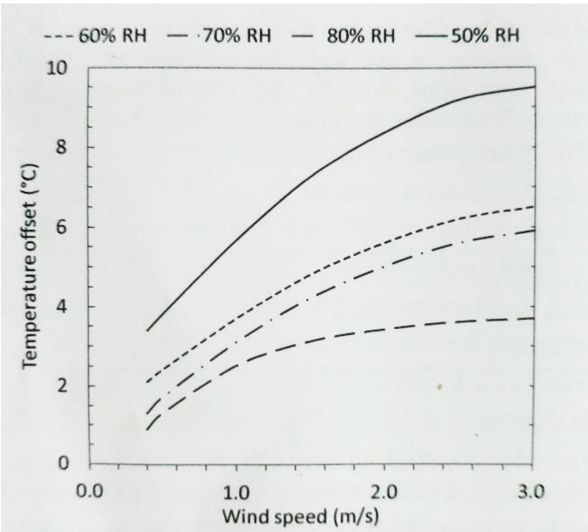

Figure 19: The different levels of relative humidity due to the cooling effect of the wind.

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016,p172

Furthermore, the relative effect is higher at low wind speeds; for wind speeds above about 3m/s the additional cooling effect is minor. Besides, too high wind speeds may be experienced as annoying (disturbs the hair, difficult to read newspaper, etc. According to the Table 05, wind speeds above 15 m/s the wind starts to be dangerous, making people lose balance, and above 20 m/s there is a strong risk of being blown over.

Wind speed (m/s) at pedestrian level*	**Effect on humans**
0-1.1	No effect
1.2-2.5	Wind felt on face
2.6-4.0	Hair is disturbed, clothing flaps
4.1-5.9	Hair disarranged
6.0-8.0	Force of wind felt on body
8.1-10.3	Umbrellas used with difficulty, difficult to walk steadily

*i.e. the wind speed at 2m height which is assumed to be 75% of the wind speed at 10m.

Table 05: Impact of wind speed for the human body

Source: Emmanuel R., Urban Climate Challenges in the Tropics, 2016, p174

2.3 Urban Geometry and Built Form and the Microclimate

2.3.1. Definition of the Urban Geometry

Urban Geometry can define as the quantitative composition of the volume of the buildings which have different characteristics and open spaces. Their Urban configuration is the major modification factor on its urban microclimate.

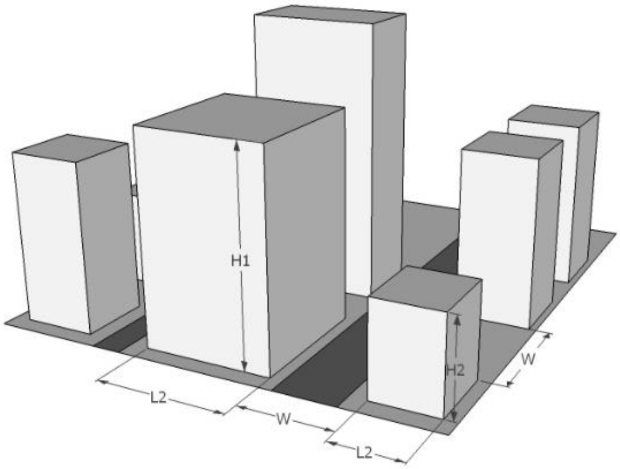

Figure 20: Urban geometry

Source: Author

2.3.2. Urban Form / Built From

Urban from is the most essential modification factor to create a comfortable urban environment. At the urban Form can be built form elements at the surroundings also.

There were very fewer studies done explored the influence of different built form elements to the outdoor thermal comfort.

The authors Olgay and Oke were completed the first studies regarding to the exploring the relationship between architects and urban designers from the climatic point of view and focused the interrelationship between buildings and other different microclimatic designs.

Further the author Taleghani in 2014 was highlighted that the author Givoni's study as impact of urban forms may be vary from under the climate conditions. A study was done by the author Steemers et *al* and proposed six type of general urban forms for the London and compared the characteristics and its behavior under the variables of solar radiation, built potential and considering the direct day light.

2.3.2.1. Definition and Classification of Urban Form/ urban built form

Urban built form is a main another factor affects to the urban microclimate for their Outdoor Thermal Comfort.

Several classifications from different authors for the urban form/ built form are as follows;

- The Institute in 2015 was made a definition for the urban form as physical characteristics of the built-up urban areas consist with different shapes, density, composition and the size. Further, it was highlighted that urban form usually develops with the social, environmental, economic and technical developments.

- Furthermore, the author Anderson et al in 1996 was classified the Urban form as different spatial pattern created from human activities at the certain time.

- The Tsai in 2004, classifies the urban form as a composition of three categories of density, diversity and spatial-structure pattern.

- Elmira in 2015 was mentioned that the urban form has two different scales as macro scale and the micro scale. The macro scale urban form explained as the overall form and the type of the city and its categorized by their size, level of compactness and the extent of the other infrastructure developments.

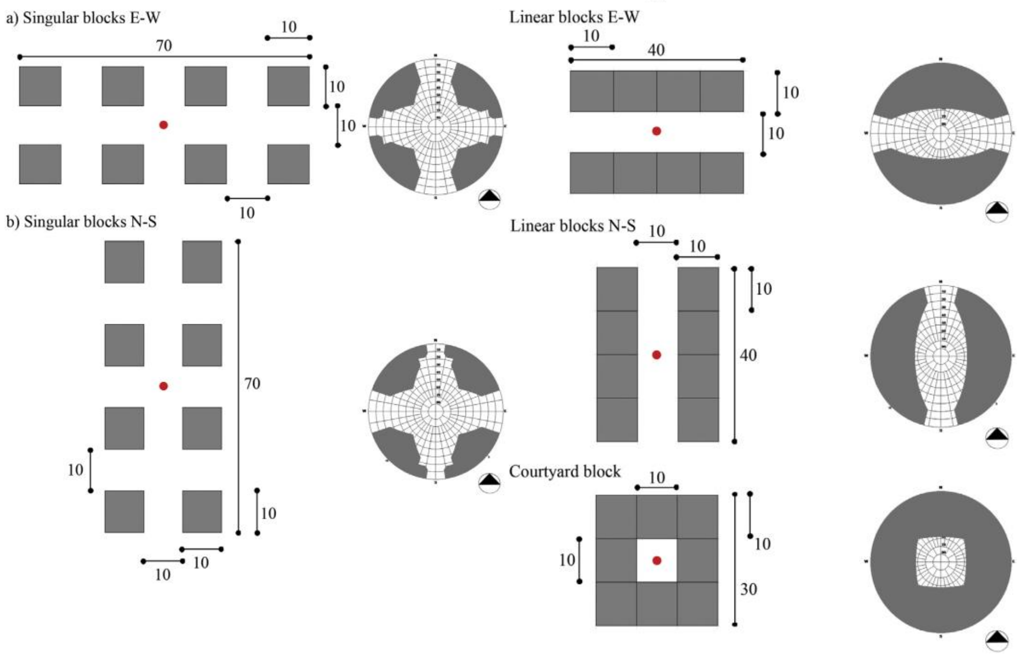

Figure 21: Different Urban Forms

Source: Mohammad Taleghani, 2014

2.3.3. Urban Canyon

Urban canyon is a part of the urban built forms and its defined as the three- dimensional built form bounded by a street and the building volumes. Generally, urban canyons are defined as Urban streets and it restrict the view of the sky dome. Depend on the Sky View Factor can categorize different urban canyons. Due to have the restricts of sky dome cause to occur different reflection of solar radiation, and generally restrict the free movement of air as shown in the Figure 22.

As the author Emmanuel stated that the aspect ratio, its height of building/width of street (H:W) ratio effect to classify the different types of urban canyons further.

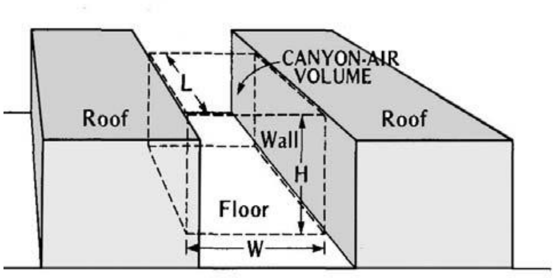

Figure 22: Urban Canyon
Source: Author

Furthermore, the author Oke in 1987 was defined the urban canyon as a components consist with walls, grounds, roads, gardens, which are spaces between two adjacent buildings as well as the that’s air volume named as the canyon air volume. That e active surfaces such as walls and grounds and three open sides with ends and tops.

2.3.3.1. Classifications of the Urban Canyon

Classifications of the Urban canyon can clearly explain by studying the street orientation, Aspect ratio (Height to width H/W ratio) and Sky view factor (determining the size of the sky dome created I between the buildings at the canyon area)

2.3.3.1.1. Aspect Ratio

Aspect ratio is the one of the key parameters in measuring the urban canyon geometry. Its defined as the ratio of the average height (H) the canyon and the width of the canyon. (W) (H/W ratio)

As the author Elmira stated in 2015, the urban canyons were classified as, 1.) If the aspect ratio is equal to 1, 2.) If the aspect ratio is below 0.5 as shallow canyons, and 3.) If the aspect ratio is equal to 2 as Deep canyons.

(a) An open flat country

(b) A built-up area with
H/W ratio of about 1

(c) A high-density urban
area with H/W ratio
of about 4

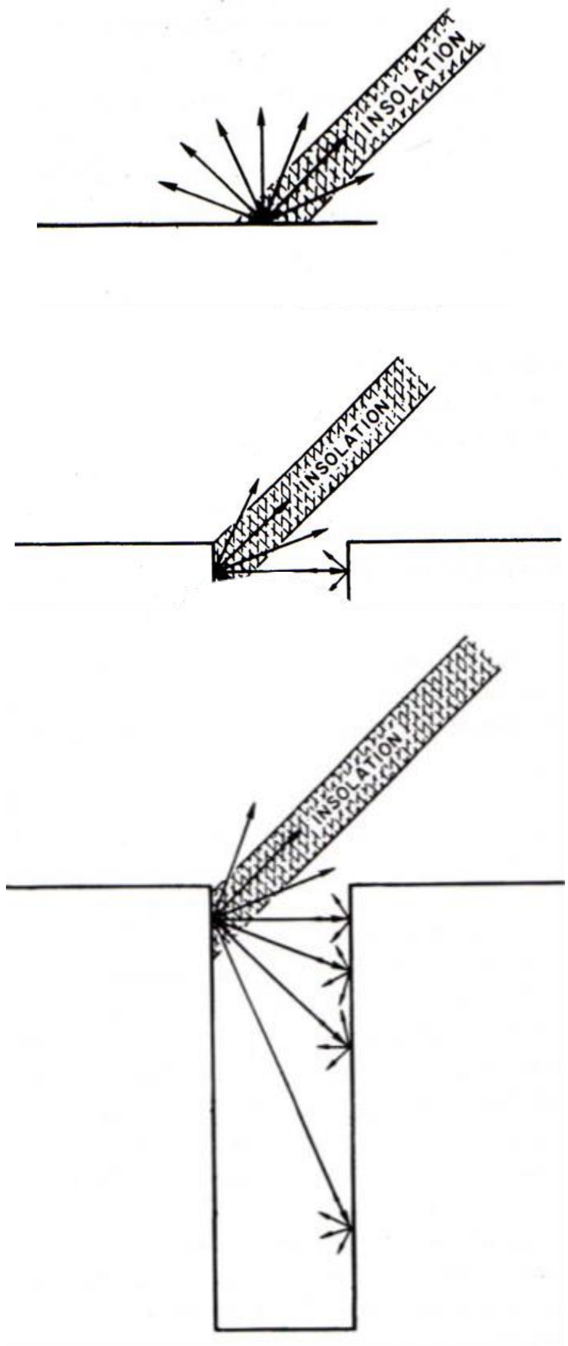

Figure 23: Radiation effect on an urban canyon reference to its aspect ratio

Source: Givoni,1998:248

2.3.1.1.2. Orientation of Streets

Solar radiation and the behavior of the air movement patterns are most important in as the key part of the climate. This directly affect to the performance of an Urban area.

As the author Elmira highlighted in 2015 from their studies as the street orientation is the most significant parameter to determine the pattern of solar access and wind speed in urban canyons and it is further important in thermal comfort levels in sidewalks.

Orientation of streets are categorized as East –West (E-W), North-South (N-S), North East – South West (NE-SW) and North West- South East (NW-SE) as shown in the Figure 23.

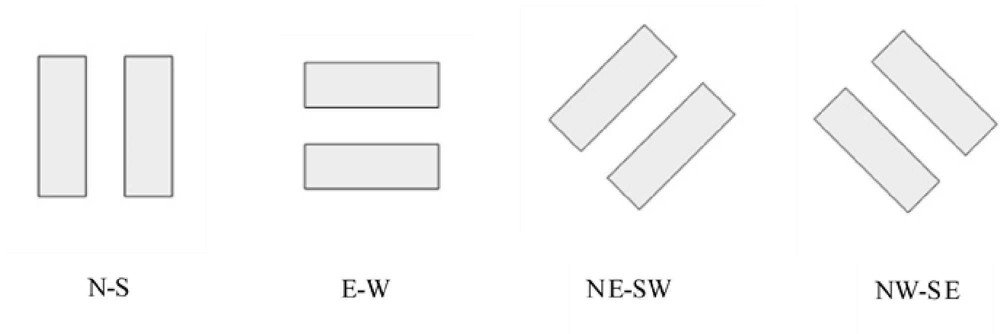

Figure 24: Orientation of Urban canyons

Source: Author

2.3.1.1.3. Sky View Factor (SVF)

Sky View factor can define as the "ratio of the amount of the sky" which visible from the given location or a point on a possible surface.
The author Elmira in 2015 clearly stated that the buildings and vegetation are considered as obstacles in an urban area which mentioned the level of the vision towards the sky.

Further the author was highlighted that the Sky View Factor is a dimension have with less number in between the "0" and the "1", and also it is a most significant parameter in creating and the controlling the Heat Island Effects in an Urban area.

The sky view factor can introduce as a typical parameter for the building compactness and the Layout. The author Watson and Johnson in 1987 and the author Akbari in 2014 was stated as SVF is the ratio of the Received or emitted radiation by a surface to the emitted radiation or the received radiation by the entire outdoor environment and also they stated as SVF affects to the urban radiation exchanges and to the urban microclimate.

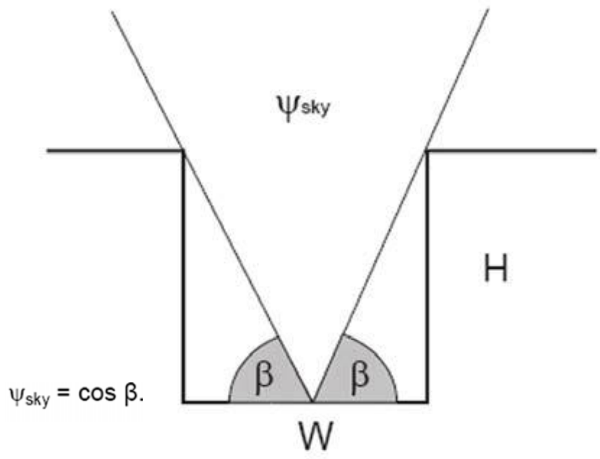

Figure 25: : The sky view factor in a symmetrical street canyon

Source: Author

The value of the Sky View Factor basically dependent of the prominent and strong buildings and its geometry. As the author Oke in 1981 stated that the Sky View Factor symbolizes the ratio at a point in a space between the visible sky and a arranged location to the analyze. The entire sky is blocked from the view from different obstacles when the SVF is equal to zero.

(a)

(b)

Figure 26:SVF-photos taken at the measurement points at (a) Matsudo Station Square (SVF 0.61) and (b) Matsudo Central Park (SVF 0.58).

Source :Thorsson, Honjo, Lindberg, Eliasson, Lim, 2004; 03

2.4 Public Life and Urban Geometry and Form

2.4.1. Public Life and Urbanization

Urbanization Generates urban life through an increase in population in an area commonly known as urbanization. Urbanization is taking place around large cities with good infrastructure such as transport, electricity and water. Definition of urban life is actually difficult and complex. Basically, it is defined as a distinct life style that lives in a very dense environment.

2.4.2. Public Life and Street Urban Canyon

With rapid urban development, “Streets” converted in to urban canyons including with different varieties of canyons.

The author Bright in 2013, highlighted that street canyons in urban areas, formed by parallel rows of buildings enclosing a vehicular road and represent a unique atmospheric environment.

The "urban streets" creates a sense of the minds of those who have met the basic needs of the people, and can, with other factors, accessibility, bring together people, the general public, living, security, comfort, participation and accountability. When users who fit this need are a factor that has created a nice picture in the users, they evaluate with optimal quality and the previous criteria are essential parts, perhaps rarely exceptions.
“Urbaneness and urbanization are matter of immediate personal experience. For another, a town is not the result of a design program; it is the reflection of a way of life. If someday someone wants to opt for a more dignified city life, the street will be first on list to come in for rehabilitation.” (Street for People, 1964: p21)

Figure 27: Life in Urban street canyon

Source: Author

In the book “Street for People” , the author Rudofsky was highlighted that at all times and long before people’s actions and emotions were showed against pavement on the stage. Therefor street can be introduce as the great world theater. Different kinds of

Drama and comedy presenting as unplanned events and it assets to increase the quality of the daily life.

Further, streets will use to have funeral and wedding festivals as shown in the Figure 28 and Figure 29.

Figure 28: Street as a place of festivity

Figure 29: Street as a place for community activities

Figure 30: Street as a recreational area

2.4.3. Public Life and Open Spaces.

Now the significance of the open space is bound up with the surrounding society and their economic life.

Novel public spaces and meeting places are now being converting to the towns and cities which is significant of social interaction for urban residents. Success of public spaces depends on the well designing doing by the urban designer or the city planners as stated Harun in 2014. The public places should consist with people adapting, using and the managing the place. Further he stated that “people make places, as much as places make people”.

The authors Jellicoe in 1975, Ward Thompson in 1998; Antrop in 2005 and Scazzosi in 2007 were stated as in landscape architecture and urban planning, understanding of the involvement of open spaces in the urban area and the association between people and this environment have been developed as early as 1900s .

Figure 31: Urban Open spaces act as Public Plaza . (Public Plaza infront of the Pettah Railway Station in Sri Lanka.
Source: Author

Urban Plaza, emphasizes the magnetic life and conservation of the open space in a city is essential in reaching to the social sustainability and quality of urban life. Urban plazas mainly use by people for their day to day activities such as to meet people, for advertising, for selling goods, and for entertainment etc.

Moreover, urban open spaces use for surface parking which providing parking facilities for people who go for work , shopping activities and to meet people etc.

a.) Car park at China Town in Pettah.

b.) Charmer’s car Park in Pettah

Figure 32: Urban Open spaces use for surface parking.

Source: Author

CHAPTER THREE: RESEARCH DESIGN

3.1. Selection of the Case study.

The sample for the study selected by purposely with following specified criteria's in a same microclimatic condition within a highly pedestrianize urban area.

1.) An Urban Plaza
2.) East-west canyon (Wider and Narrower)
3.) North-south canyon
4.) Parking Precinct

3.2. Site Selection

Pettah which is a highly pedestrianize urban area in the main commercial hub in Colombo city was purposely selected as the case study in order to measure the weather parameters over selected different urban forms.

When considering Colombo, it is the largest city in Sri Lanka inhibits a warm humid climate with no significant seasonal differences in temperature or moistness and the year around rainfall. According to the collected information by JICA report in 2014, it was highlighted that the land uses of Colombo city is predominantly residential (i.e, 42% of the land use within the city limits is residential) with 3.5 % of commercial and other business uses are occupying 4.5%.

When analyzing the Census data and Statistics data in 2012, it was highlighted that the City of Colombo is fast changing in terms of land use patterns, building morphology and population density. Further, it has indicated that the population growth rate in Sri Lanka has drastically dropped over last decades from 2.8% per annum in 1950s to 0.7% per annum in 2010. Moreover, population density of Colombo city has increased by 32% during the same period. Therefore, considering all above information, the City of Colombo is mainly highlighted as the Most Urbanized area in the Sri Lanka.

Accordingly, Pettah which is the most magnetic urbanized commercial hub situated in Colombo city was purposely selected as the case study area for the research.

3.2.1 Pedestrian Movements and Patterns

For the site selection it was mainly considered the pedestrian Movements and patterns at the Pettah area.

Pedestrian movement pattern of the Pettah is very high due to attraction of more people to the grid roads for shopping and many other activities. Pettah is act as the main transport terminal node (railway station and central bus stand) of the Colombo and it attracts more commuters to the area. The highest attraction of pedestrian movements can be identified in centers and gradually it decreases towards neighborhoods, suburbs and business parks or industrial areas.

Figure 33:Pedestrian Movement and Pattern at Pettah.

Considering the above pattern of the pedestrian movement, Pettah in Colombo was selected as the case study area.

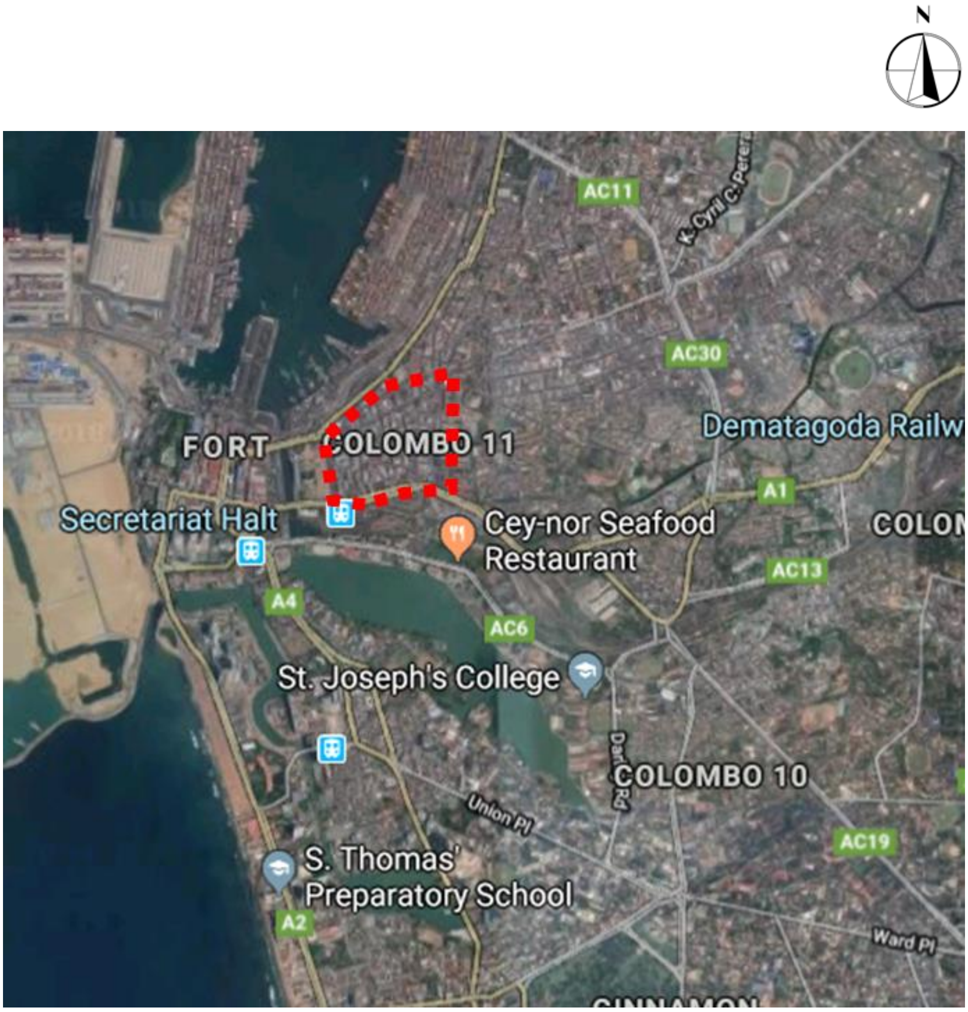

Figure 34: Highly pedestrianized Urban Area as the selection of the case study

Within the selected urban area, five different built form elements in the same microclimatic conditions were selected to measure weather condition and to carry out the simulation study on thermal comfort levels of pedestrians.

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3.3 Selection of different Built Form at the Study Area

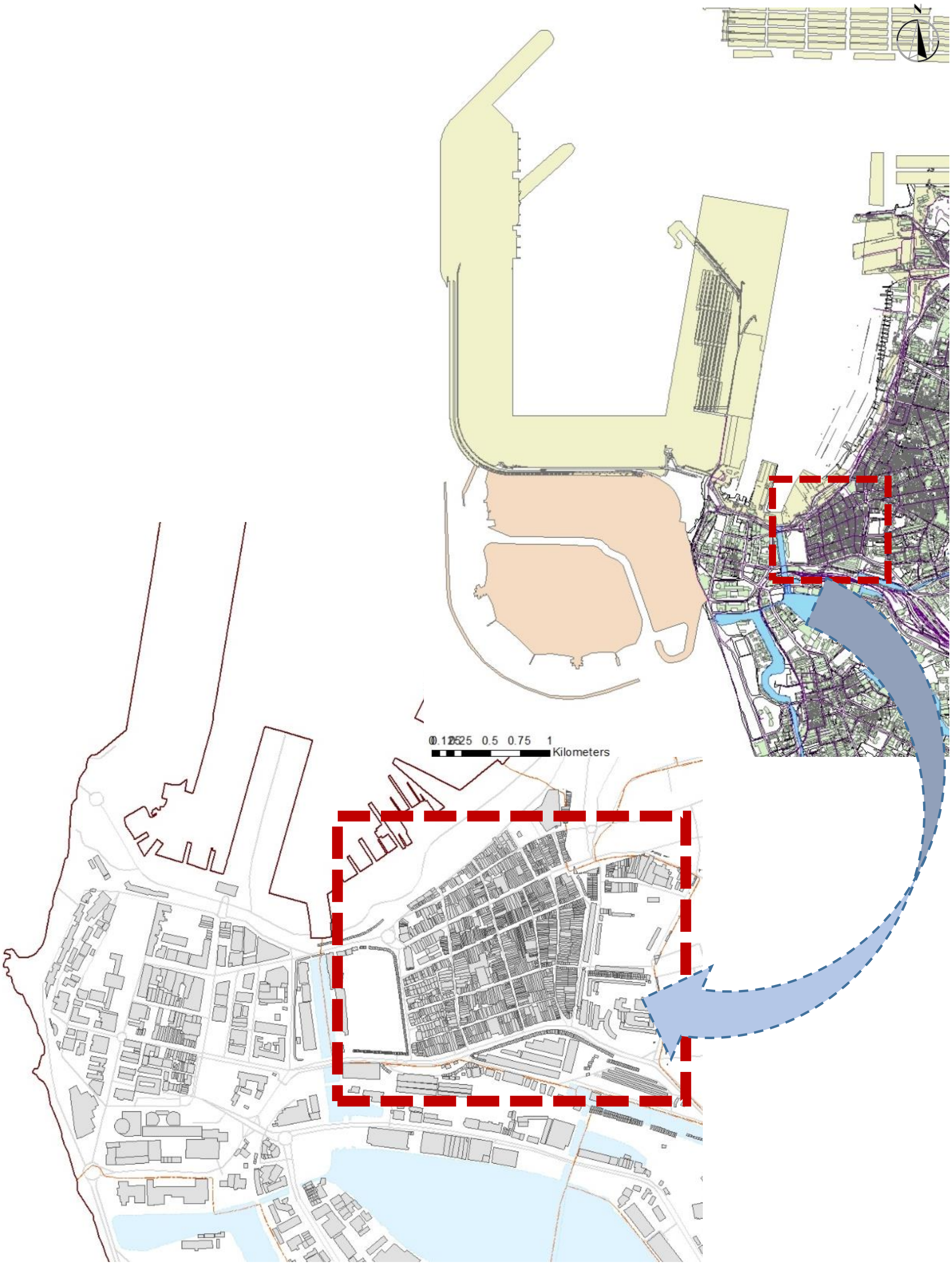


Figure 35: Location Map

Source: Author

3.3.1 Selected Different Built Form Elements

Following different built form elements in Pettah were purposely selected to carry out the field survey which were situated in the same microclimatic conditions.

1. Urban plaza
2. East –west canyon (Narrow) – (A) Prince street
3. North -east canyon – 02nd Cross street
4. East –west canyon (Wider) – (B) Main street
5. Parking precinct - Gunasinghapura bus stand

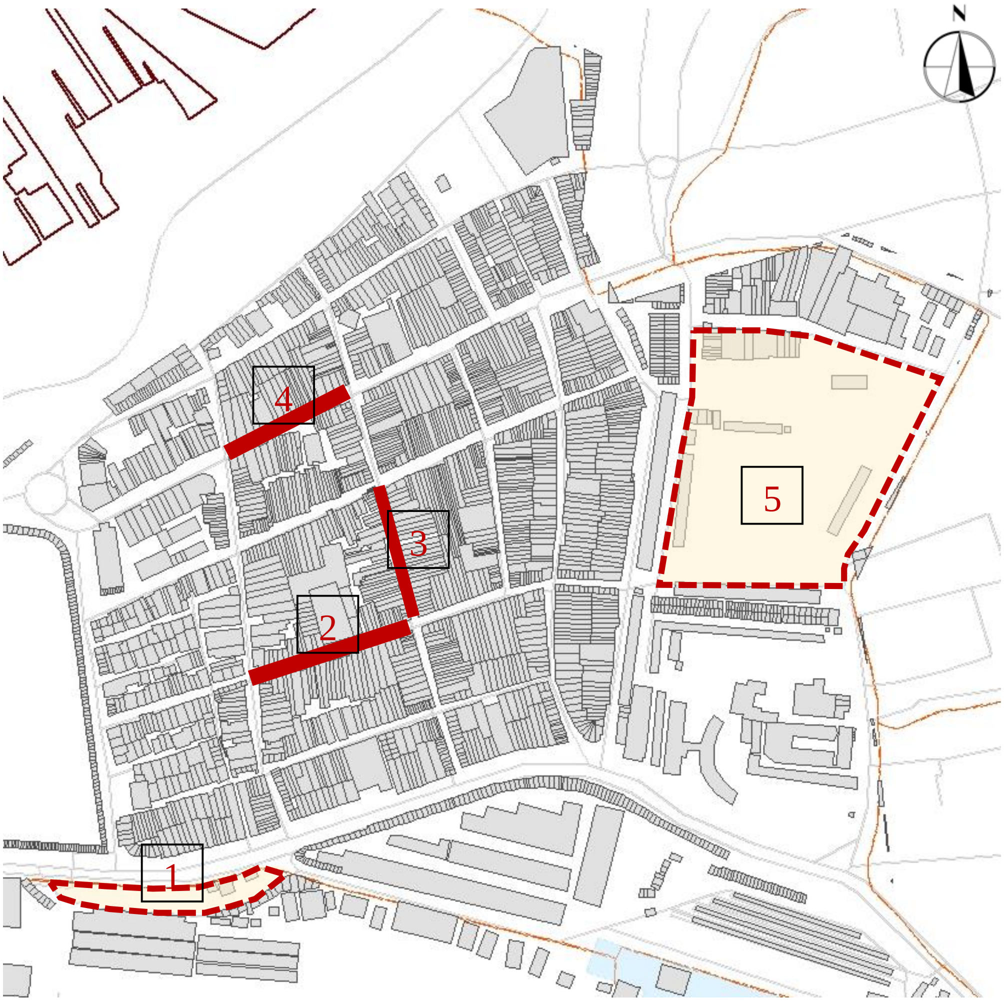


Figure 36: Location Map with Different Built Form Elements

Source: Author

3.3.1.1 An Urban Plaza

The “station plaza” in front of the Pettah railway station was purposely selected as an the Urban plaza for the case study considering many social activities which are happening there as in Figure 37.

Figure 37: An urban Plaza – Station Plaza

Source: Author

3.3.1.2. East –West Canyon

Considering the highly pedestrian movement, Orientation, geometry and built form the Prince street and the Main Street was purposely selected as the East –West Canyons in Pettah which is in the same microclimatic conditions. In here there were selected two canyons with having different width of the roads and different building heights to compare the geometrical impacts.

Figure 38: East –West Canyon – a.) Prince Street

Source: Author

Figure 39: East –West Canyon – b.) Main Street

Source: Author

3.3.1.3. North - East Canyon

Considering the highly pedestrian movement, Orientation, geometry and built form the 02nd cross street was purposely selected as the North -East Canyon in Pettah which is in the same microclimatic conditions. These streets are highly commercialized with heavy pedestrian traffic. Yet for the easy of the study streets were selected without trees and with few traffic disturbances, while having appropriate building density.

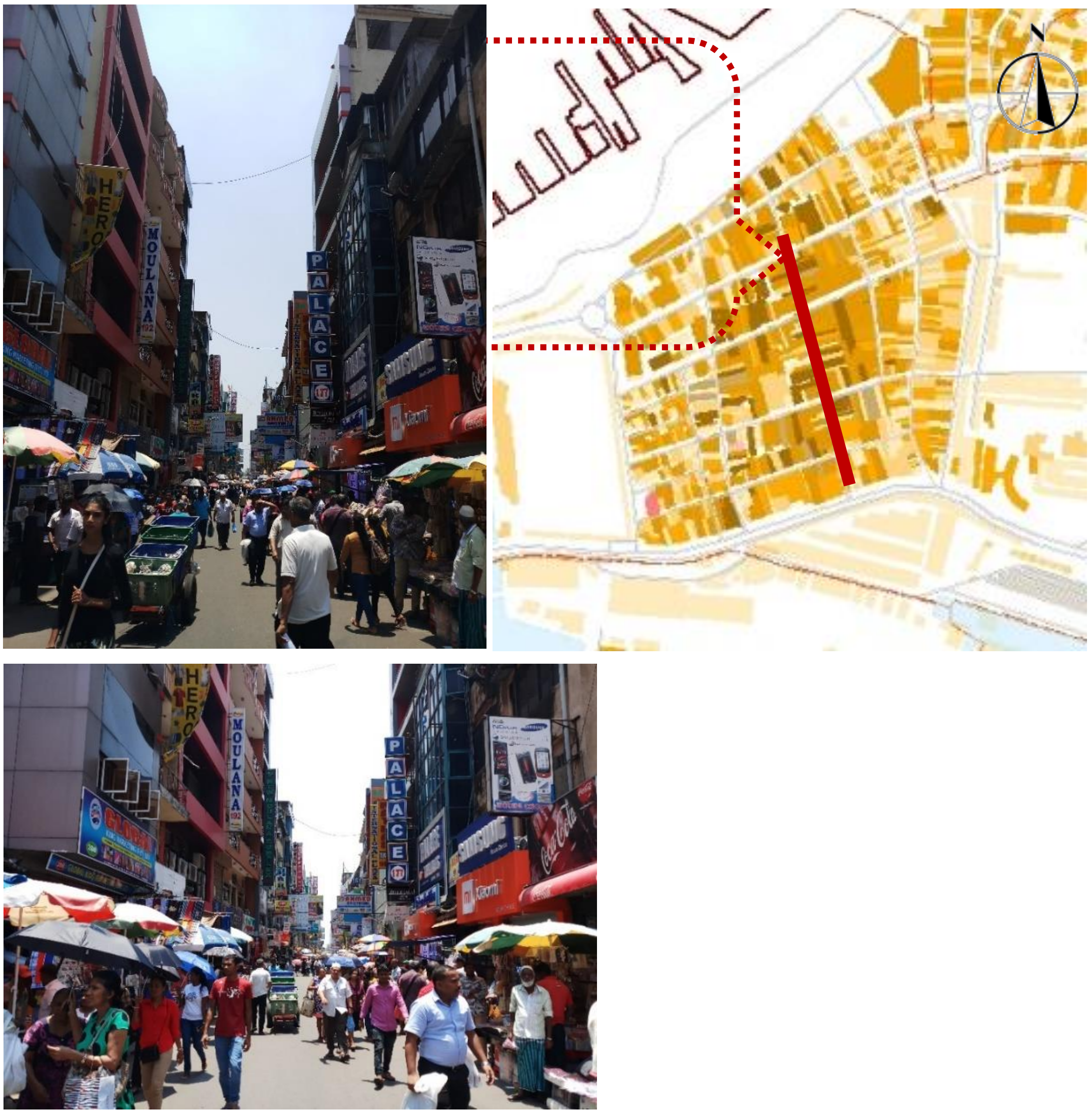


Figure 40: North –East Canyon – 02nd Cross Street

Source: Author

3.3.1.4. Parking Precinct

The Gunasighapura bus stand was selected for the study purposely as the surface parking which located in the same microclimatic conditions and also having a different built form.

Figure 41: Parking Precinct- Gunasinghapura Bus Stand

Source: Author

3.4. Obtaining weather data required for estimating thermal comfort levels at the five-selected locations.

Historical climatic data on (Air Temperature, Rainfall, Humidity and Wind pattern was) collection from Meteorological Department, Sri Lanka as the first step of the method of study. The data was utilized to identify the climate condition of the case study area and the durations of the highest and the lowest status of each parameter. Accordingly, End- March was selected as the best period of the year to obtain weather readings to explore and simulate thermal comfort levels.

Field measurements of weather conditions were obtained for evaluating the existing thermal comfort levels for the selected five locations on a same day. The survey was conducted on the 27th March 2019 from 11.00 a.m. to 1.00 p.m. (i.e., the first session) and from 4.00 p.m. to 6.00 p.m. (i.e the second session). These two time periods were selected considering the most congested time period from the pedestrians movements.

The following equipment needs to carry out the field survey to measure physical variables.

	Equipment	Description
01	Hobo Meter (With a shield and a movable stand) 	HOBO 1 and HOBO 3 data loggers for take reference point. HOBO 2 and HOBO 4 data loggers for take on site measurements. Made in MA **Measurement range:** **Air Temperature: -20-70C (-4-158F)** **Air Temperature and Humidity can measure from it.**

	Equipment	Description
02	Wind Anemometer 	Wind Anemo meter Data is recorded automatically. Air movement is measured by its velocity (v, in m/s) **Measurement range:** **Air Velocity**
03	Digital Thermometer 	Data is represented in digital display. Easy to handle and transport. This is using to get RH% and Temperature. This can use to measure the surface Temperature. **Measurement range:** **Temperature and Relative Humidity**

Figure 42: : Equipment utilized to measure weather parameters

Source: Author

All Air temperature measurements was taken on the 1.2m level from the selected streets and on selected locations by using HOBO meter. Measured air temperature on a reference point also for the accuracy of THI values.

The data measuring sheet prepared for the Field Survey; contains the following information: Air Temperature, Relative Humidity, Surface Temperature, Wind Speed and the Wind Direction.

Data measuring sheet prepared for each selected Locations for the Field Survey for session 01 (11.00 a.m. to 13.00 p.m.) and session 02 (16.00 p.m. to 18.00 p.m.) is as follows;

Data Sheet No: 01

TIME : 11 a.m. to 13.00 p.m.

LOCATION 01 : RAILWAY PLAZA

STARTING TIME :
ENDING TIME :
WIND SPEED :
WIND DIRECTION :
SURFACE TEMPERATURE :
DATA FROM THERMOMETER :
BUILDING HEIGHTS :
SURFACE MATERIALS :
PHOTOS :
REMARKS :

Charmer's Grannery Car Park was selected as the reference point in measuring weather parameters.

Selected of Locations and the reference points are depicted in the map as follows;

1.) Location 01 - An Urban Plaza, 2.) Location 02 - East-west canyon – Prince Street, 3.) Location 03 - East - West Urban Canyon – Main Street , 4.) Location 04- North – South Urban Canyon – 0nd Cross Street 5.) Location 05 - Parking Precinct.

R - Reference Point

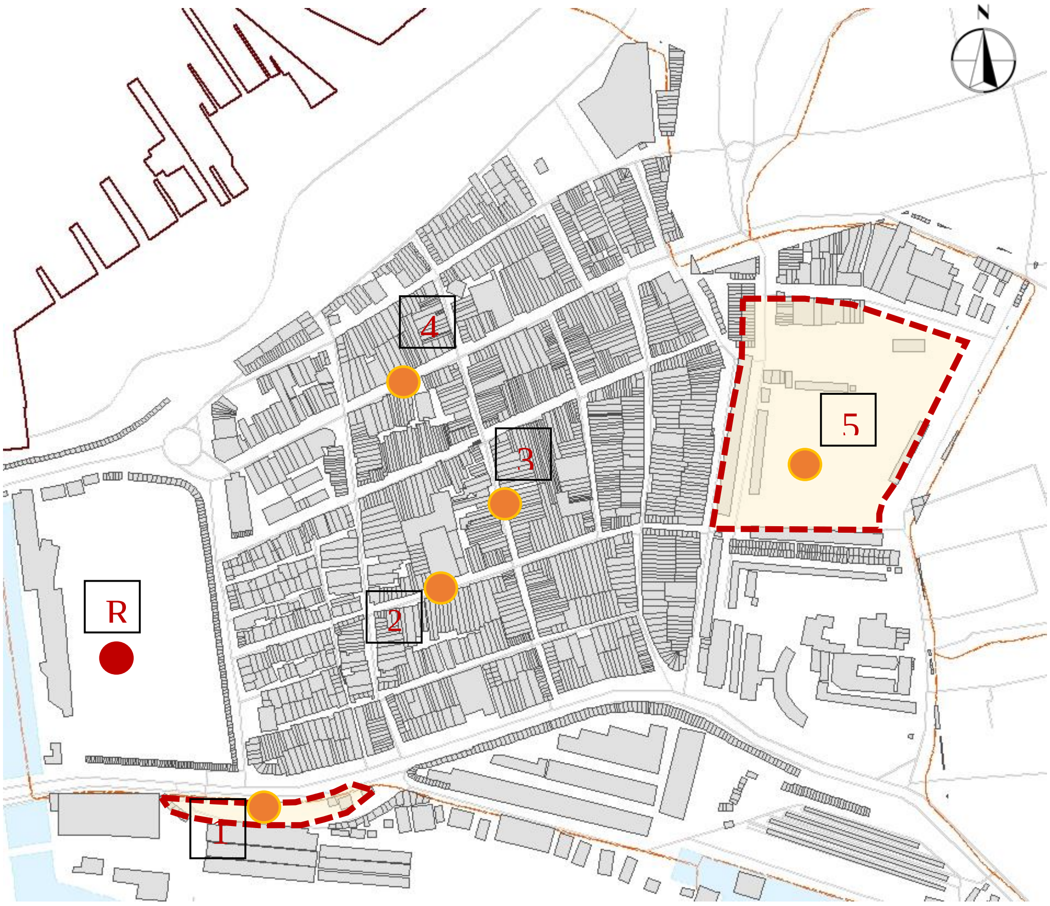


Figure 43: Location Map for Field survey

Source: Author

3.5. Simulating the micro-climatic condition of the five- selected sites.

3.5.1. Selection of the simulation tool.

Urban microclimate models vary widely, based on their physical basis and spatial/ temporal resolution. AliToudert and Mayer (2006) provide a detailed critique of the most popular models at the microscale with fine temporal resolutions. They inferred that ENVI-met (Bruse, 1990) is the most suitable model for analyzing the thermal comfort regime within the different built forms. It is a three-dimensional non-hydrostatic model for the simulation of surface-plant-air interactions, especially within the urban canopy layer. It is designed for micro scale with a typical time frame of 24 - 48h with a time step of 10s at maximum. This resolution allows the investigation of small – scale interactions between individual buildings, surfaces and plants (Bruse,2004). (R. Emmanuel, 2007)

Therefore, selected the ENVI –met 4.1 as the numerical model to analyze the impact of different urban forms of this study.

3.5.2. Executing Numerical Modeling utilizing the ENVI- met 4.1 software.

To carry out the numerical modeling Using ENVI –met software it is essential to have following data as its input data.

Input data required to initiate ENVI-met simulations are as follows;

<u>For ENVI –met Modelling;</u>

• Main model area	= 100x100x100
• No.of Nesting grids	= 05
• Size of grid cell in meter	= 05
• Type of Soil: Soil A	=Default unseald soil
Soil B	= Default unseald soil
• Latitude	=79.51
• Longitude	=6.56
• Time Zone	= CET/UTC+5.30
• Reference Longitude	=7.8131

To Run the Simulation;

• Start Date	= 26.03.2019
• Start Time	= 23h:00m:00s
• Total Simulation Time (h)	= 30
• Wind Speed measured in 10m height (m/s)	= 3.94
• Wind direction (deg)	= 240
• Roughness length at measurement site	= 0.1
• Initial temperature at model top (2500m,g/kg)	= 305.15K
• Specific humidity at 2500m (g/kg)	= 6.06
• Relative humidity in 2m (%)	= 71
• Output interval for files	
- Receptors and Buildings (min)	= 30
- All other files (min)	= 30

Source: Meteorological Department of Colombo.

All scenarios were modeled by using ENVI –met 4.1. Samples of modeled scenarios done for the Existing scenario shown on Figure 44, Figure 45, Figure 46 and Figure 47.

3.5.3. Envisaging the scenarios for simulation.

Following six scenarios were proposed for the ENVI- met 4.1 simulation.

Scenario 01: Existing Situation.

Scenario 02: Changing Building Heights.

Scenario 03: Alternative Green.

Scenario 04: Create an Open Space.

Scenario 05: Create Wind Corridors.

Scenario 06: Changing existing Surface Materials.

For each of the above mentioned scenarios, there have alternatively detailed cases as follows;

Scenario 01: Existing Situation

Base Case

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Scenario 02: Changing Building Heights.

Case 01 – Low Rise (with 03 storied Buildings)

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03 -NS Canyon – 02nd Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Case 02 – Intermediate Rise. (with 08 storied Buildings)

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02^{nd} Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Case 03 – Medium Rise. (with 12 storied Buildings)

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02^{nd} Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Case 04 – High Rise (with 14 storied Buildings)

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location
03-NS Canyon – 02^{nd} Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Scenario 03: Alternative Green.

Case 05 – Green

a.) Increasing the existing Tree canopy width two times.
   - i.) L1-Location 01-An Urban Plaza
   - ii.) L5- Location 05 – A Parking Precinct

b.) Adding More Trees and More green cover for the existing open spaces. (infill with Green) i.) L1-Location 01-An Urban Plaza

ii.) L5- Location 05 – A Parking Precinct

c.) Adding a Tree Line along the Main Street. (Location 04- EW Canyon Main Street)

<u>Scenario 04</u>: Create an Open Space.

Case 06 – Create Open Spaces/ Open Plaza (Location 02 and Location 03)

<u>Scenario 05</u>: Create Wind Corridors.

Case 07 – Create Wind corridors.

a.) by create an opening at existing harbor wall along the 02nd Cross Street.

b.) By completely removing the existing harbor wall and other obstructions along the 02nd Cross Street.

<u>Scenario 06</u>: Changing existing Surface Materials.

Case 08 – Changing existing Surface Materials on each location.

a.) L1-Location 01-An Urban Plaza

b.) L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street

c.) L4 – Location 04 – EW Canyon Main Street

d.) L5- Location 05 – A Parking Precinct

Modelling Existing Scenario – Base Case by Using the ENVI –met 4.1

a.) L1-Location 01-An Urban Plaza

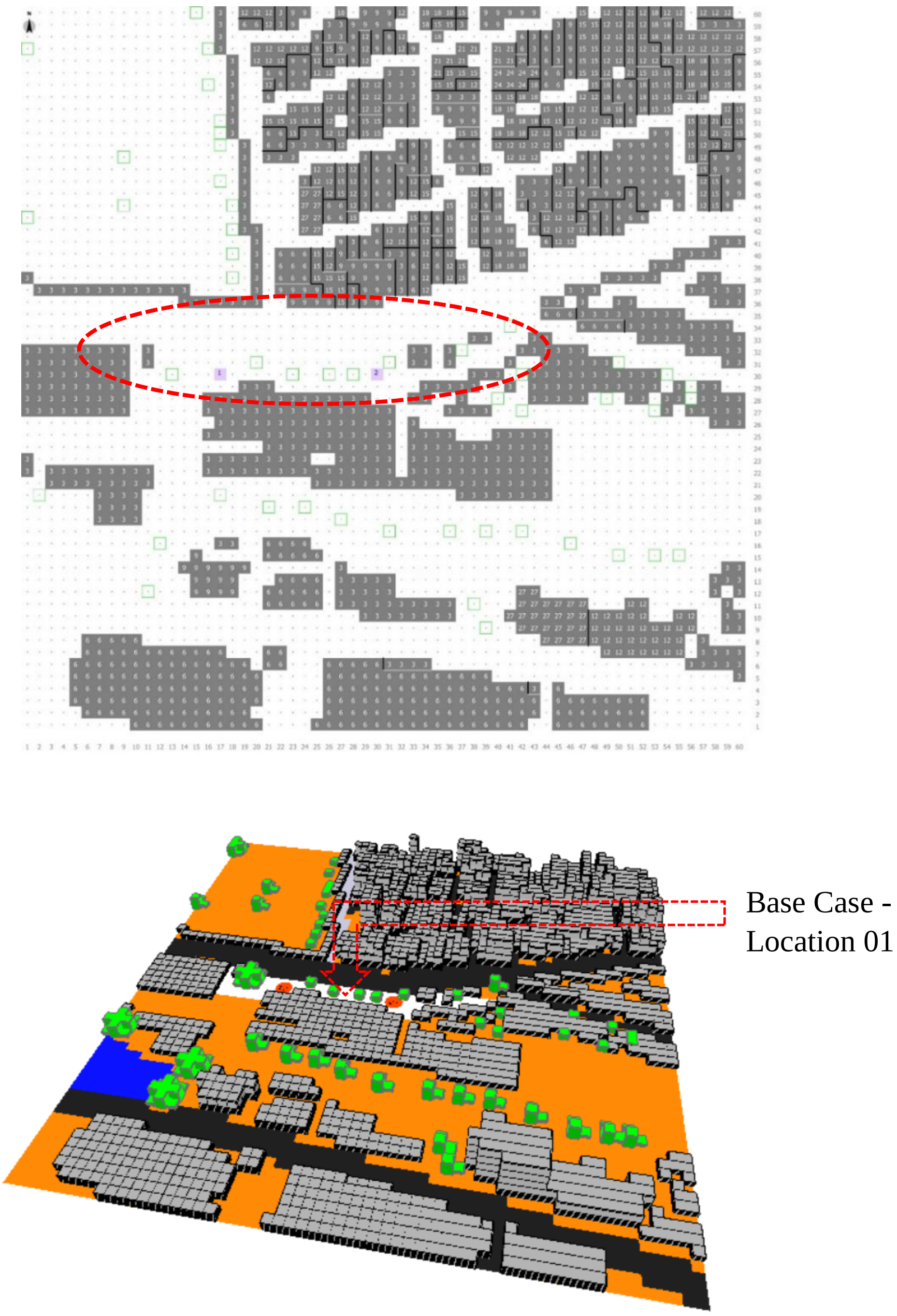


Figure 44: Modelling of Base Case Location 01 – An Urban Plaza

Source: Author

b.) L2 and L3 – Location 02- EW Urban Canyon –Prince Street and Location 03-NS Urban Canyon – 02nd Cross Street

Figure 45: Modelling of Base Case Location 02 & Location 03

Source: Author

c.) L4 – Location 04 – EW Canyon Main Street

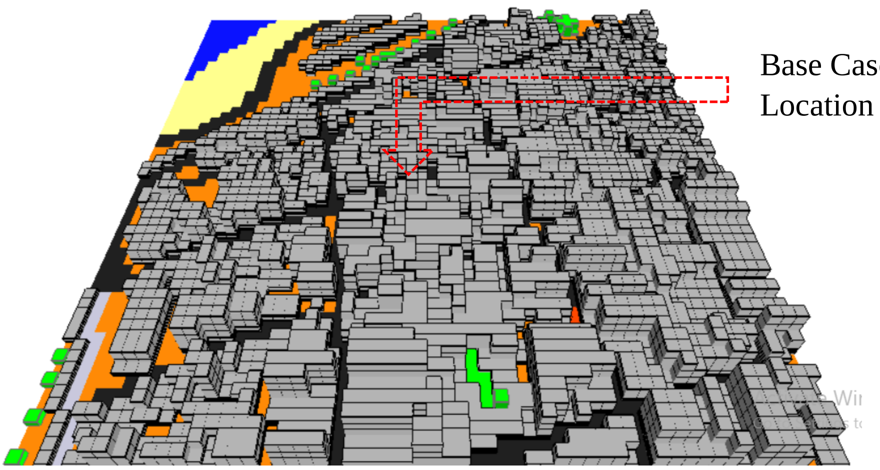


Figure 46: Modelling of Base Case Location 04 – EW Urban Canyon – Main Street

Source: Author

d.) L5- Location 05 – A Parking Precinct

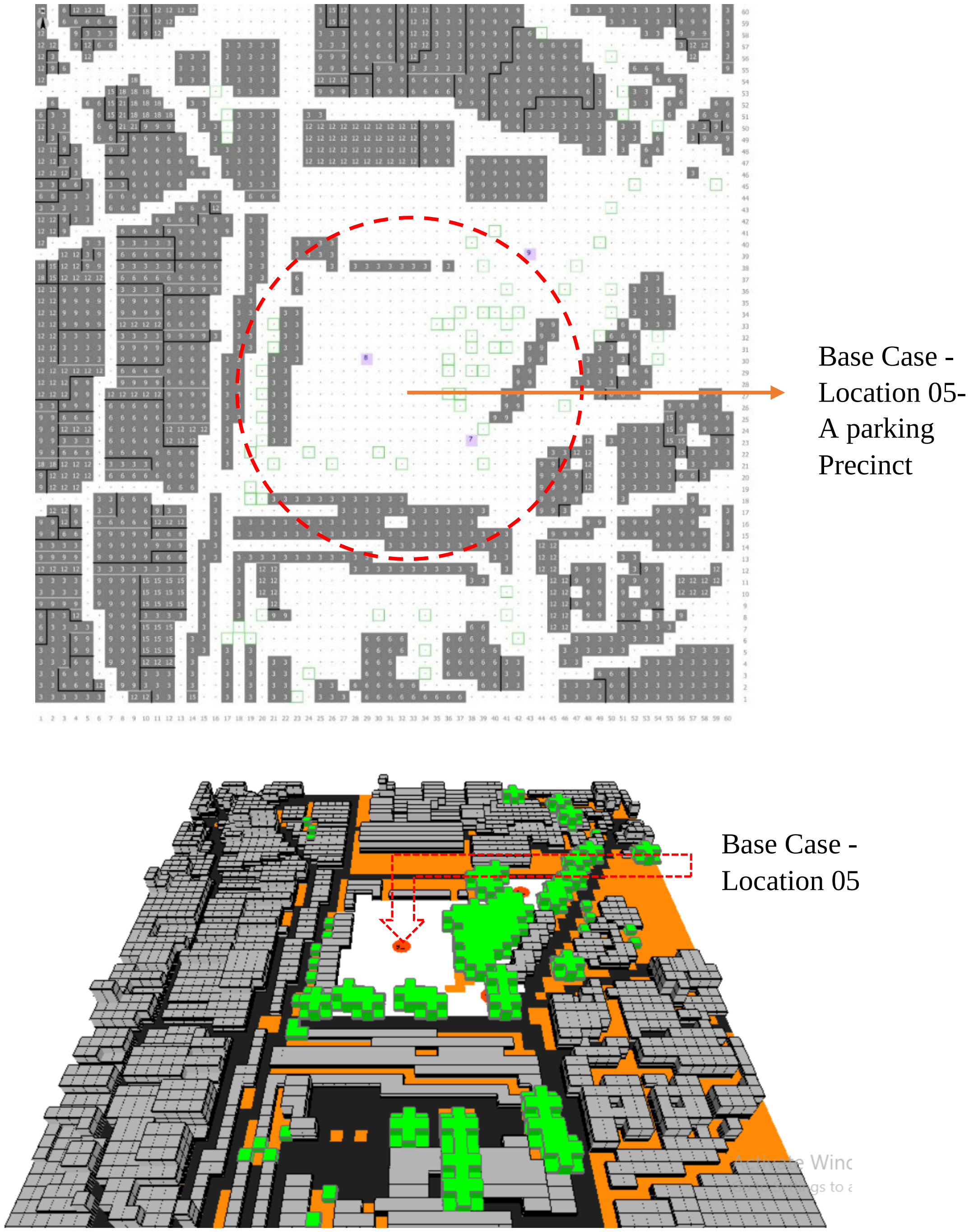


Figure 47: Modelling of Base Case Location 05 – A Parking Precinct

Source: Author

3.5.4. Measured and Simulated Data Analyzing to computer thermal comfort level of users.

3.5.4.1. Computing Thermal Heat Index

Air temperature, Relative Humidity and Surface Temperature values were utilized to compute the Thermal Heat Index (THI) value and then, discussed the Difference of THI values (THI Variations) .

Thermal Heat Index (THI) values and Thermal Heat Index (THI) variations were calculated using following formula;

Thermal Heat Index (THI)

To evaluate the thermal comfort level in each point it is important to calculate "Thermal Heat Index" (THI) in each point by using the formula,

$$\mathbf{THI} = 0.8t + \frac{RH \times t}{500}$$

Wherein,

T = Dry bulb temperature (0C)

RH = Relative Humidity (%)

The thermal heat index is a parameter for analyzing the level of thermal comfort within a selected space.

Suggested comfort limits are as follows;

$21 \leq THI \leq 24$ – 100% of the subjects feel comfortable;

$24 < THI \leq 26$ – 50% of the subjects feel comfortable;

THI >26 - 100% of the subjects feel uncomfortably hot.

(Emmanuel R. , 2016)

The THI values and THI variations on each location and discuss the thermal comfort levels on each selected locations was compared.

3.5.4.2. Analyzing Tools for Simulated data for Existing scenario and envisaged scenarios.

First, the study compared the Simulated Air temperature and Simulated Mean Radiant Temperature (MRT) variations of the envisaged six scenarios with the respective Base line condition. The baseline condition of each location was referred to the simulated values for the day time (13:00h, i.e., day-time peak hour of thermal heat) and night time (21:00h, i.e., night –time peak hour of thermal heat) based on the empirical data obtained on 27th March 2019.

Second, the study discussed the thermal stress by interpreting the calculated Predicted Mean Vote (PMV) at the level of 1.5m for the Day time 13:00:00h and the Night Time 21:00:00h respectively by preparing relevant graphs by using the Leonardo 2014, of all different Five built forms. To discuss the PMV value use BIOMET V1.01 to obtain the calculated PMV values for each Locations and for each scenarios.

- Predicted Mean Vote (PMV) is an index to predict the average vote of a huge set of people on the seven –point thermal Sensation /feeling scale.
  Use the Thermal Sensation Scale which introduced by the Franger to evaluate the comfort levels for all Five selected Locations.

Thermal Sensation Scale;	
Scale	***Comments***
+3 = Hot	intolerably warm
+2 = Warm	tolerably uncomfortable, warm
+1 = Slightly Warm	too warm
0 = Normal	Comfortable
-1 = Slightly Cool	tolerably un comfortable, cool
-2 = Cool	too cool
-3 = Cold	intolerably cool

Table 06 : Thermal Sensation Scale,

Source: Franger's comfort Equation

CHAPTER FOUR: RESULTS AND ANALYSIS

4.0 Introduction to Chapter.

This chapter is organized into 03 sections. The First section describes the existing status of climatic conditions and built form as per the data collected from secondary sources and primary surveys. The second section discusses the thermal comfort levels of each case study under the simulated baseline conditions and empirical data. The third presents the findings of the simulated scenarios explaining the degree in which the different planning interventions (such as changing of building height, increasing green cover, increasing open spaces, creating wind corridors) may reduce the thermal stress, particularly with reference to the Mean Radiant temperature (MRT) and Psychological Mean Value (PMV).

4.1 Existing status of climatic conditions and Built Form

4.1.1. Climatic data for Colombo.

Monthly Mean Temperature and humidity obtained for the March 2018 to March 2019 and Annual Mean Temperature were obtained for last 20 years from the Meteorological Department situated in Colombo 07.

4.1.1.1 Air Temperature

- Monthly Mean Temperature

The monthly mean temperature varies between the $29.8C^0$ to $32.2C^0$. According to the Figure 48 , the highest Monthly mean temperature is the $32.2C^0$ and it shows in the March 2019. The lowest monthly mean temperature indicated in the August 2018.

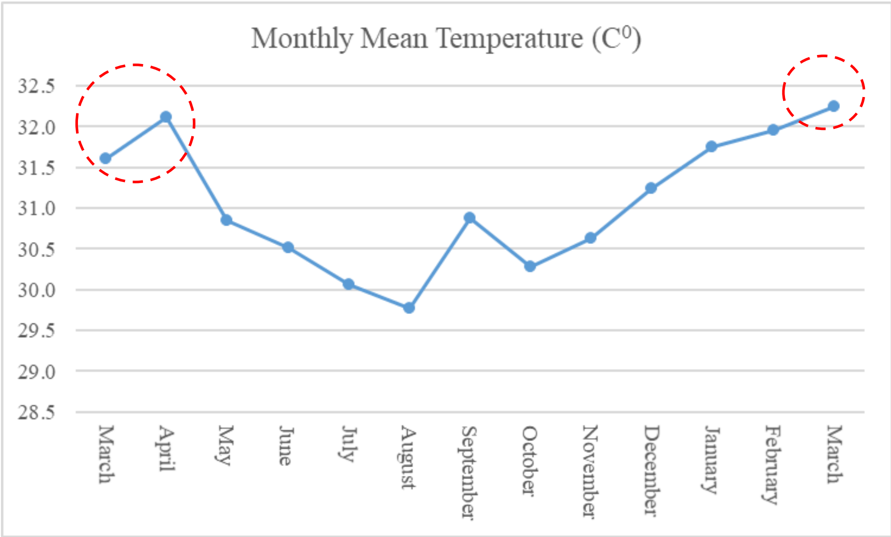


Figure 48: Monthly Mean Temperature (Data from March 2018 to March 2019).

Source: Meteorological Department situated in Colombo 07.

4.1.1.2 Relative Humidity

- Monthly Mean Relative Humidity

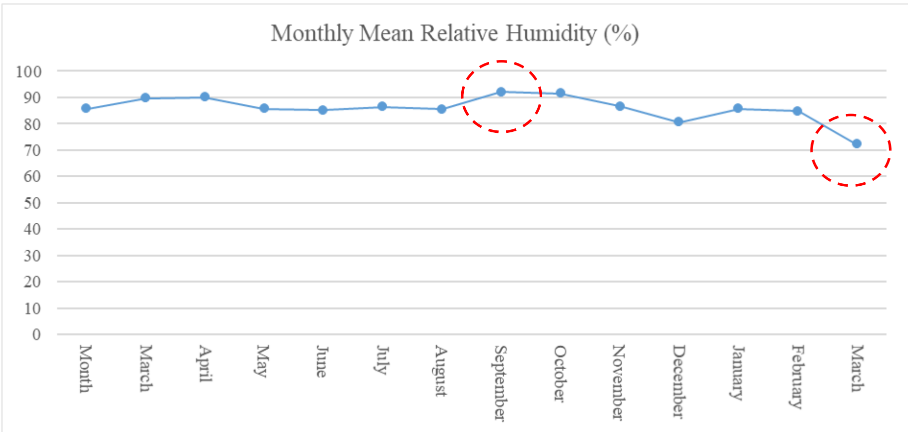


Figure 49: Monthly Mean Relative Humidity
(Data from March 2018 to March 2019).

Source: Meteorological Department situated in Colombo 07.

- The highest monthly mean Relative Humidity shows in September 2018 as 92%. The Lowest Monthly mean relative Humidity shows in March 2019 as 72%.

4.1.2. Weather measurements, Building Height data and Photographs obtained at the Field Survey.

4.1.2.1 Location 01- Urban Plaza

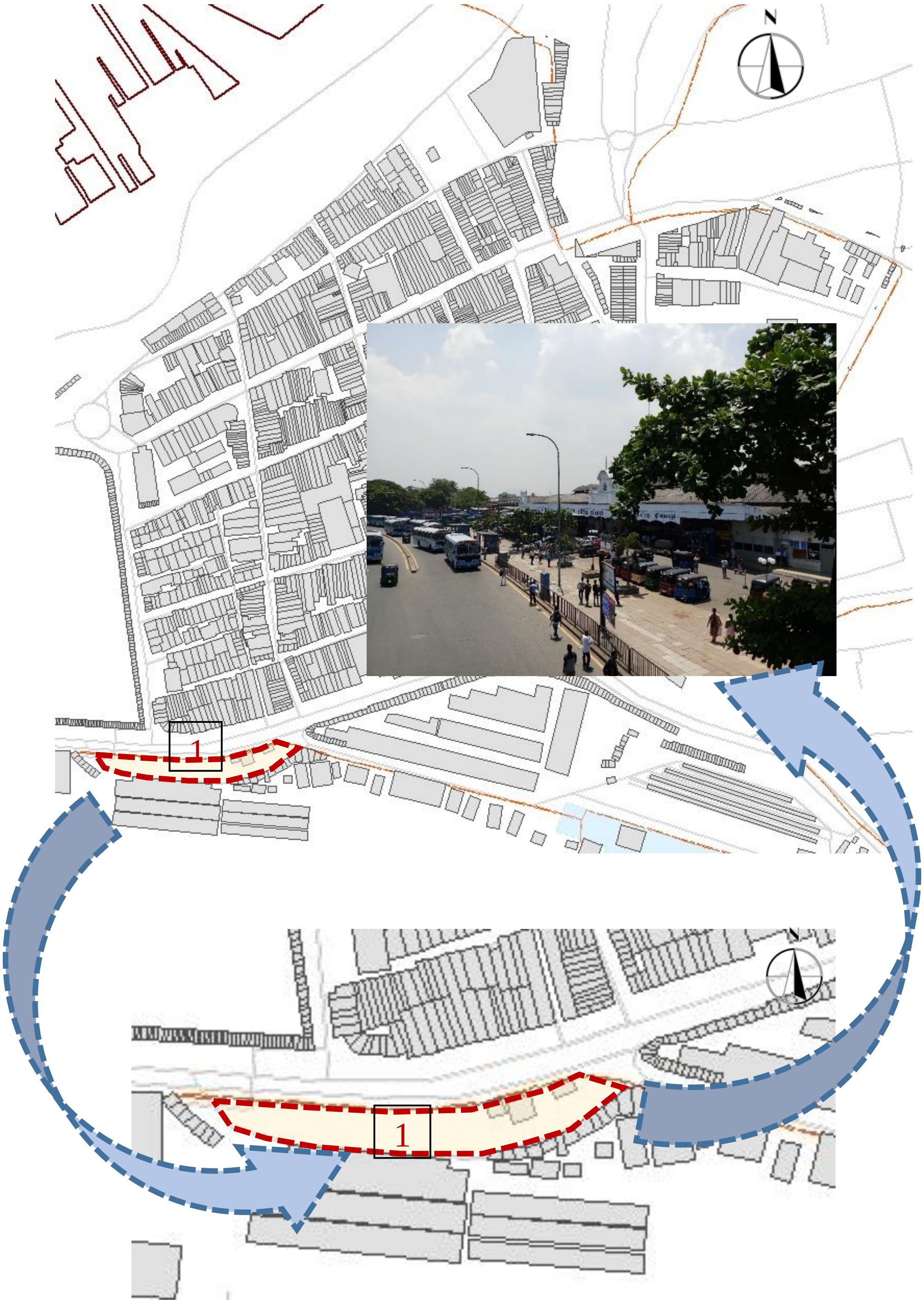


Figure 50: Field Survey Map – Location 01 – An urban Plaza

Source: Author

4.1.2.1.1 Location 01- Urban Plaza - Photographic Survey

Figure 51: Photographic Survey – Location 01 – An urban Plaza

Source: Author

Most of people are use this station plaza as a gathering pocket, worshiping and as a waiting point.

4.1.2.1.2 Building Heights of Surrounding Buildings.

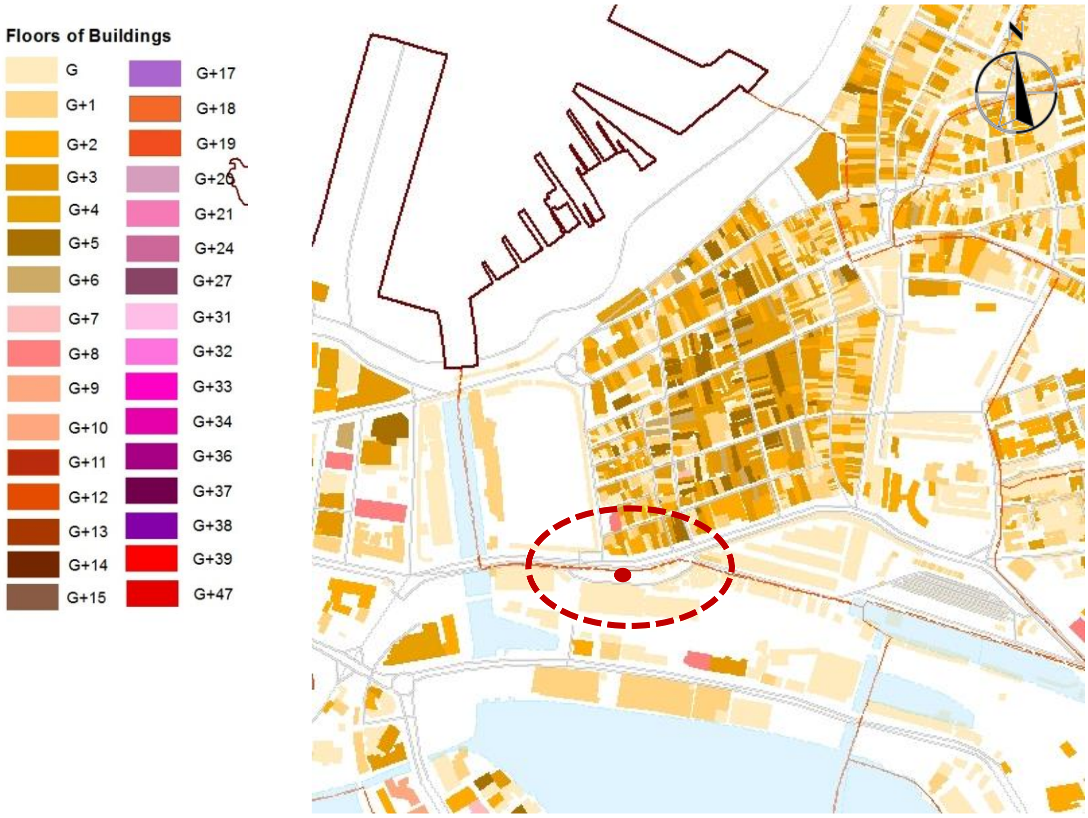


Figure 52: Building height Distribution Survey – Location 01 – An urban Plaza

Source: Author

Heights of the buildings at the surrounding area of the urban station plaza in single story, two storied and maximum five storied.

4.1.2.1.3. Location 01- Urban Plaza - Field Measurements of the weather condition.

Climatic data measured on Urban Plaza at the in front of the Pettah railway station. For the Location 01 – at the urban plaza the time was 11.00 a.m. to 11.15 a.m. and 16.00 p.m. to 16.15 p.m.

Location 01 – Urban plaza			**Session 01 (11.00a.m. to 13.00 p.m.)**	**Session 02 (16.00 p.m. to 18.00 p.m.)**
			11.00 a.m. -11.15 a.m.	**16.00 p.m. – 16.15 p.m.**
	01	Measurement Staring Time	11.00 a.m.	16.00 p.m.
	02	Measurement Ending Time	11.15 a.m.	16.15 p.m.
	03	Wind speed and wind direction	1.07 ms^{-1} (11.00 a.m.) 2.52 ms^{-1} (11.08 a.m.) 1.17 ms^{-1} (11.15 a.m.)	1.85 ms^{-1} (16.00 p.m.) 1.47 ms^{-1} (16.10 p.m.) 2.63 ms^{-1} (16.16 p.m.)
	04	Average Surface Temperature	43.95 C° Surface material- concrete	47 C° Surface material- concrete

Table 07: Field Measurements – Location 01 – An Urban Plaza

Source: Author

According to the ***HOBO meter 02*** and ***HOBO meter 04*** measured Average Air temperature and Average Relative Humidity is as follows;

	Average Air temperature (C°)	**Average Relative Humidity (%)**
Location 01 – Urban plaza	**11.00 a.m. -11.15 a.m. (Morning Session)**	
	35.36	55.5
	16.00 p.m. – 16.15 p.m. (Evening Session)	
	34.21	48.27

Table 08: Field Measurements obtained from Hobo meters– Location 01 – An urban Plaza

Source: Author

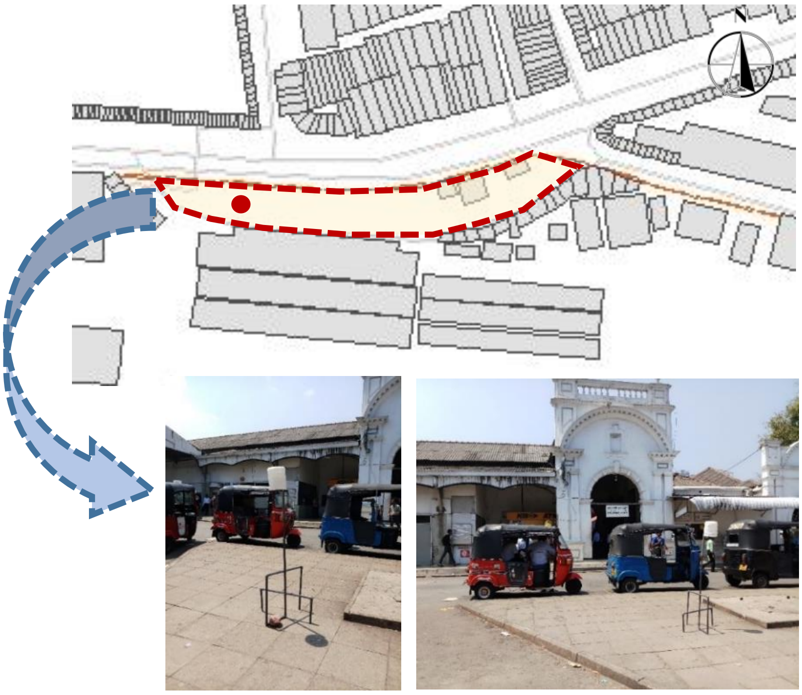


Figure 53: Point of Filed Survey – Location 01 – An urban Plaza

Source: Author

4.1.2.2 Location 02 - East –West Canyon –(A) *Prince Street*

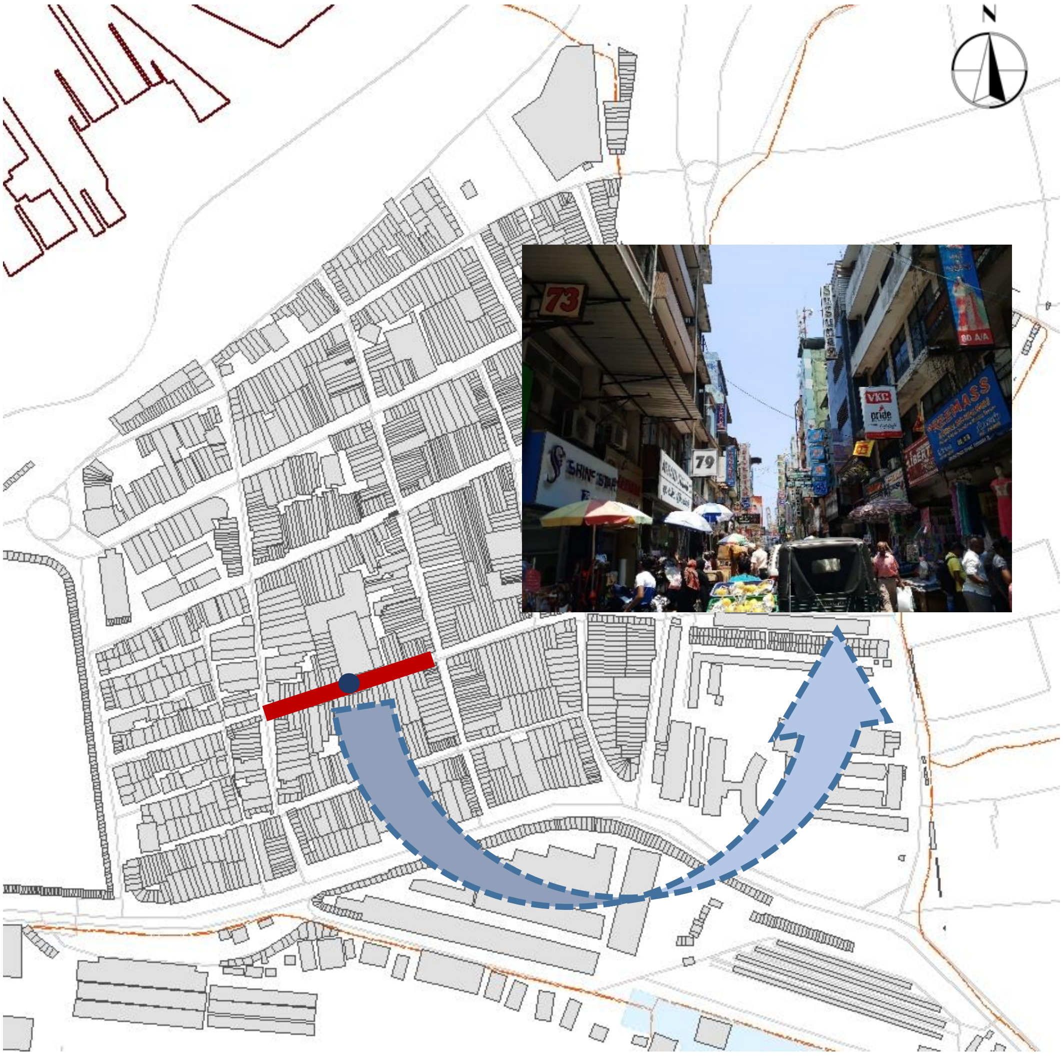


Figure 54: Field Survey Map – Location 02 – East-West Canyon – Prince Street

Source: Author

4.1.2.2.1. Location 02- East –West Canyon –(A) – Prince Street- Photographic Survey

Figure 55: Photographic Survey – Location 02 – An urban Plaza

Source: Author

4.1.2.2.2. Building Heights of Surrounding Buildings

Figure 56: Building height Distribution Survey – Location 02 – East West (EW) Urban Canyon – Prince Street

Source: Author

Most of the buildings comprised with G+ 5, G+4 storied. But it was observed that there is a single storied building called as the Dutch Museum which have a heritage value.

4.1.2.2.3. Location 02 – East – West Canyon – (a) Prince Street – Field Measurements of the weather condition.

Climatic data measured on two numbers of East - West canyons which are the different road widths and different building heights. Location 02 East - West Canyon (Prince street) comprised with the less building height and the less road width than the Location 04 – other East - West canyon. (Main street)

For the Location 02 – **East –West Canyon- (A) *Prince Street*** the data measured time was 11.25 a.m. to 11.40 a.m. for the session 01 and 16.25 p.m. to 16.40 p.m. for the session 02.

Location 02 – East –west Canyon- (A) Prince Street			**Session 01 (11.00a.m. to 1.00 p.m.)**	**Session 02 (4.00 p.m. to 6.00 p.m.)**
			11.25 a.m. -11.40 a.m.	**16.25 p.m. – 16.40 p.m.**
	01	Measurement Staring Time	11.25a.m.	16.25 p.m.
	02	Measurement Ending Time	11.40 a.m.	16.40 p.m.
	03	Wind speed and wind direction	0.56 ms^{-1} (11.25 a.m.) 0.66 ms^{-1} (11.34 a.m.) 1.04 ms^{-1} (11.40 a.m.)	2.29 ms^{-1} (16.28 p.m.) 1.32 ms^{-1} (16.33 p.m.) 1.53 ms^{-1} (16.40 p.m.)
	04	Average Surface Temperature	40.45 C° (11.30 a.m.) Surface material- Tar	39.4C° Surface material- Tar

Table 09: Field Measurements – Location 02 – East West Canyon – (a) Prince Street

Source: Author

According to the ***HOBO meter 02*** and ***HOBO meter 04*** measured Average Air temperature and Average Relative Humidity is as follows;

<table>
<tr><td rowspan="5">Location 02 –
East –West Canyon-
(A) Prince street</td><td>Average Air temperature (C°)</td><td>Average Relative Humidity (%)</td></tr>
<tr><td colspan="2">11.25 a.m. -11.40 a.m. (Morning Session)</td></tr>
<tr><td>35.60</td><td>44.99</td></tr>
<tr><td colspan="2">16.25 p.m. – 16.40 p.m. (Evening Session)</td></tr>
<tr><td>33.32</td><td>52.5</td></tr>
</table>

Table 10: Field Measurements obtained from Hobo meters– Location 02 – East-West (EW) Canyon – (A) Prince Street

Source: Author

Figure 57: Point of Filed Survey – Location 02 – East West Canyon – (a) Prince Street

Source: Author

4.1.2.3. Location 03 - North -South Canyon – *02nd Cross Street*

Figure 58: Field Survey Map – Location 03 – North South Canyon – 02nd Cross Street.

Source: Author

4.1.2.3.1. Photographic Survey

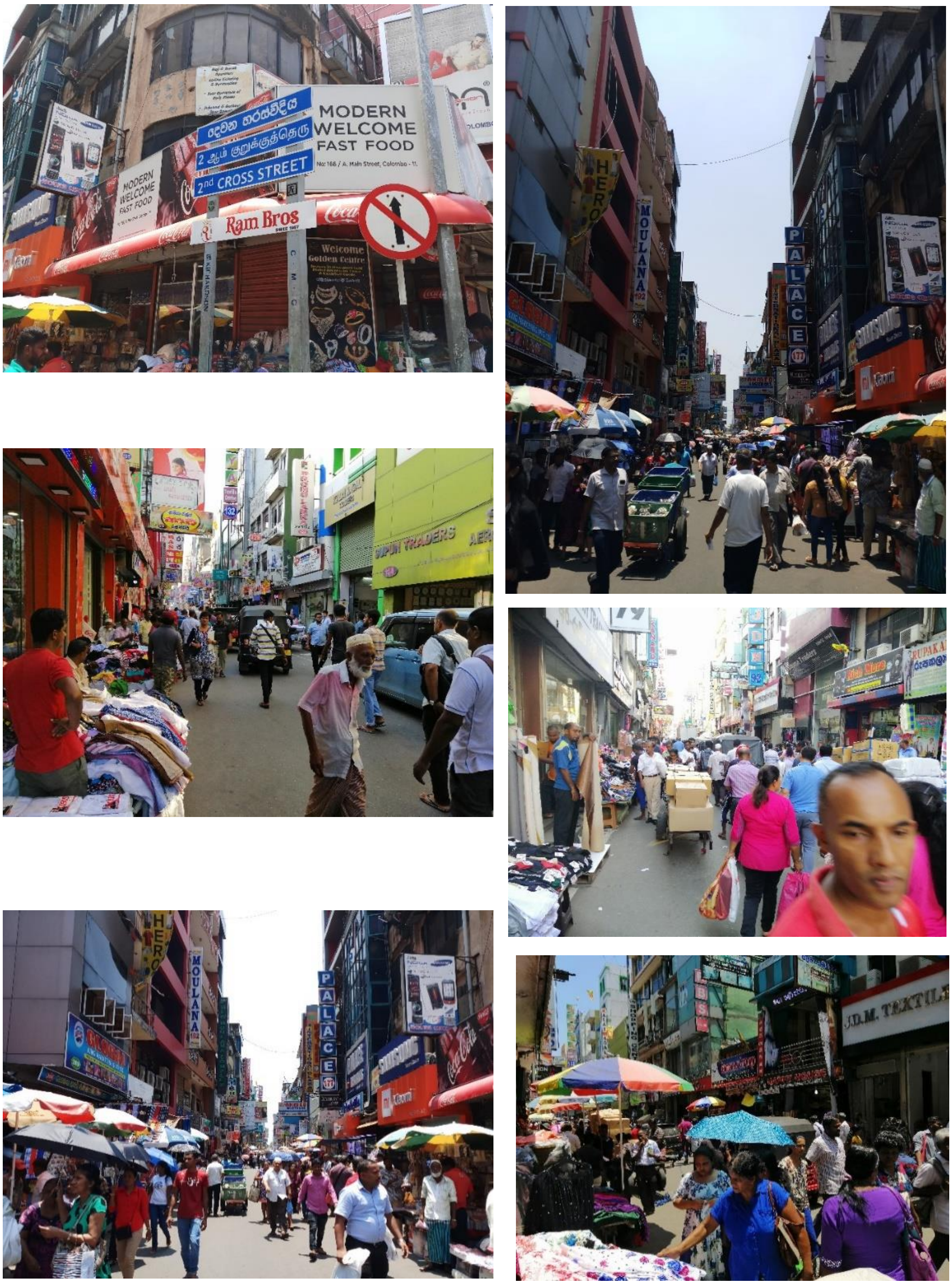


Figure 59: Photographic Survey – Location 03 – North South (NS) Canyon – 02nd Cross Street

Source: Author

4.1.2.3.2. Building Heights of Surrounding Buildings

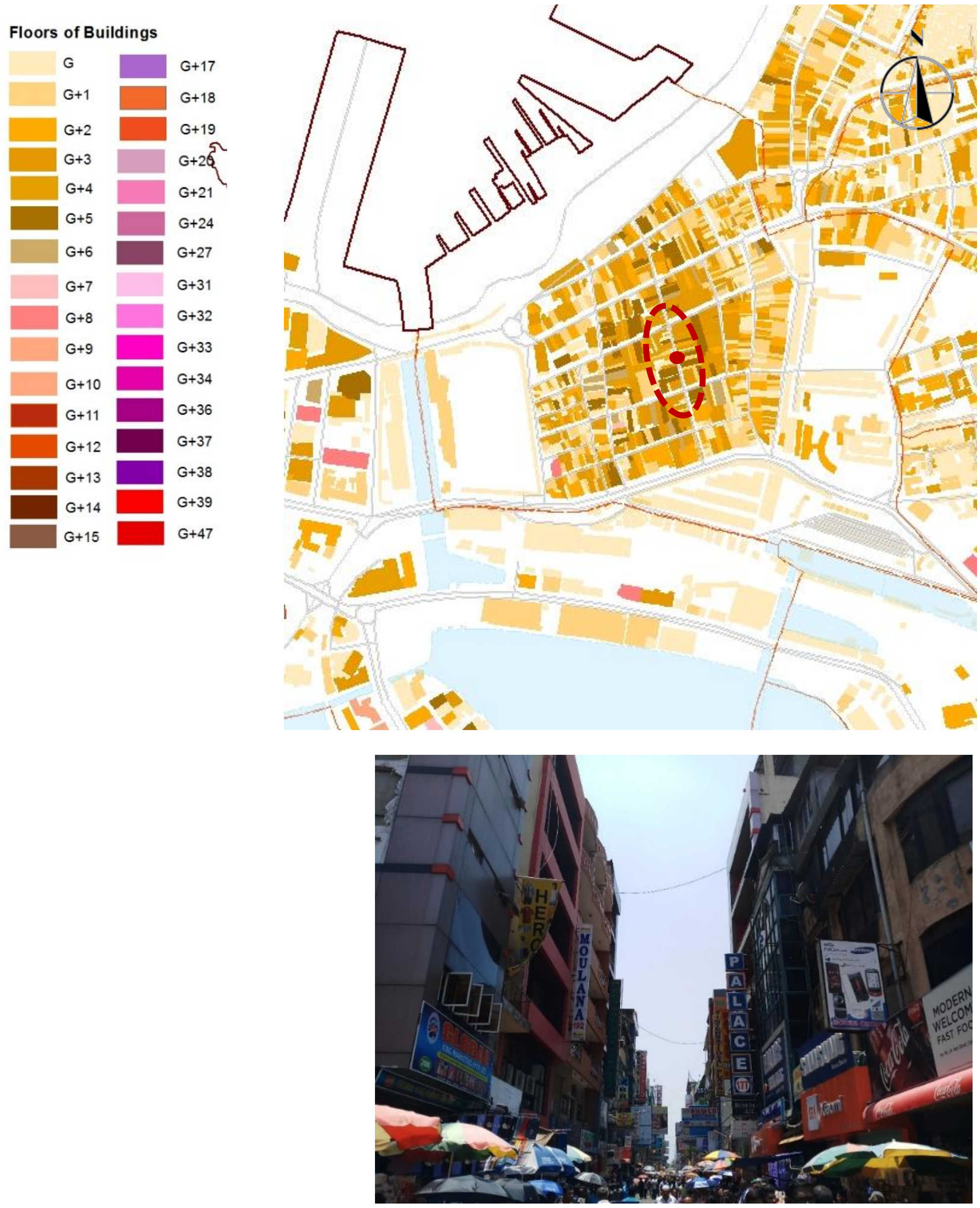


Figure 60: Building height Distribution Survey – Location 03 – North South (NS) Canyon – 02nd Cross Street

Source: Author

Most of the buildings were comprised with G+ 5, G+4 storied.

4.1.2.3.3. Location 03 - North -South Canyon – *02nd cross street*

- Field measurements of the weather condition.

Climatic data measured on selected North - East canyon, 02nd cross street as the location 03.

For the Location 03 – **North –South Canyon- *02nd Cross Street*** the data measured time was 11.25 a.m. to 11.40 a.m. for the session 01 and 16.25 p.m. to 16.40 p.m. for the session 02.

			Session 01 (11.00a.m. to 13.00 p.m.)	Session 02 (16.00 p.m. to 18.00 p.m.)
Location 03 – North –South canyon- *02nd cross street*			**11.45 a.m. -12.00 noon**	**16.47 p.m. – 17.02 p.m.**
	01	Measurement Staring Time	11.45 a.m.	16.47p.m.
	02	Measurement Ending Time	12.00 noon	17.02 p.m.
	03	Wind speed and wind direction	0.26 ms^{-1} (11.45 a.m.) 0.52 ms^{-1} (11.53 a.m.) 0.35 ms^{-1} (12.00 noon)	0.49 ms^{-1} (16.48 p.m.) 0.53 ms^{-1} (16.55 p.m.) 0.30 ms^{-1} (17.01 p.m.)
	04	Average Surface Temperature	40.55 C° Surface material-Tar	36.8C° Surface material-Tar

Table 11: Field Measurements – Location 03 – North South Canyon – 02nd Cross Street.

Source: Author

According to the ***HOBO meter 02*** and ***HOBO meter 04*** measured Average Air temperature and Average Relative Humidity at the time of 11.45 a.m. -12.00 noon at the morning session and the time of 16.47 p.m. – 17.02 p.m. at the evening session is as follows;

	Average Air temperature (C°)	**Average Relative Humidity (%)**
Location 03 – North –south canyon- *02nd cross street*	**11.45 a.m. -12.00 noon (Morning Session)**	
	35.84	44.93
	16.47 p.m. – 17.02 p.m. (Evening Session)	
	33.22	63

Table 12: Field Measurements obtained from Hobo meters– Location 03 – North South Canyon – 02nd Cross Street.

Source: Author

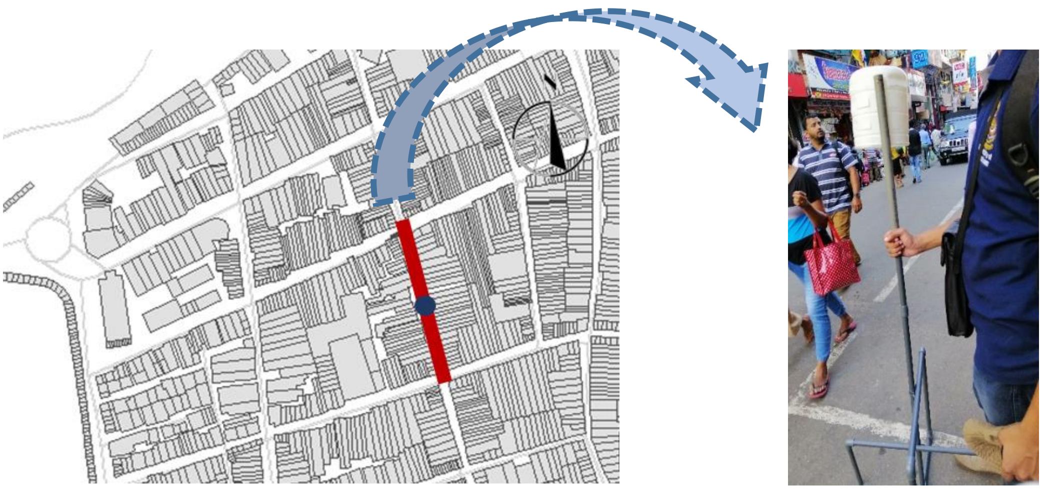


Figure 61: Point of Filed Survey – Location 03 – North South Canyon – 02nd Cross Street.

Source: Author

4.1.2.4. Location 04 - East –West Canyon – *(B) Main Street*

Figure 62: Field Survey Map – Location 04 – East West Canyon – Main Street

Source: Author

4.1.2.4.1. Photographic Survey

Figure 63: Photographic Survey – Location 04 – East West Canyon – Main Street

Source: Author

4.1.2.4.2. Building Heights of Surrounding Buildings

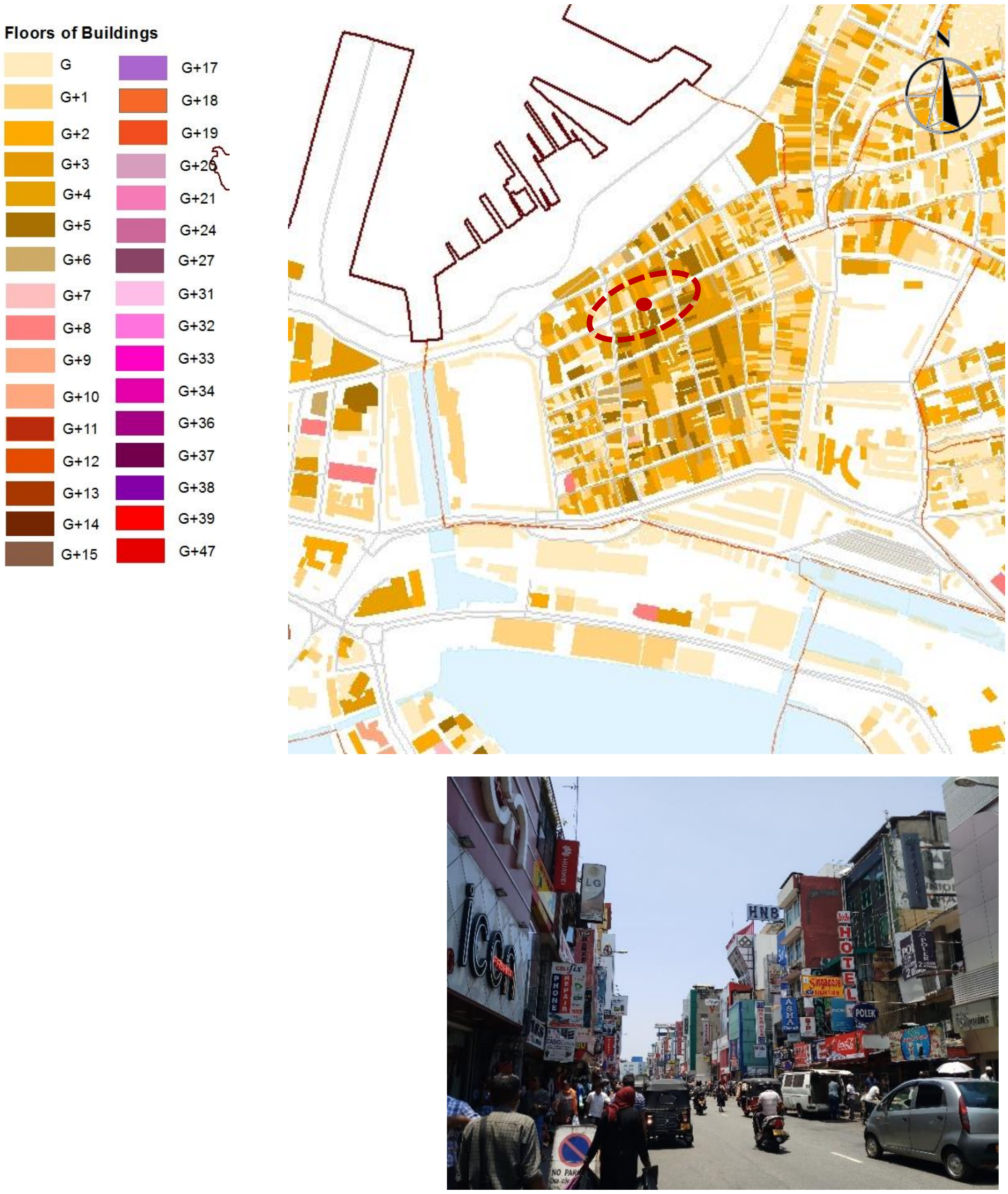


Figure 64: Building height Distribution Survey – Location 04 – East West Urban Canyon – Main Street
Source: Author

Most of the buildings were comprised with G+4 storied.

4.1.2.4.3. Location 04 - East –West Canyon – (B) Main street

- Field Measurements of the weather condition

Climatic data measured on selected East- West canyon – (B) Main Street, as the location 04 with different width of the road comparing to the location 02.

For the Location 04 – **East –West Canyon- *(B) Main Street*** the data measured time was **12.06 p.m. to 12.22 p.m.** for the session 01 and **17.10 p.m. to 17.25 p.m.** for the session 02.

			Session 01 (11.00a.m. to 1.00 p.m.)	**Session 02 (4.00 p.m. to 6.00 p.m.)**
Location 04 – East –West Canyon – *(B) Main street*			**12.06 p.m. -12.22 p.m.**	**17.10 p.m. – 17.25 p.m.**
	01	Measurement Staring Time	12.06 p.m.	17.10 p.m.
	02	Measurement Ending Time	12.22 p.m.	17.25 p.m.
	03	Wind speed and wind direction	0.67 ms^{-1} (12.06 p.m.) 1.15ms^{-1} (12.10 p.m.) 1.17 ms^{-1} (12.22 p.m.)	1.23 ms^{-1} (17.12 p.m.) 1.08 ms^{-1} (17.23 p.m.) 0.70 ms^{-1} (17.25 p.m.)
	04	Average Surface Temperature	41.15C° Surface material- Tar	36.3C° Surface material- Tar A shadow was appeared.

Table 13: : Field Measurements – Location 04 – East West (EW) Canyon – Main Street.

Source: Author

According to the ***HOBO meter 02*** and ***HOBO meter 04*** measured Average Air temperature and Average Relative Humidity at the time of 11.45 a.m. -12.00 noon at the morning session and the time of 16.47 p.m. – 17.02 p.m. at the evening session is as follows;

	Average Air temperature (C°)	**Average Relative Humidity (%)**
Location 04 – East –West Canyon – *(B) Main street*	**12.06 p.m. -12.22 p.m. (Morning Session)**	
	36.11	44.76
	17.10 p.m. – 17.25 p.m. (Evening Session)	
	32.68	57.5

Table 14: Field Measurements obtained from Hobo meters– Location 04 – East West (EW) Canyon – Main Street

Source: Author

4.1.2.5. Location 05 – A Parking precinct - *Gunasinghapura bus stand*

Figure 65: Field Survey Map – Location 05 – A Parking Precinct

Source: Author

4.1.2.5.1. Photographic Survey

Figure 66: Photographic Survey – Location 05 – A Parking Precinct

Source: Author

4.1.2.5.2. Building Heights of Surrounding Buildings

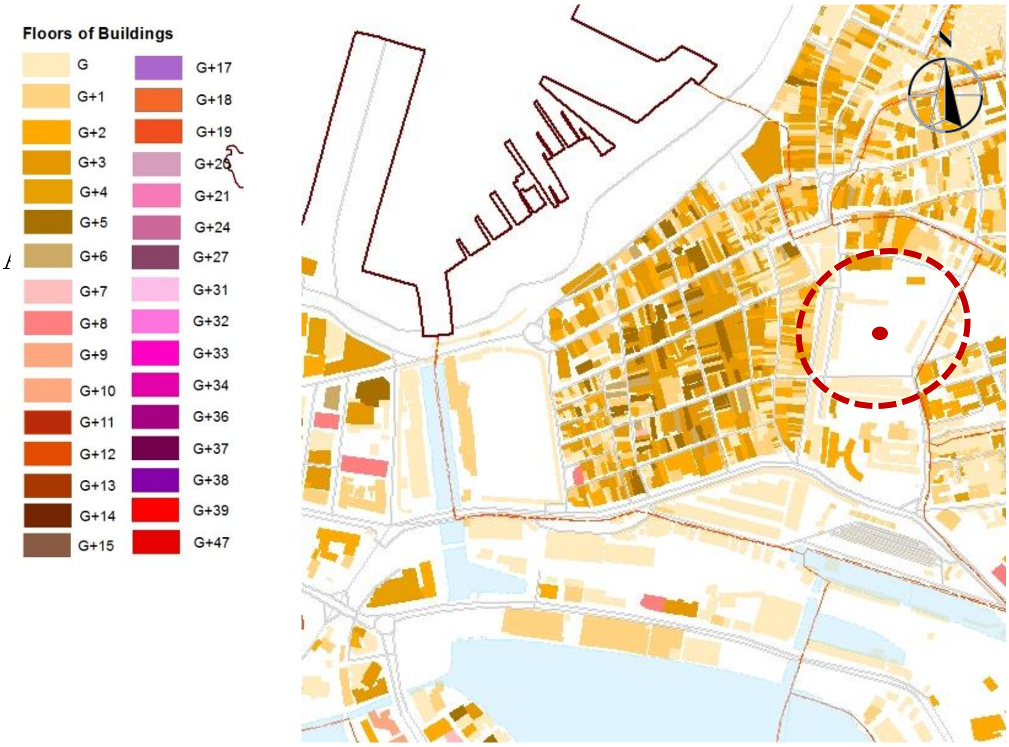


Figure 67 : Building height Distribution Survey – Location 05 – A Parking Precinct.

Source: Author

According to the photographic survey it was observed that there were less buildings surrounding the location 05. It is a parking precinct.

Bidding heights that were in the surrounding are G+4, beside the road.

4.1.2.5.3. Location 05 – A Parking Precinct - Gunasinghapura bus stand

- Field measurements of the weather condition

Climatic data measured on selected a Parking precinct which has the different built form from other locations. The Gunasinghapura Bus stand in Pettah was selected as the Parking precinct as Location 05.

For the Location 05 – A **Parking precinct - *Gunasinghapura bus stand*** the data measured time was **12.40 p.m. to 12.56 p.m.** for the session 01 and **17.40 p.m. to 17.55 p.m.** for the session 02.

			Session 01 (11.00a.m. to 13.00 p.m.)	**Session 02 (16.00 p.m. to 18.00 p.m.)**
Location 05 – A Parking precinct - *Gunasinghapura bus stand*			**12.40 p.m. -12.56 p.m.**	**17.40 p.m. – 17.55 p.m.**
	01	Measurement Staring Time	12.40 p.m.	17.40 p.m.
	02	Measurement Ending Time	12.56 p.m.	17.55 p.m.
	03	Wind speed and wind direction	1.35ms^{-1} (12.40 p.m.) 1.61ms^{-1} (12.50 p.m.) 1.17 ms^{-1} (12.56 p.m.)	0.65 ms^{-1} (17.42 p.m.) 1.33 ms^{-1} (17.50 p.m.) 1.67 ms^{-1} (17.55 p.m.)
	04	Average Surface Temperature	44.7 C° Surface material-Concrete	36.2C° Surface material-Concrete • Shadow effect

Table 15: Field Measurements – Location 05 – A Parking Precinct

Source: Author

According to the ***HOBO meter 02*** and ***HOBO meter 04*** measured Average Air temperature and Average Relative Humidity at the time of **12.40 p.m. -12.55 p.m.** at the morning session and the time of **17.40 p.m. – 17.55 p.m.** at the evening session is as follows;

	Average Air temperature (C°)	**Average Relative Humidity (%)**
Location 05 – A Parking precinct - ***Gunasinghapura bus stand***	**12.40 p.m. -12.55 p.m. (Morning Session)**	
	36.69	43.9
	17.40 p.m. – 17.55 p.m. (Evening Session)	
	31.21	62.02

Table 16: Field Measurements obtained from Hobo meters– Location 05 – A Parking Precinct.
Source: Author

4.1.2.6. The Reference Point – Charmer's Granaries Land at Pettah

The Charmer's Granaries Land which is a bare land was selected as the Reference point to calculate reference values for the accuracy of THI values and Hobo meter 01 and Hobo meter 03 were installed as permanently from 10.10 a.m to 18.23 p.m on the date of 27th March 2019.

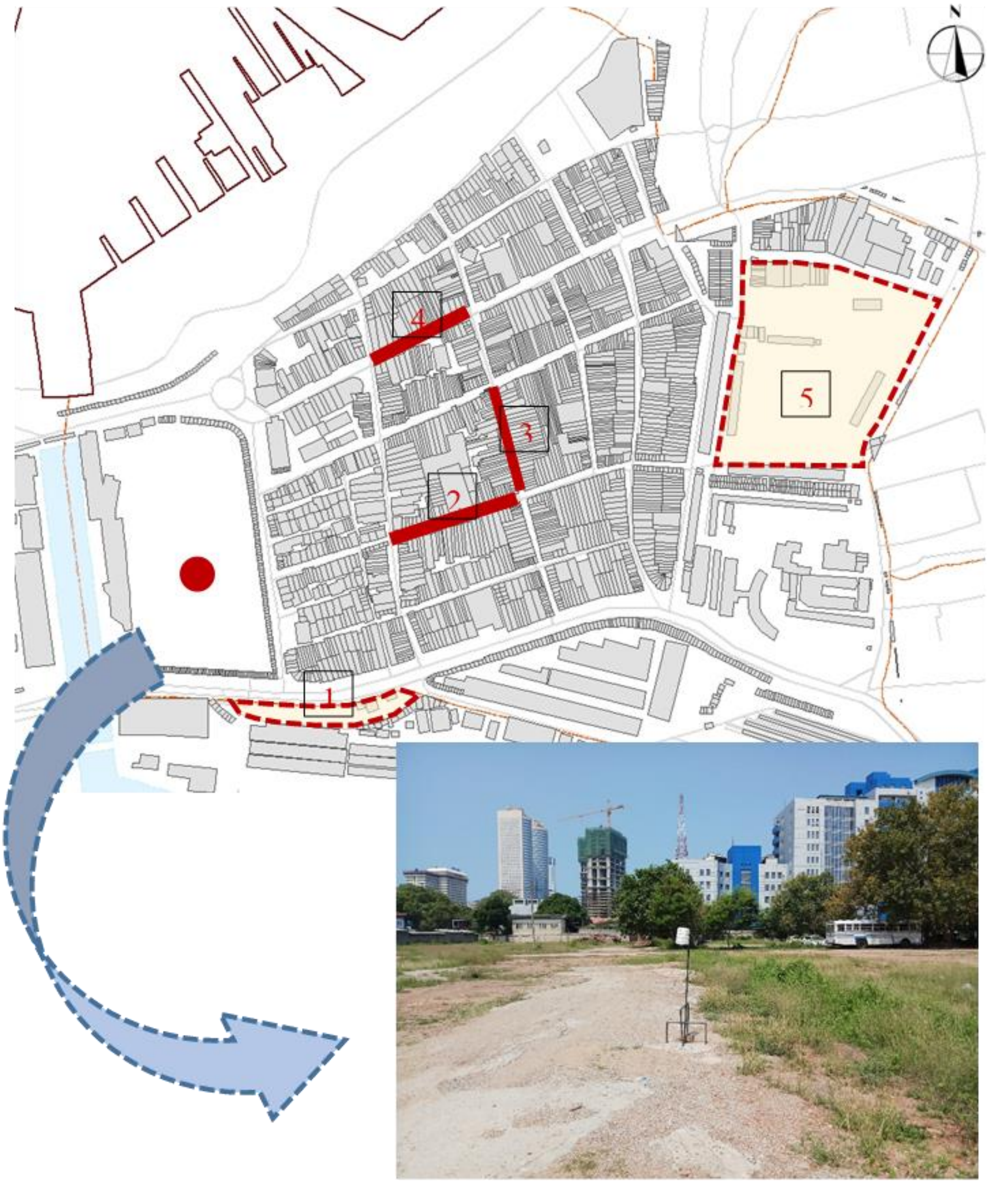


Figure 68: Field Survey Map – Reference Point

Source: Author

According to the ***HOBO meter 01*** and ***HOBO meter 03*** measured Air temperature and Relative Humidity at the time of **11.00 a.m. to 18.00 p.m.** for Reference point.

A reference point was used to compare the variations with the measured value for accuracy of the data.

	Average Air temperature (C°)	**Average Relative Humidity (%)**	**THI value (C°)**
Reference Point – Charmer's Granaries Land At Pettah	**11.00 a.m. to 13.00 p.m. (Morning Session)**		**30.77**
	38.37	38.63	
	16.00 p.m. to 18.00 p.m. (Evening Session)		**27.24**
	33.97	50.19	

Table 17: Field Measurements obtained from Hobo meters– Reference Point
Source: Author

4.1.2.7. Summary of Measured Average Air Temperature, Average Relative Humidity, Average Surface Temperature and Thermal Heat Index (THI) for all Five Selected Locations.

- Calculation of Thermal Heat Index (THI)

The temperature – humidity index (THI) is an empirical index developed in the USA in the 1950 to assess discomfort in warm-humid conditions (McIntyre,1980). The index can be calculated as (Emmanuel,2005b) (Emmanuel R. , Urban Climate Challenges in the Tropics- Rethinking Planning and Design Opportunities, 2016, p. 187)

$$\mathbf{THI = 0.8T_a + \frac{RH \times T_a}{500}}$$

Where;

T_a = Air temperature (C°)

RH = Relative Humidity (%)

The suggested comfort limits are as follows; (Emmanuel,200b)

$21 \leq THI \leq 24$ - 100% of the subjects feel comfortable.

$24 < THI \leq 26$ - 50% of the subjects feel comfortable.

$THI > 26$ - 100% of the subjects feel uncomfortably hot.

4.1.2.7.1 The summary of the Measured weather data from 11 a.m. to 13.00 p.m. (Session 01)

Location	Time	Average Air Tempera -ture (C°)	Average Relative Humidity (%)	Average Surface Temperatu- re (C°)	THI Value (C°)	Remarks
01- An Urban Plaza	11.00 a.m. to 11.15 a.m.	35.36	55.5	43.95	28.47	G, G+1, G+3, G+4 Surface material-concrete
02- East – East canyon- (A) *Prince street*	11.25 a.m. to 11.40 a.m.	35.60	44.99	40.45	28.64	G+4, G+5 Surface material-Tar Shadow effect.
03- North – South canyon- *02nd cross street*	11.45 a.m. to 12.00 noon	35.84	44.93	40.55	28.83	G+4, G+5 Surface material-Tar
04 -East – Eest canyon *– (B) Main street*	12.06 p.m. to 12.22 p.m.	36.11	44.76	41.15	29.05	G+4, Surface material-Tar
05- A Parking precinct - *Gunasinghapura bus stand*	12.40 p.m. to 12.55 p.m.	36.69	43.9	44.7	29.51	G+4 , beside roads Surface material-concrete.

Table 18: Summary of Measured Average Air Temperature, Average Relative Humidity, Average Surface Temperature and calculated Thermal Heat Index for all Locations Measured data from 11.00 a.m. to 13.00 p.m. (Session 01)

Source: Author

4.1.2.7.2. The summary of the Measured weather data from 16.00 p.m. to 18.00 p.m. (Session 02)

Location	Time	Average Air Tempera -ture (C°)	Average Relative Humidity (%)	Average Surface Tempera -ture (C°)	THI Value (C°)	Remarks
01- An Urban Plaza	16.00 p.m. to 16.15 p.m.	34.9	48.27	47	**28.09**	G, G+1, G+3, G+4 Surface material- concrete
02- East – East canyon- (A) *Prince street*	16.25 p.m. to 16.40 p.m.	33.32	52.5	39.4	**26.83**	G+4, G+5 Surface material- Tar
03- North – South canyon- *02nd cross street*	16.47 p.m. to 17.02 p.m.	33.22	63	36.8	**26.85**	G+4, G+5 Surface material- Tar
04 -East – West canyon – *(B) Main street*	17.10 p.m. to 17.25 p.m.	32.68	57.5	36.3	**26.32**	G+4, Surface material- Tar -Shadow effect
05- A Parking precinct - *Gunasinghapura bus stand*	17.40 p.m. to 17.55 p.m.	31.21	62.02	36.2	**25.15**	G+4 , beside roads Surface material- concrete -Shadow effect.

Table 19: Summary of Measured Average Air Temperature, Average Relative Humidity, Average Surface Temperature and calculated Thermal Heat Index for all Locations Measured data from 16.00 p.m. to 18.00 p.m. (Session 02)

Source: Author

4.1.2.8. Summary of calculated Thermal Heat Index Difference (THI Difference)

Thermal Heat Index Difference (THI Difference) was calculate for the accuracy of the measured data.

THI Difference = Reference THI value- Site THI value (THI Value of the Location)

4.1.2.8.1. Summary of Average Air Temperature, Calculated THI values and Calculated Thermal Heat Index Difference (THI Difference) at the time 11.00 a.m. to 13.00 p.m.

Location	**Time**	**Average Air Temperature (C°)**	**THI Value (C°)**	**THI Difference (C°)**
01- An Urban Plaza	11.00 a.m. to 11.15 a.m.	35.36	28.47	**+2.3**
02- East –East canyon- (A) *Prince street*	11.25 a.m. to 11.40 a.m.	35.60	28.64	**+2.13**
03- North –South canyon- *02nd cross street*	11.45 a.m. to 12.00 noon	35.84	28.83	**+1.94**
04 -East –West canyon – *(B) Main street*	12.06 p.m. to 12.22 p.m.	36.11	29.05	**+1.72**
05- A Parking precinct - *Gunasinghapura bus stand*	12.40 p.m. to 12.55 p.m.	36.69	29.51	**+1.26**

Table 20: Summary of Measured Average Air Temperature, calculated Thermal Heat Index and Calculated THI Difference for all Locations Measured data from 11.00 a.m. to 13.00 p.m. (Session 01)

Source: Author

4.1.2.8.2. Summary of Average Air Temperature, Calculated THI values and Calculated Thermal Heat Index Difference (THI Difference) at the time 16.00 p.m. to 18.00 p.m.

Location	**Time**	**Average Air Temperature (C°)**	**THI Value (C°)**	**THI Difference (C°)**
01- An Urban Plaza	16.00 p.m. to 16.15 p.m.	34.9	**28.09**	**-0.85**
02- East –East canyon- (A) *Prince street*	16.25 p.m. to 16.40 p.m.	33.32	**26.83**	**+0.41**
03- North –South canyon- *02nd cross street*	16.47 p.m. to 17.02 p.m.	33.22	**26.85**	**+0.39**
04 -East –West canyon – *(B) Main street*	17.10 p.m. to 17.25 p.m.	32.68	**26.32**	**+0.92**
05- A Parking precinct - *Gunasinghapura bus stand*	17.40 p.m. to 17.55 p.m.	31.21	**25.15**	**+2.09**

Table 21: Summary of Measured Average Air Temperature, calculated Thermal Heat Index and Calculated THI Difference for all Locations Measured data from 16.00 p.m. to 18.00 p.m. (Session 02)

Source: Author

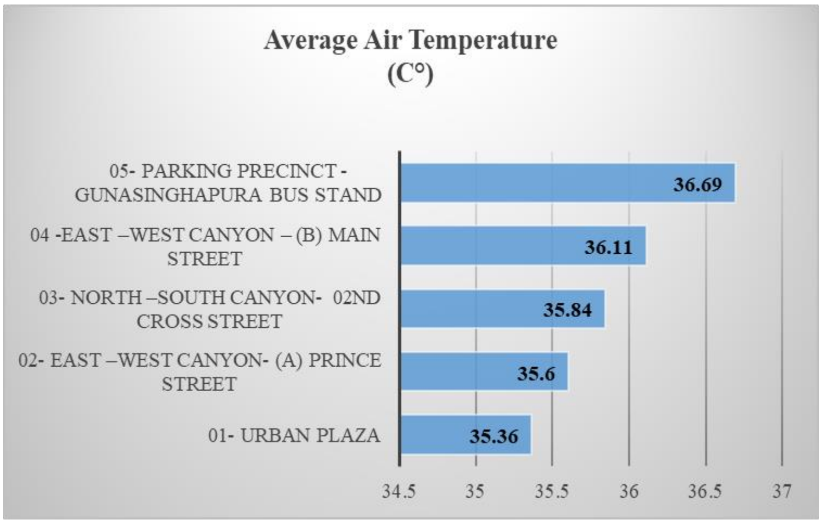
4.2 Interpreting the existing Thermal Comfort Levels.

This section discusses the variations in noon time (11.00 a.m. to 13.00 p.m.) and evening time (16.00 p.m. to 18.00 p.m.) separately.

4.2.1. Interpreting the existing thermal comfort levels around noon time. (11.00 a.m. to 13.00 p.m.)

4.2.1.1. Comparing the data on Average Air Temperature (C°).

Analyzing of Air Temperature (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations.



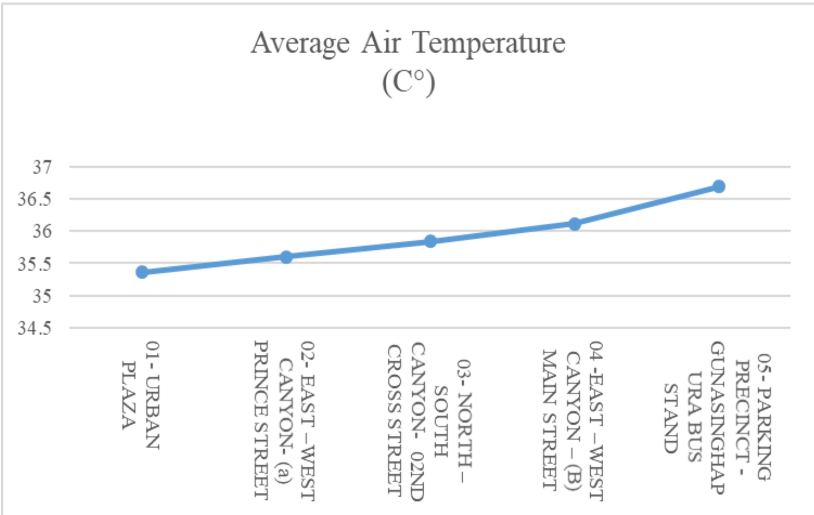


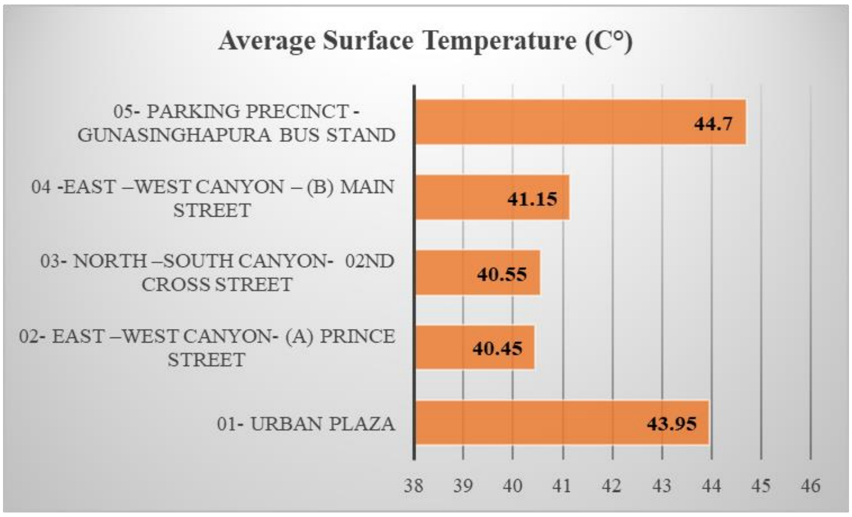
Figure 69 : Average Air Temperature (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations

Source: Author

- The highest average temperature is shown at the location 05- Parking Precinct – Gunasignahapura Bus Stand among all five locations.
- Further, the lowest average air temperature was indicated from the Location 01- Urban Plaza which is the only location having trees in the surrounding.
- Considering the Two Nos. of East –West canyons , the location 04- East-West canyon –(B) Main Street observed the higher average air temperature than the location 02- East West Canyon –(A) Prince Street due to having a higher road width than the location -02. And also location 02- - East West Canyon –(A) Prince Street having with the shade.
- When comparing to the Location 03- North South canyon- 02nd Cross Street and the Location 04 – East –West Canyon Main Street it was observed that the Location 04 having higher Average Air Temperature than the Location 03 due to the Location 04 directly expose to the solar radiation in day time.

4.2.1.2 Comparing the data on Average Surface Temperature (C°)

- The data was collected from 11.00 a.m. to 13.00 p.m. for all Five locations.



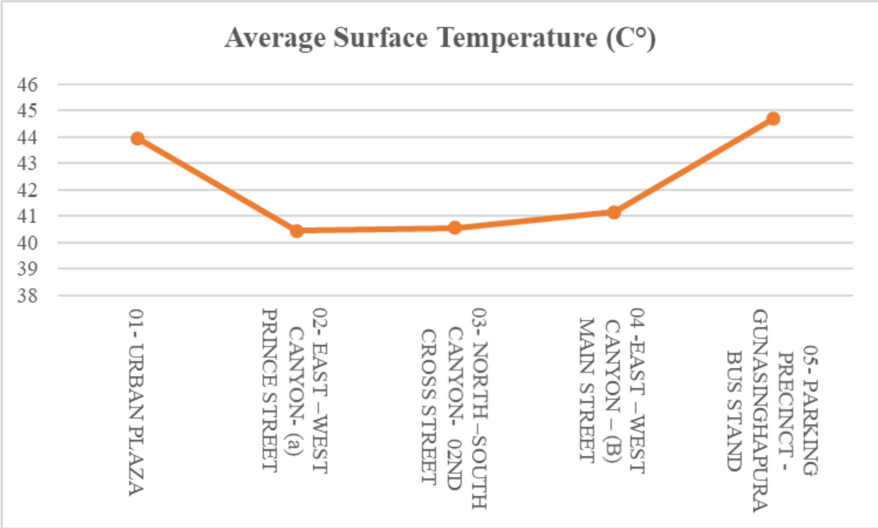


Figure 70: Average Surface Temperature (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations.

Source: Author

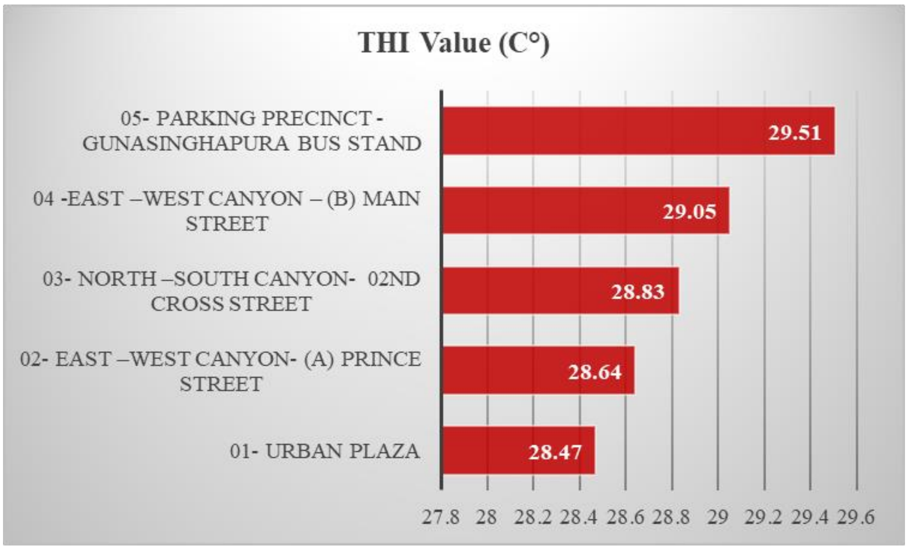
- The highest Average Surface Temperature shown from the location 05-Parking Precinct- Gunasinghapura Bus Stand. That location is more openable and comprised with vehicles. The used surface material is concrete for the ground surface.

- The lowest Surface Temperature was indicated from the Location 02 – East – West Canyon – (A) Prince Street, which used the Tar for the road surface material. It was observed there is a shade in this streel canyon at the measured time. Tar used as the Ground surface materials for the location 02.

- According to the results, it was observed that the Average surface temperature is more than 40 C° for each selected locations.

4.2.1.3. Comparing Thermal Heat Index (THI) of selected sites.

- THI values from 11.00 a.m. to 13.00 p.m. was calculated for all Five locations.



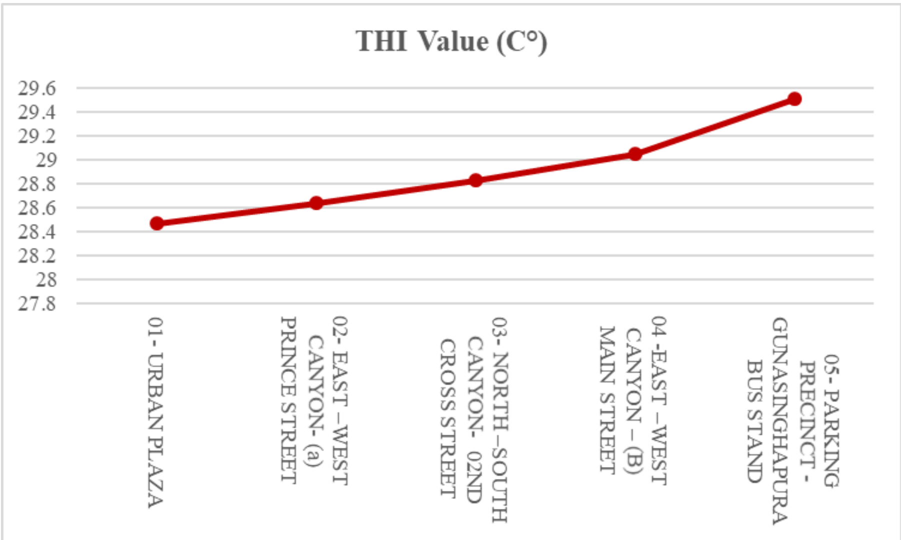


Figure 71: Calculated THI Values (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations.

Source: Author

Legend for THI values (C°)

- $THI>26$ - 100% of the subjects feel uncomfortably hot.
- $24<THI\leq26$ - 50% of the subjects feel comfortable.
- $21\leq THI\leq24$ - 100% of the subjects feel comfortable.

- As per the Figure 71, the highest THI value is shown from the Location 05-Parking Precinct- Gunasinghapura Bus Stand.
- The lowest THI value is shown from the location 01- Urban Plaza due to having Trees in that location.
- According to the results it was observed that all the THI values were more than 26 for all five locations at the time 11.00 a.m. to 13.00 p.m..
- Therefore, all five different built forms were 100% of the subjects feel uncomfortably hot for the time 11.00 a.m. to 13.00 p.m. (Session 01) considering the thermal comfort cut off for the Tropical countries.

4.2.1.4. Comparing the THI Difference of selected sites.

- From 11.00 a.m. to 13.00 p.m. for all Five locations.

- According to the empirical data in Figure 72, the highest THI difference shown from the Location 05-Parking Precinct- Gunasinghapura Bus Stand.
- The lowest THI difference shown from the Location 02- East-West Canyon – (a) Prince Street which was the consist with a narrow road width from the selected two numbers of East-West canyon for the study.
- The highest THI Difference was observed in the Location 01- Urban Plaza.
- The lowest THI difference shows in the Location 05- Parking Precinct- Gunasinghapura Bus Stand.

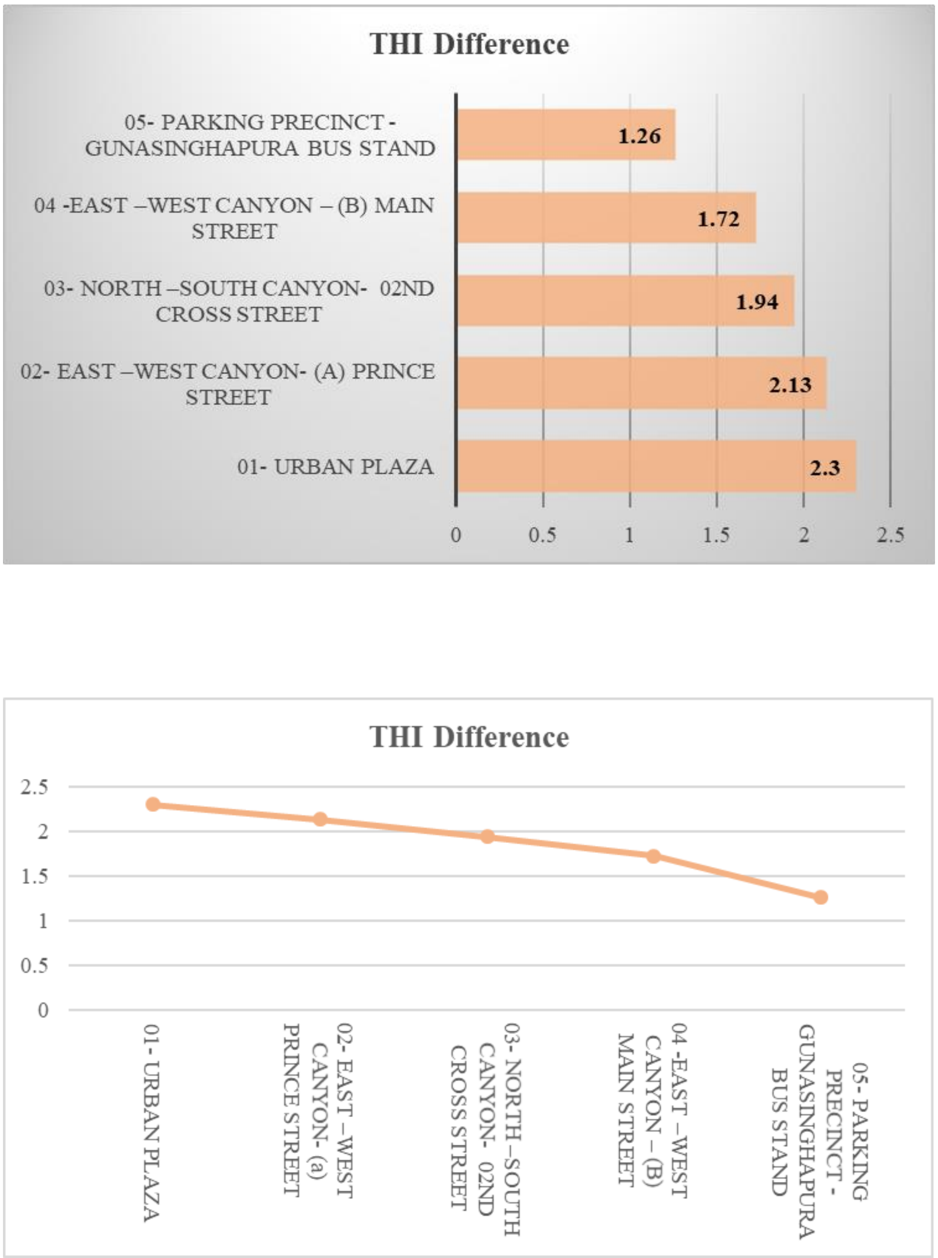


Figure 72: THI Difference from 11.00 a.m. to 13.00 p.m. for all Five location.

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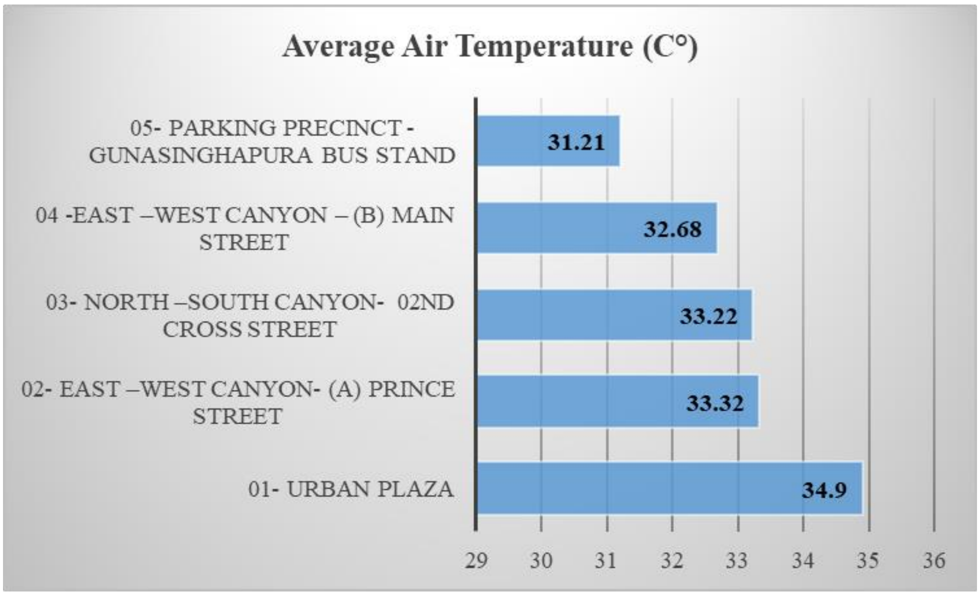
Source: Author

4.2.2. Interpreting the existing Thermal Comfort Levels at evening time. (16.00 p.m. to 18.00 p.m.)

4.2.2.1. Comparing the data on Average Air Temperature (C°) .



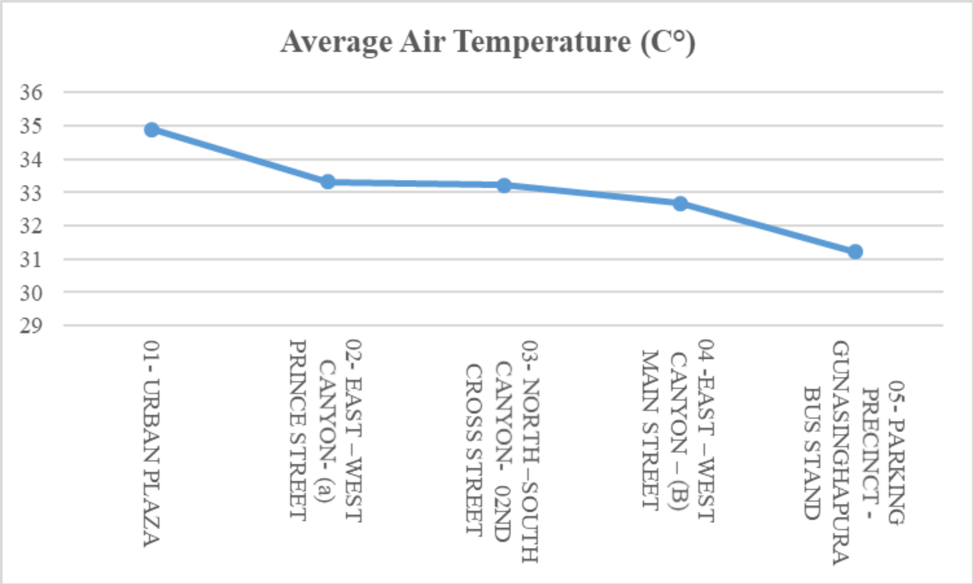


Figure 73: Average Air Temperature from 16.00 p.m. to 18.00 p.m. for all Five locations.

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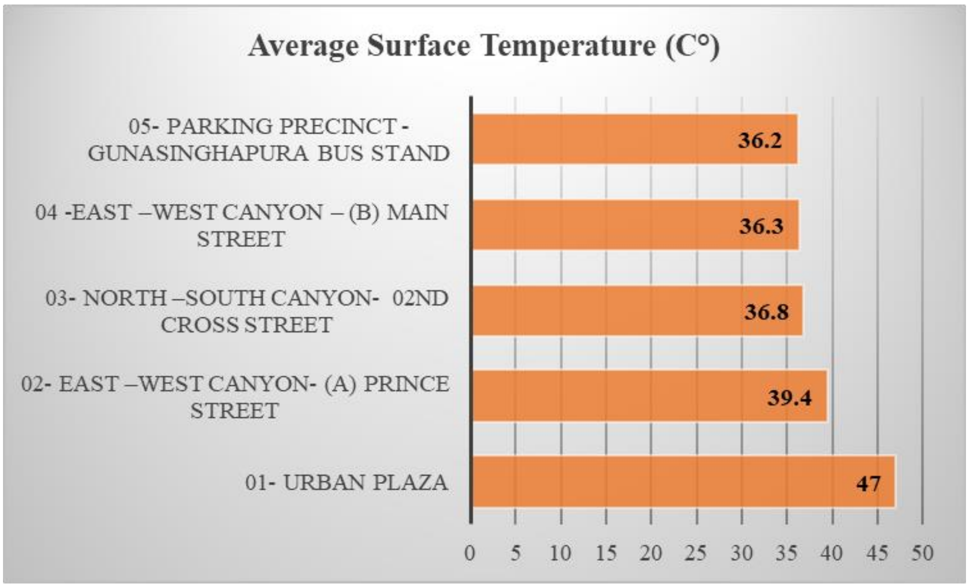
Source: Author

- According to the measured data, the highest Air Temperature observed from the location 01 - Urban Plaza at the Session 02 – time 16.00 p.m. to 18.00 p.m.
- The lowest Air temperature was observed from the Location 05- Parking Precinct- Gunasinghapura bus stand.
- Although there should have an impact of sea breeze to the North - South canyons most of the canyons were physically obstructed from the physical man-made barriers such as buildings, parapet wall etc. In theoretically the Air temperature in the Location 03 – North South canyon – 02nd Cross Street should be Lower than East –West canyons. But it was observed that the Air temperature is higher at the Location 03 – North-South Canyon – 02nd Cross Street comparatively two Numbers of East – West canyons at the Location 02 and the Location 04.

4.2.2.2 Comparing the data on Average Surface Temperature (C°).



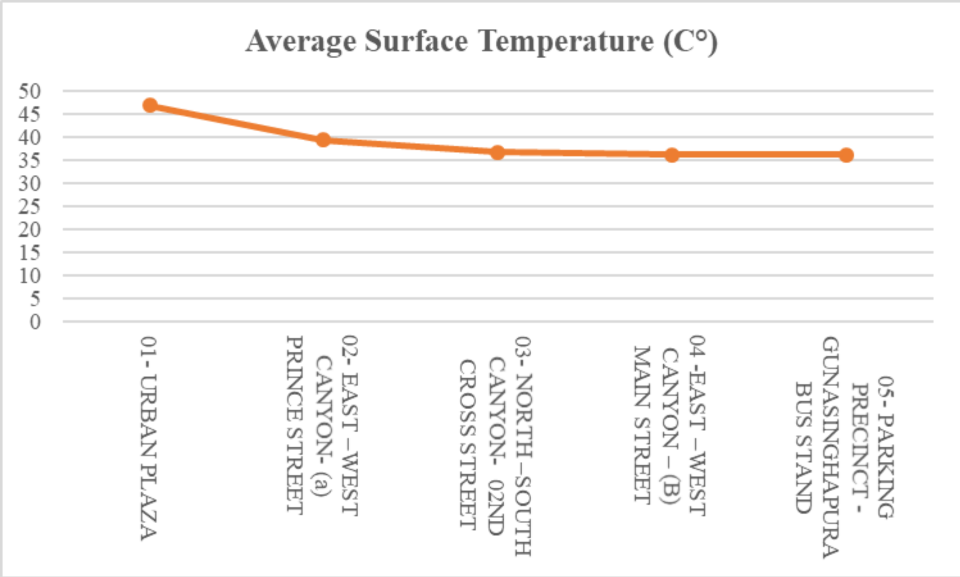


Figure 74: Average Surface Temperature from 16.00 p.m. to 18.00 p.m. for all Five locations.

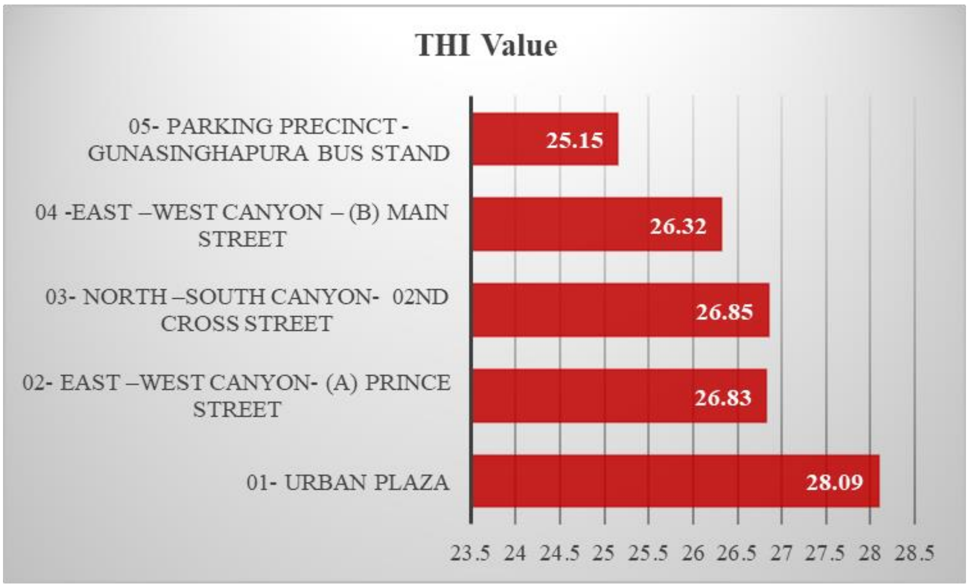
Source: Author

- According to the measured data, the highest Surface Temperature can be observed from the Location 01 – Urban Plaza at the evening session. (Session 02- 16.00 p.m. to 18.00 p.m.)

- The lowest Surface Temperature shows from the Location 05 - Parking Precinct- Gunasinghapura Bus Stand.

4.2.2.3 Comparing Thermal Heat Index (THI) of selected locations.

Analyzing of THI values from 16.00 p.m. to 18.00 p.m.



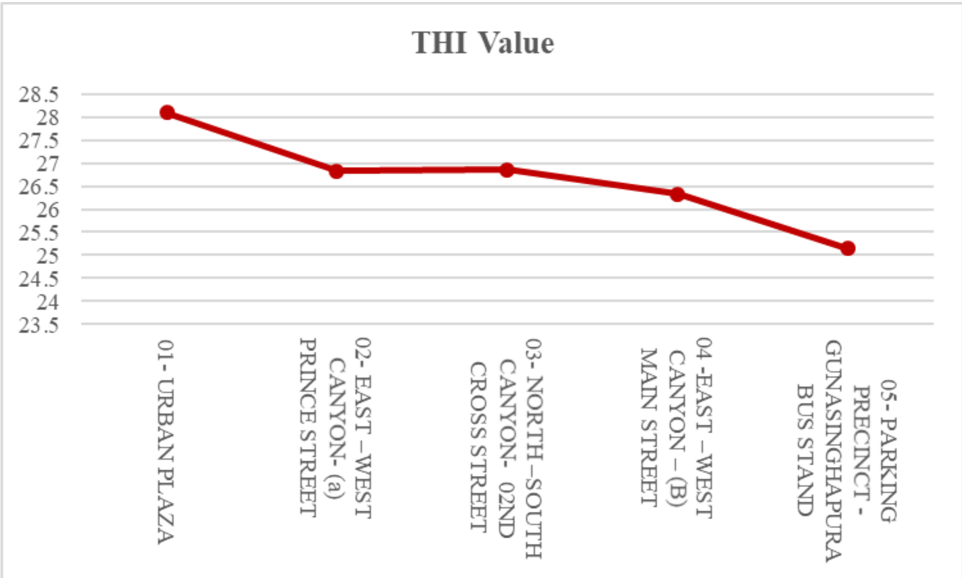


Figure 75: Calculated THI values from 16.00 p.m. to 18.00 p.m. for all Five locations.

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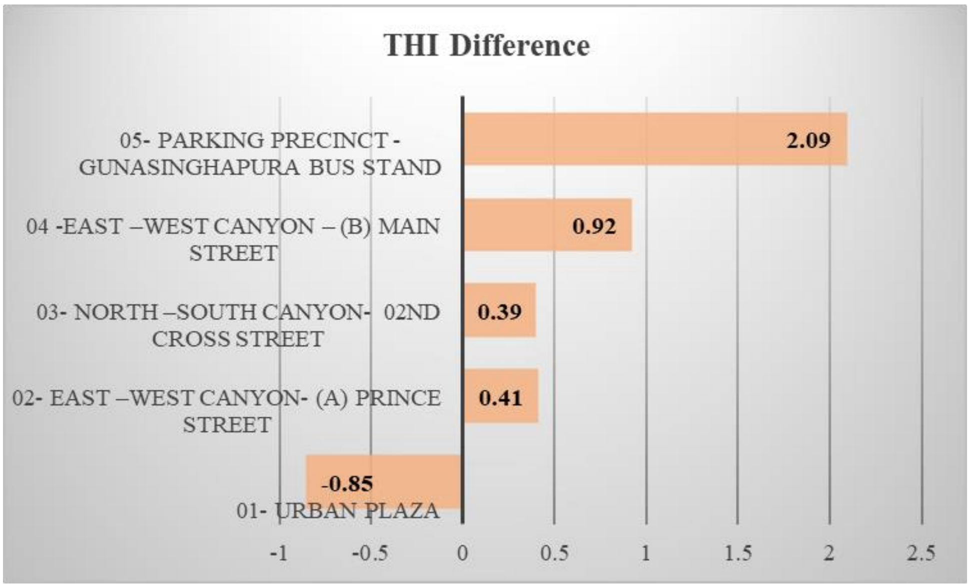
Source: Author

- According to the calculated THI values, the highest THI value is shown from the Location 01- Urban Plaza.
- The lowest THI value is shown from the Location 05 - Parking Precinct- Gunasinghapura Bus Stand.
- According to the results it was observed that all the THI vales were more than 26 for Location 01 to Location 04.
- But at the Location 05 - Parking Precinct Gunasinghapura Bus Stand observed that the THI value is Lower than 26 and it's in the comfortable level range 24<THI≤26 - 50% of the subjects feel comfortable.

4.2.2.4 Comparing the THI Difference of selected Locations.



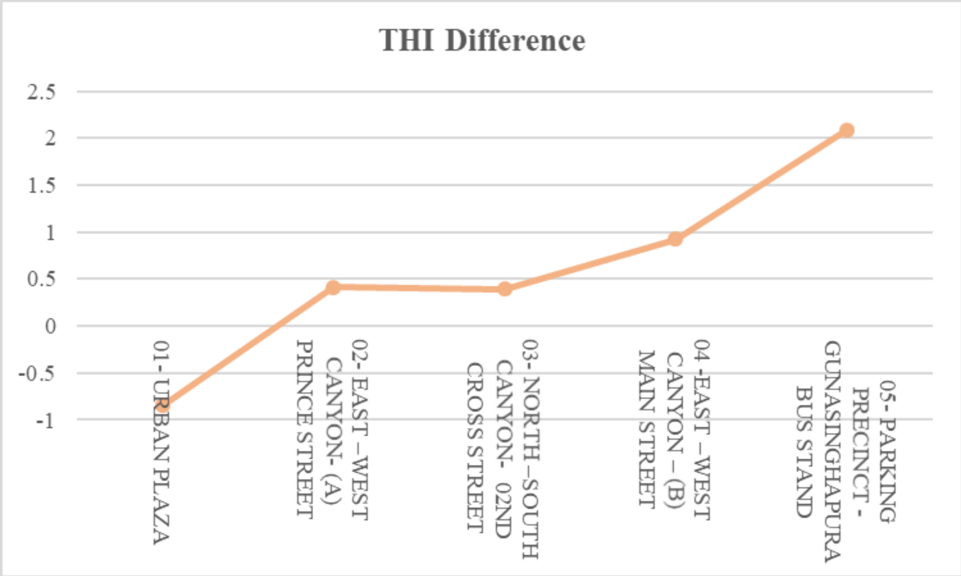


Figure 76: Calculated THI Difference from 16.00 p.m. to 18.00 p.m. for all Five locations.

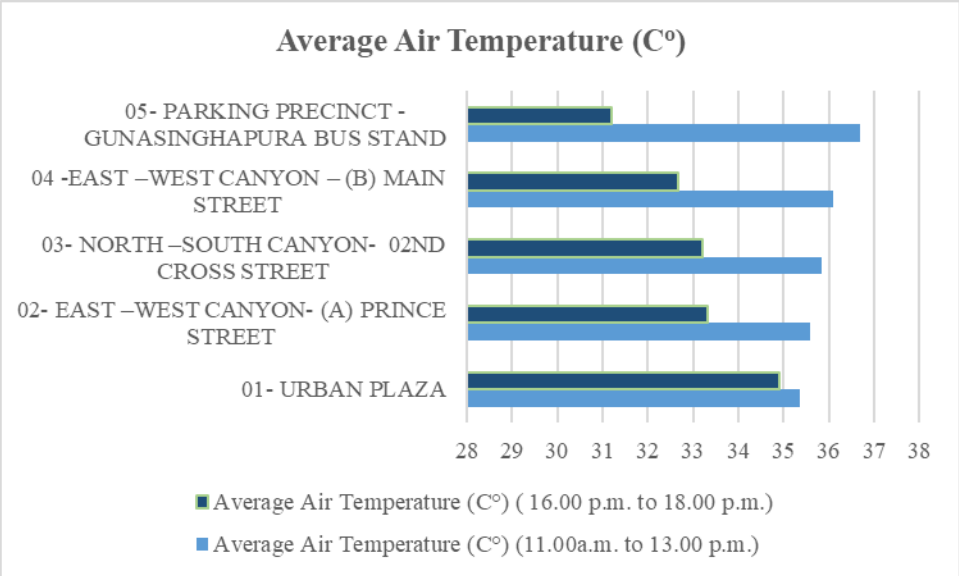
Source: Author

- According to the results, the highest THI difference shows from the Location 05- Parking Precinct- Gunasinghapura Bus Stand, comparing with the Reference point located in the Charmer’s Granary Land in the same area.

- The lowest THI difference shown from the Location 01- Urban Plaza comparing with the Reference point located in the Charmer’s Granary Land in the same area.

4.2.3. Comparing the Thermal comfort levels of noon time (Session 01-11.00 a.m. to 13.00 p.m.) and Evening time (Session 02-16.00 p.m. to 18.00 p.m.)

4.2.3.1. Comparison of Average Air Temperature.



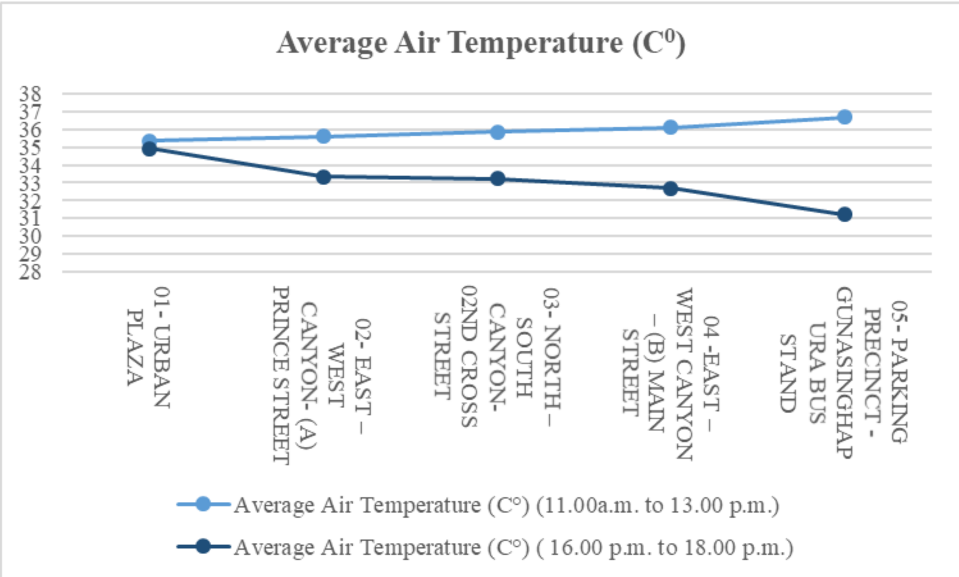


Figure 77: Average Surface Temperature for both Sessions for all Five Locations.

Source: Author

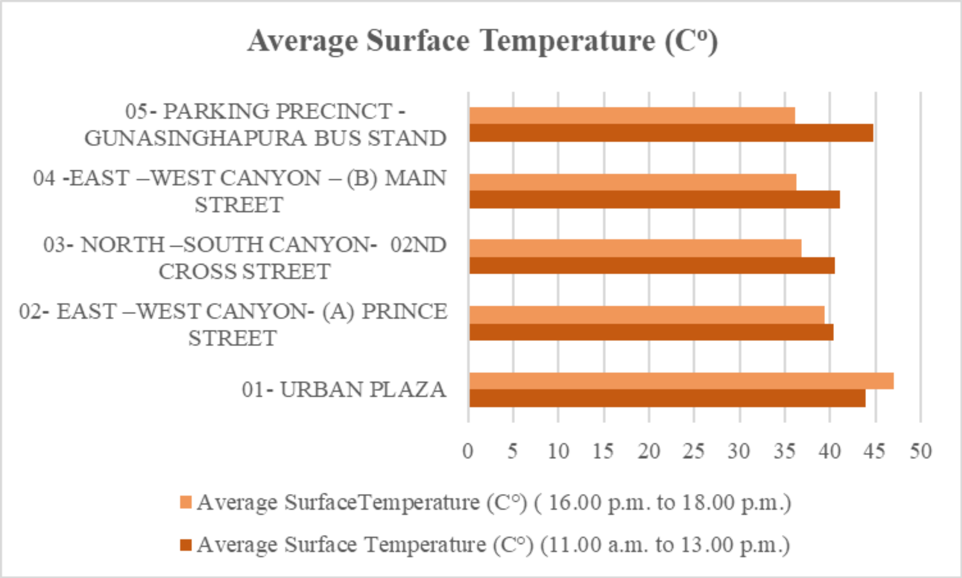
- Comparing the average Air Temperature on Two sessions (at time 11.a.m. to 13.00 p.m. / Morning Session and the time 16.00 p.m. to 18.00 p.m./ Evening sessions) it was observed that the Session 01 (Morning Session) has shown the highest Average Air Temperature. At the Evening Sessions shows the lowest Average Air Temperature comparatively.

- Location 04- East-West Canyon- (B) Main Street, observed a higher Average Air Temperature than the Location 03- North South Canyon- 02nd Cross Street at the time of 11.00 a.m. to 13.00 p.m.

- Location 04- East-West Canyon- (B) Main Street, observed a higher Average Air temperature than the Location 02- East –West Canyon –(A) Prince Street at the time of 11.00 a.m. to 13.00 p.m.

- At Evening session, the time 16.00 p.m. to 18.00 p.m. the Average Air temperature is higher in Location 02 – East West Canyon (A) Prince Street than the Location 04- East-West Canyon- (B) Main Street. Comparing Three Canyons the highest Average Air Temperature observed at the Location 03 - North South Canyon- 02nd Cross Street.

4.2.3.2. Comparison of Average Surface Temperature.



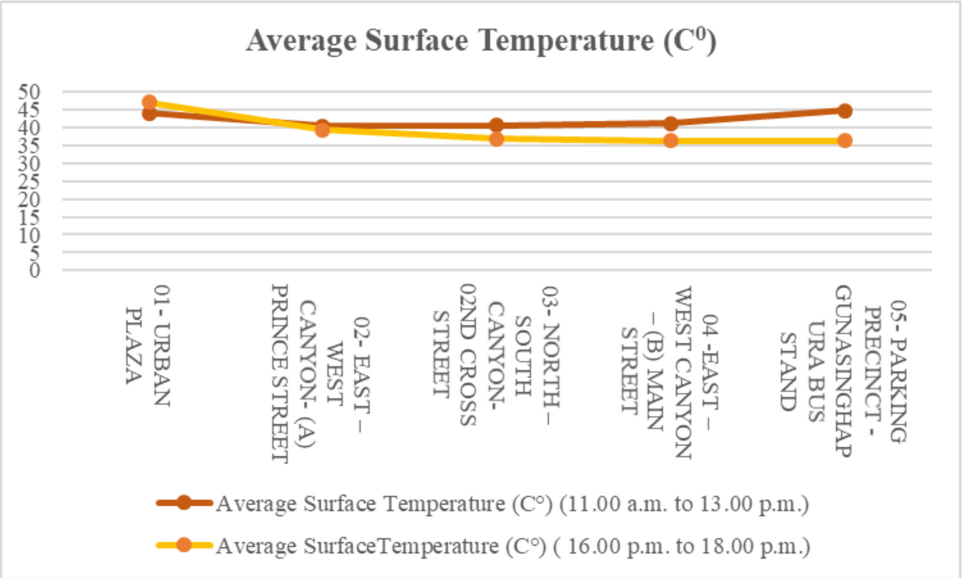
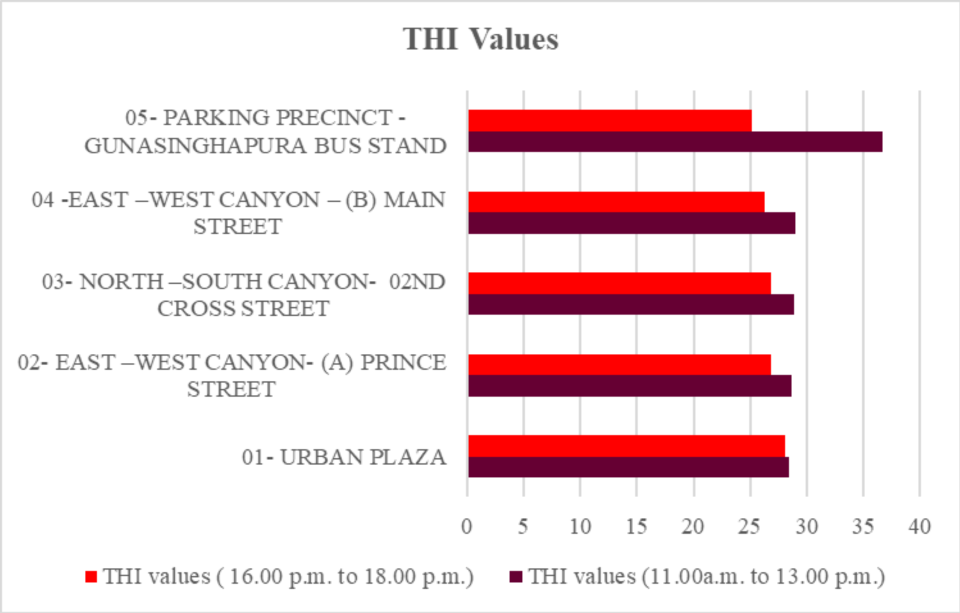


Figure 78: Average Surface Temperature for both Sessions for all Five Locations.

Source: Author

- Comparing all empirical data, it was observed that the Surface Temperature for all locations at the evening session is lower than except Location 01- Urban Plaza.
- The Location 05- Parking Precinct indicated the highest average surface temperature at the Morning session, the time of 11.00 a.m. to 13.00 p.m.

4.2.3.3. Comparison of Thermal Heat Index (THI) values.



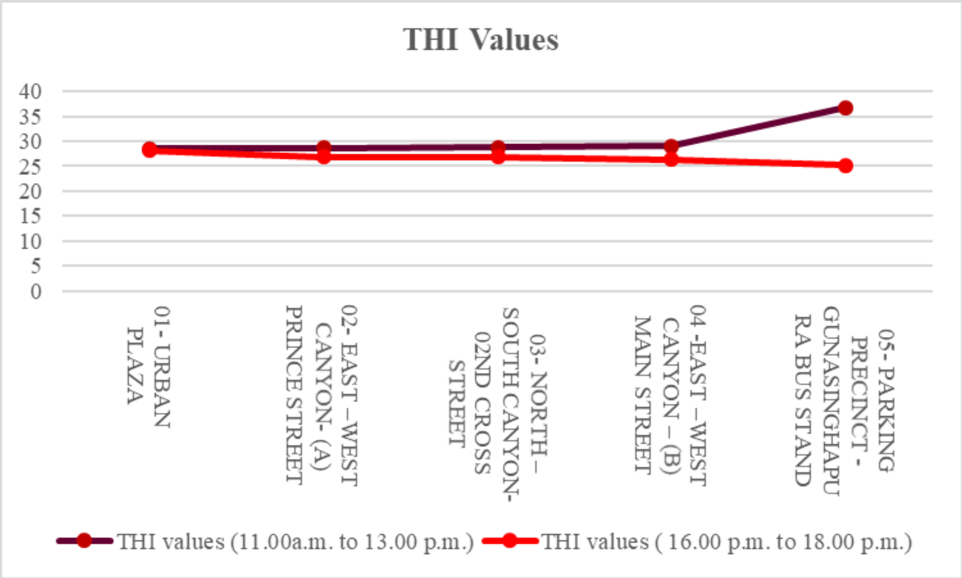


Figure 79: Average THI values for both Sessions for all Five Locations

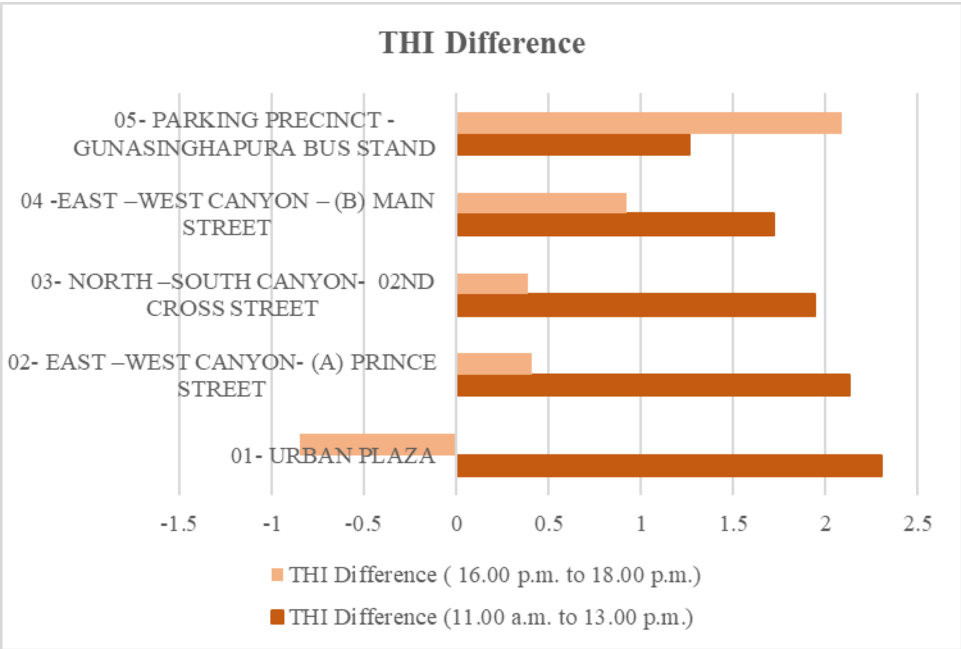
Source: Author

- According to the data it was observed the Thermal Heat Index (THI) at the time 11.00 a.m. to 13.00 p.m.is higher than the measured time 16.00 p.m. to 18.00 p.m.

- All THI values were over than the 26 which is considered as the 100% subject feel uncomfortable according to the comfort levels relevant to the Tropical countries at the time 11.00 a.m. to 13.00 p.m.

- The Location 05- Parking Precinct – Gunasinghapura Bus Stand shows the THI value as 25.15 at the time of 16.00 p.m. to 18.00 p.m. This value is in the limits of $24<THI\leq 26$ which is 50% of the subjects feel comfortable.

4.2.3.4. Comparison of Thermal Heat Index Difference (THI Difference)



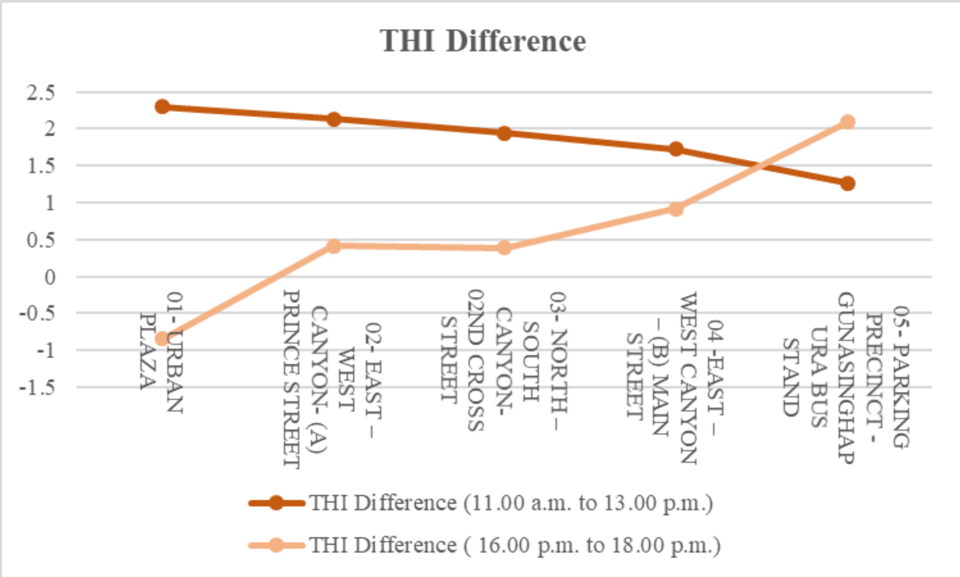


Figure 80: THI Difference for both Sessions for all Five Locations

Source: Author

- According to the data it was observed the Thermal Heat Index Difference (THI Difference) at the time 11.00 a.m. to 13.00 p.m.is higher comparing with the Reference point.

- The Location 01 – Urban plaza shows the THI Difference as – 0.85 comparing with the Reference point at the time 16.00 p.m. to 18.00 p.m.

4.3 Computer Simulation Using with Numerical Modelling ENVI-met 4.0.

Base case Scenarios were modeled and simulated using the ENVI-met 4.0 urban simulation software to analyze of Air temperature, to analyze of mean Radiant Temperature (MRT), to analyze of Physiological Equivalent Temperature (PET) and to analyze of Predicted Mean Vote (PMV) and remodeled to assess the degree of effectiveness of different planned interventions to improve the thermal comfort levels at the five selected locations.

4.3.1. Air Temperature Analysis

4.3.1.1 Air Temperature Analyze for Existing Locations. (Base Cases)

Simulated Air temperature were analyzed at the time 0f 13:00:01h for the Day time and the 21:00:01h as the Night Time of existing site conditions on selected different five numbers of built forms to compare with the modifications.

a.) Simulated Air temperature on ,L1-Location 01-An Urban Plaza

- <u>At Day Time, 13:00:01h</u>

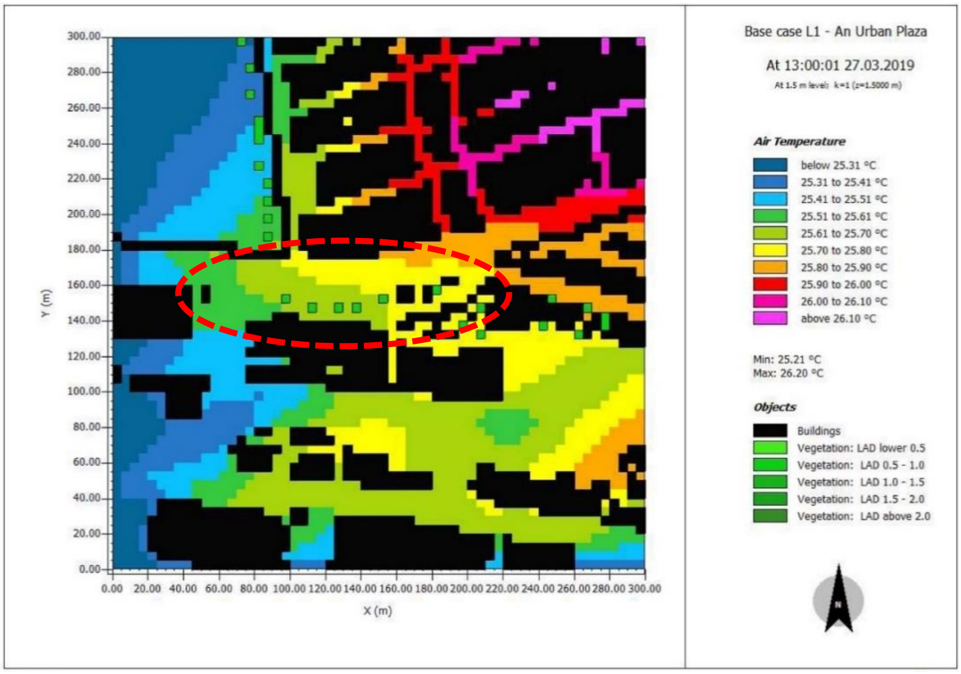


Figure 81: Simulated Air temperature map on ,L1-Location 01-An Urban Plaza At Day Time, 13:00:01h.

Source: Author

- The Simulated Air Temperature for the location 01 varied between 25.51C^0 to 25.80 C^0 at the Day time, 13:00:01 as shown in the Figure 81.

  - <u>At Night Time, 21;00:01h</u>

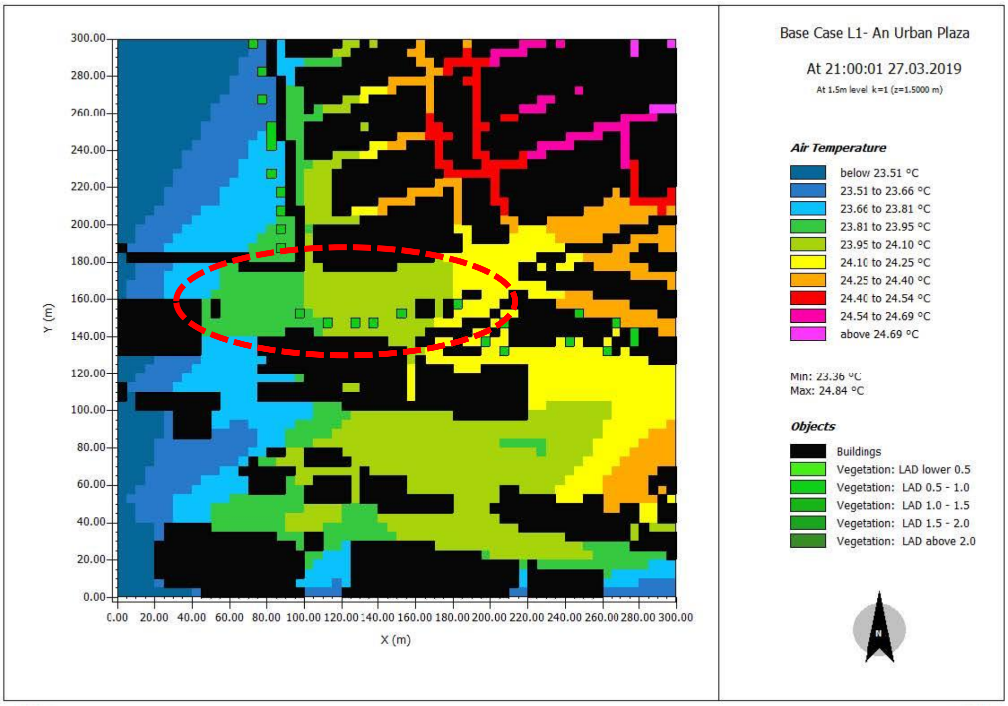


Figure 82: Simulated Air temperature map on ,L1-Location 01-An Urban Plaza at Night-time, 21:00:01h
Source: Author

- The Simulated Air Temperature for the location 01 – An Urban Plaza varied between 23.81C^0 to 24.10 C^0 at the Night time, 21:00:01h as shown in the Figure 82.

- Considering the Day time and the Night time, Air Temperature at the Day time for the Base Case, Location 01 – Urban Plaza is higher than the Night Time.

b.) Simulated Air temperature on L2 and L3 – Location 02- East West Canyon –(A) Prince Street and Location 03-North South Canyon – 02nd Cross Street.

<u>- At Day Time, 13:00:01 h</u>

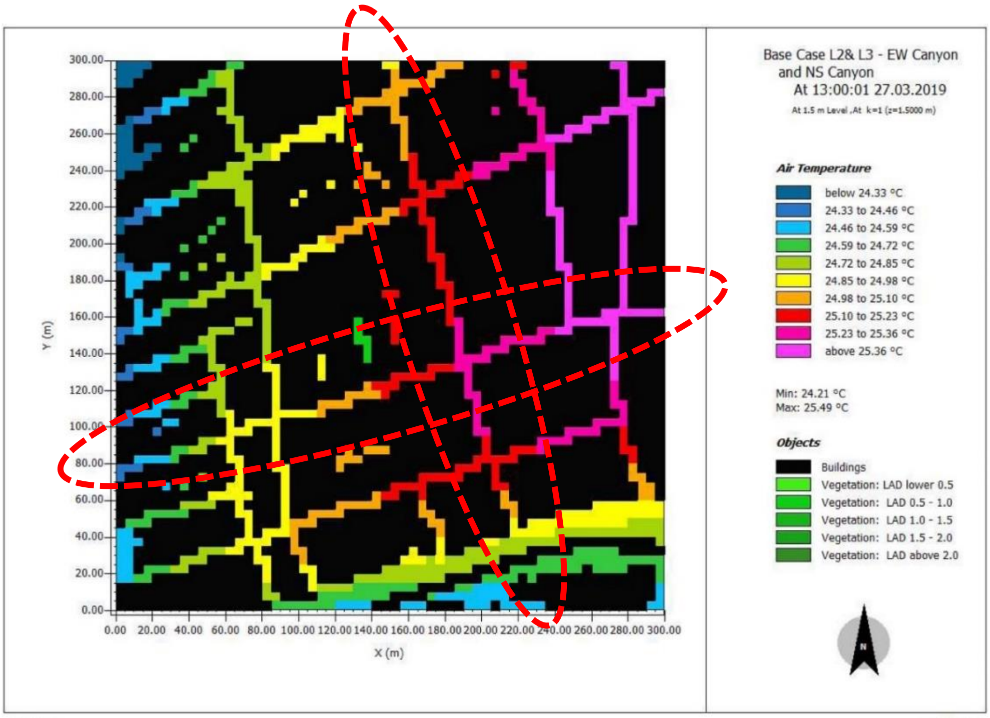


Figure 83: Simulated Air temperature map on, L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street at the Day-time, 13:00:01h

Source: Author

- The Simulated Air Temperature for the Location 02 – East West Canyon – (A) Prince Street varied between 24.98 C^0 to 25.10 C^0 at the Day time.
- The Simulated Air temperature for the Location 03 –North South Canyon – 02nd Cross varied between the value of 25.10C^0 to 25.36 C^0 at the Day time, 13:00:01h as shown in the Figure 83.
- When comparing the both locations the Location 02 indicated the lowest temperature than the Location 03 for the existing scenarios at the Day time.

- <u>At Night Time,21:00:01h</u>

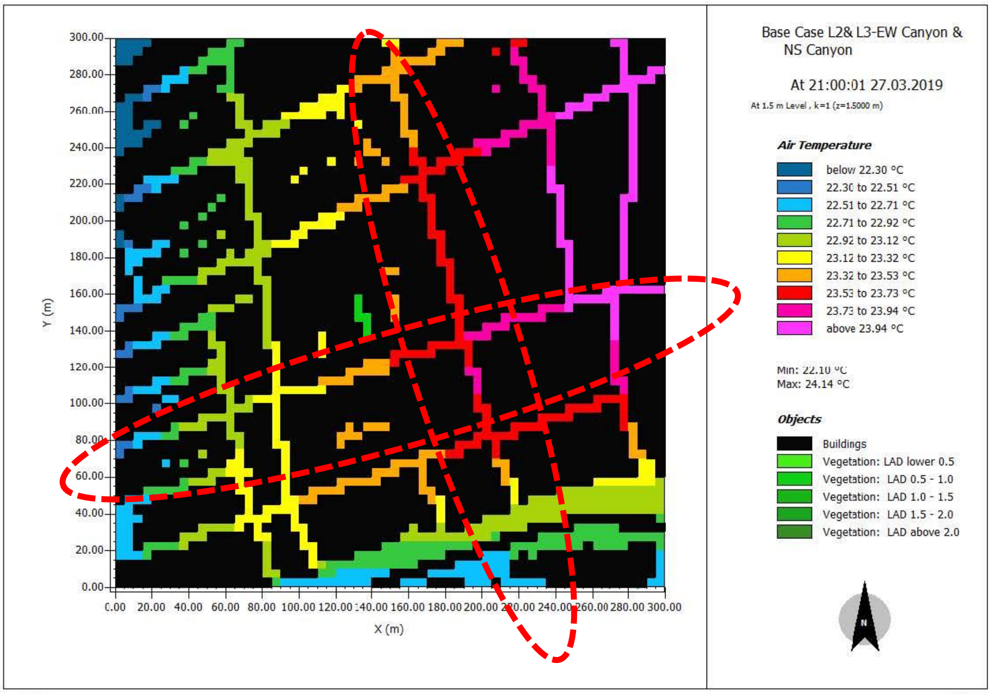


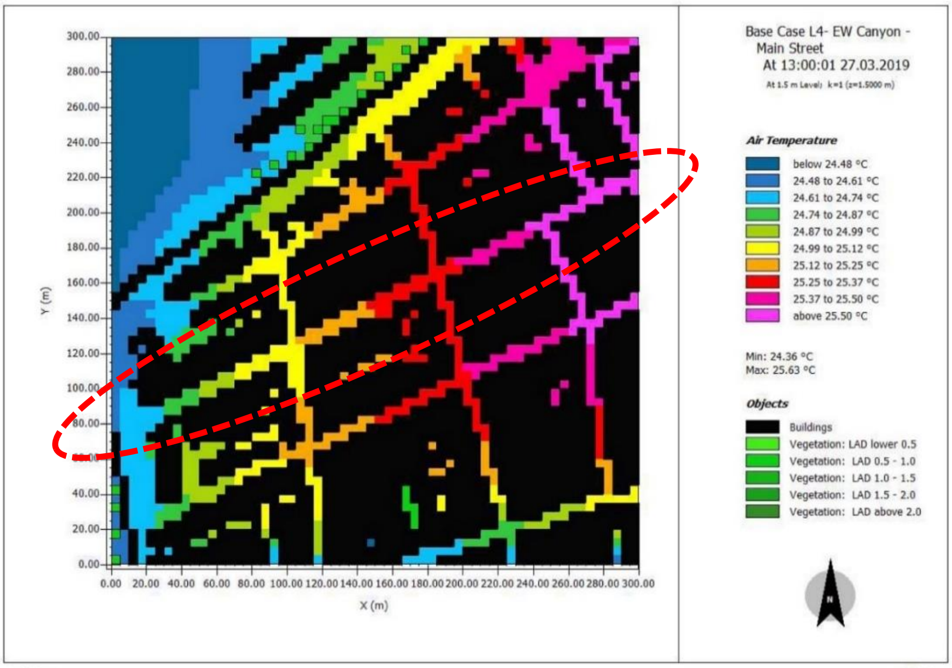
Figure 84: Simulated Air temperature map on, L2 and L3 – Location 02- EW Canyon – (A) Prince Street and Location 03-NS Canyon – 02nd Cross Street at Night-time, 21:00:01h.

Source: Author

- The Simulated Air Temperature for the Location 02 – East West Canyon – (A) Prince Street varied between 23.32 C^0 to 23.53 C^0 at the Night time.
- The Simulated Air temperature for the Location 03 –North South Canyon – 02nd Cross street, varied between the value of 23.53C^0 to 23.73 C^0 at the Night time, 21:00:01 as shown in the Figure 84.
- When comparing the both locations the difference of the air temperature for the Night time is very less.

c.) Simulated Air Temperature on, L4 – Location 04 – EW Canyon - Main Street.

i.) At Day Time, 13:00:01h



ii.) At Night Time, 21:00:01h

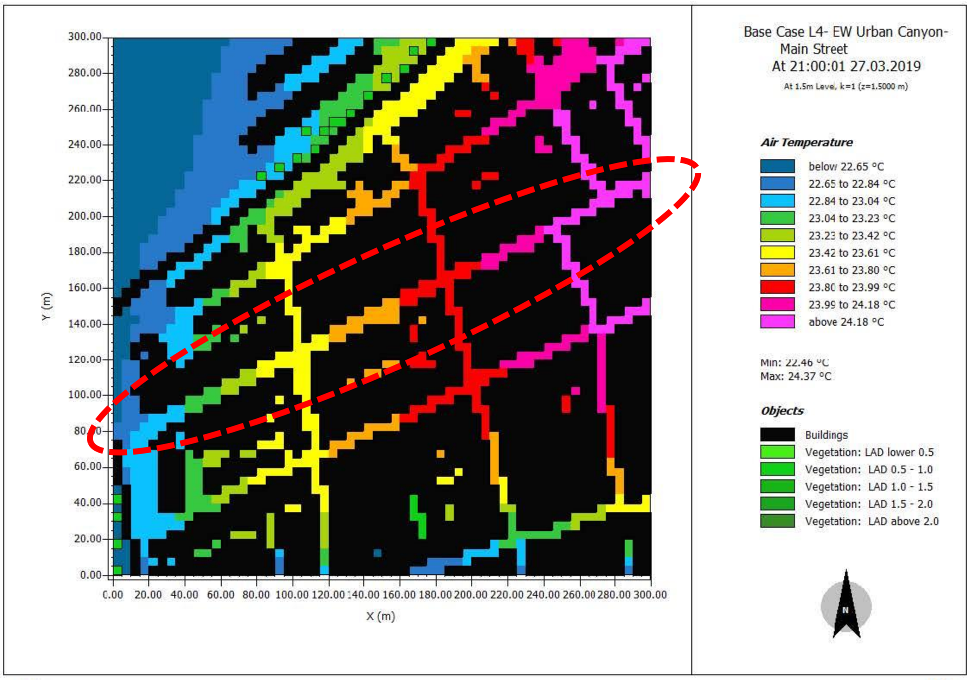


Figure 85: Simulated Air temperature map on, L4 – Location 04- EW Canyon –Main Street at i.) Day-time,13:00:01h and ii.) Night time, 21:00:01h

Source: Author

- The Simulated Air Temperature for the Location 04 – East West Canyon –Main Street varied between 25.25 C^0 to 25.37 C^0 at the Day time as shown in Figure 85 (i).
- At the Night time the simulated Air temperature is in between 23.61 C^0 to 23.80 C^0 .
- Night time Air Temperature is less than the Day time temperature as shown in Figure 85 (ii).

d.) Simulated Air Temperature on, L5- Location 05 – A Parking Precinct.

<u>- At Day Time. 13:00:01h</u>

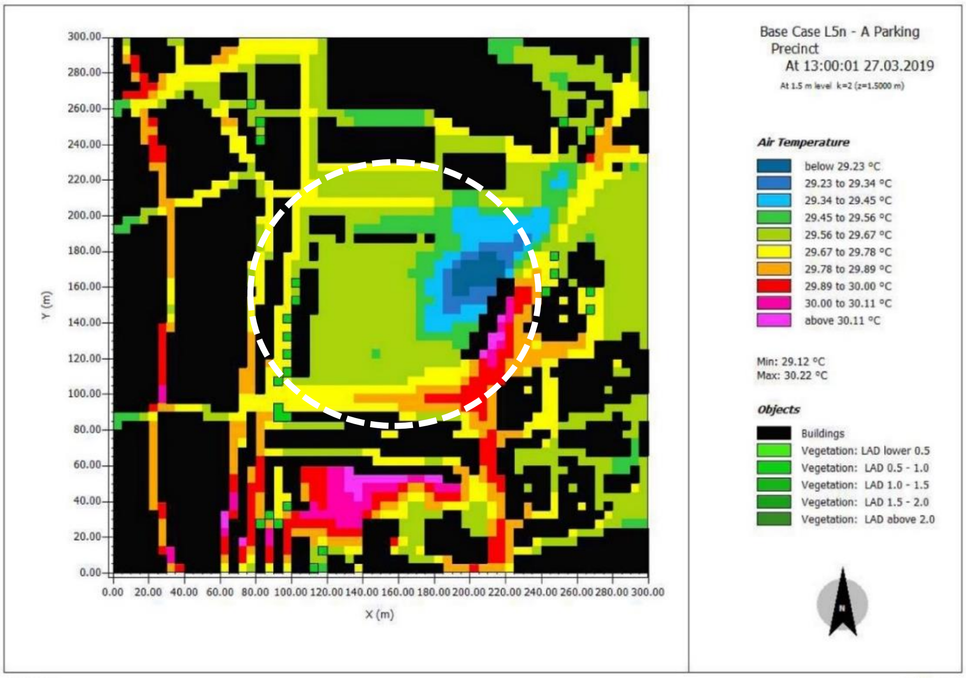


Figure 86: Simulated Air temperature map on, L5– Location 05- A Parking Precinct at Day-time, 13:00:01h.

Source: Author

- The Simulated Air Temperature for the Location 05 – A Parking Precinct varied between 29.56 C^0 to 29.67 C^0.at the Day time.

- <u>At Night Time 21:00:01h</u>

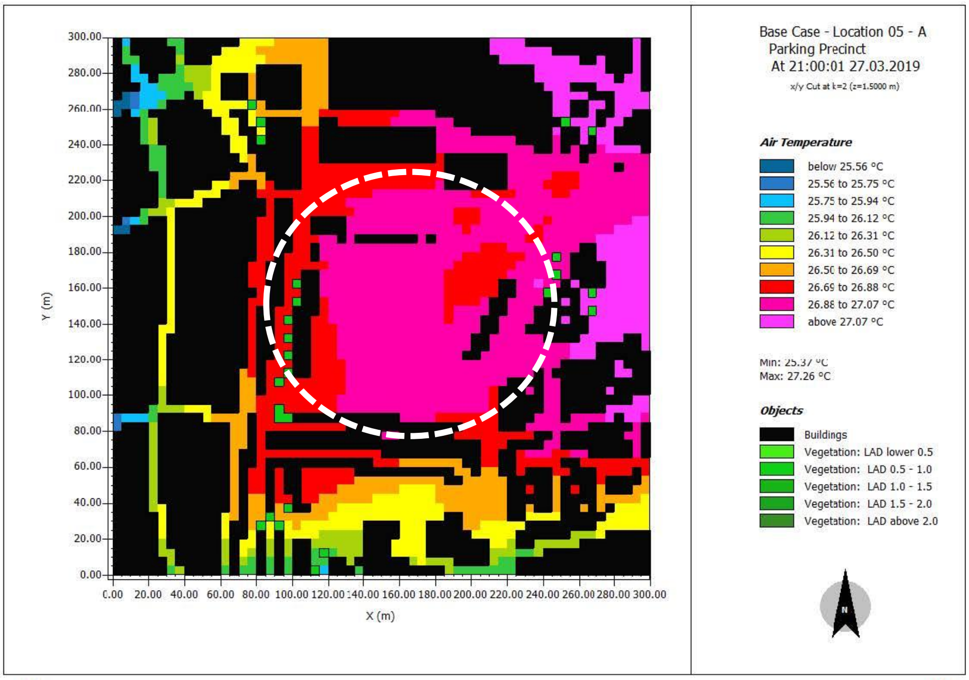


Figure 87 : Simulated Air temperature map on, L5– Location 05- A Parking Precinct at Night-time, 21:00:01h

Source: Author

- At the Night time, the Simulated Air Temperature for the Location 05 – A Parking Precinct is above 27.07 C^{0}.

- Night time Air temperature is lower than the Day time Air Temperature as shown in the Figure 86 and the Figure 87.

4.3.1.2. Air Temperature Analysis for Envisaged Scenarios.

Different Following Scenarios were modeled and simulated using the ENVI-met 4.1 urban simulation software to Analyze of Air Temperature, to Analyze of Mean Radiant Temperature (MRT), and to Analyze of Predicted Mean Vote (PMV) with the existing scenario at all different five locations.

01. Changing of Building Heights (Case 01, Case 02, Case 03, Case 04)

Analyzing simulated Air Temperature by increasing Building Heights of all different Built forms dated on 27.03.2019 at 13:00:01h at the level 0f 1.5m for the Day Time as well as for the Night time as previously discussed in Chapter Three.

Building heights were categorized according to the Urban Development Authority Guide Lines. (Appendix I – 'C' Form of City of Colombo Development Plan, UDA)

Data were analyzed with considering the Air Temperature on relevant Receptor point of each location.

- <u>Day Time, 13:00:01h</u>

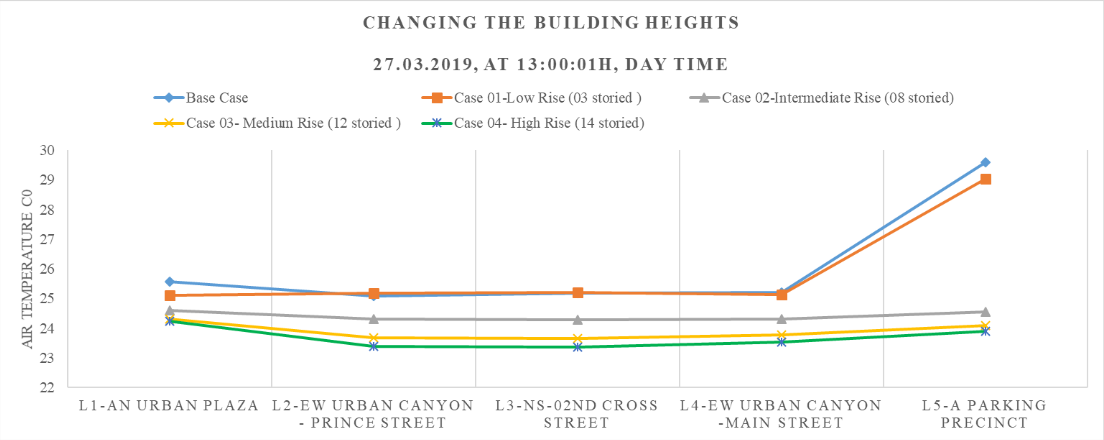


Figure 88 : Analysis of simulated Air Temperature by changing Building Heights of all different Built forms dated on 27.03.2019 at 13:00:01h – Day Time.

Source: Author

- According to the Figure 88 and Appendix II, it was clearly identified the behavior of simulated Air temperature when increasing the building heights for all selected locations at the day time.
- The Lowest Air temperature was observed in the case 04 of High Rise with 14 storied height scenario for all Locations.
- The heights Air temperature was indicated from the case 01, Low Rise scenario with 03 storied building height.
- Further Location 02, East West canyon (Prince Street) and Location 03, North south Canyon (02nd Cross Street) were observed that the lowest Air temperature for all scenarios in increasing of building heights.
- Therefore, the Increasing of building height for Urban Canyons can suggests a mitigation option to achieve a lowest Air temperature at the day time.

\- <u>Night Time, 21:00:01h</u>

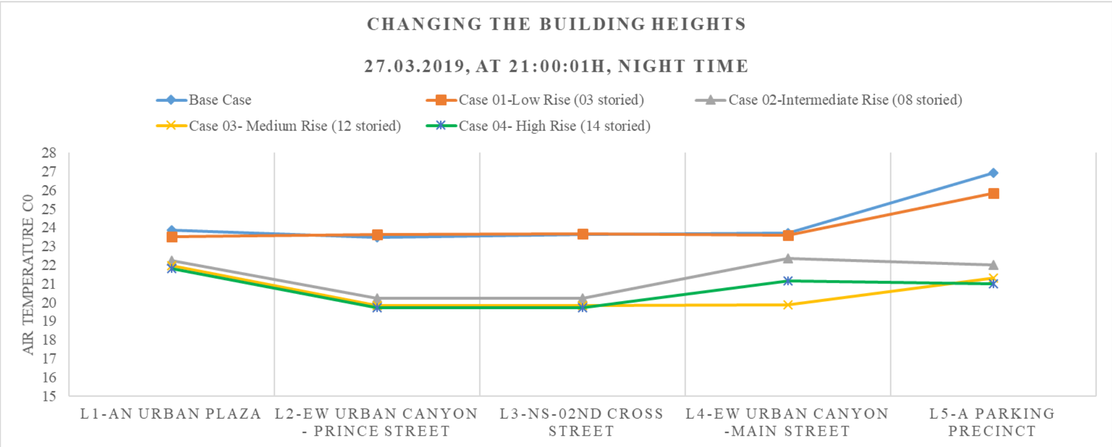


Figure 89: Analysis of simulated Air Temperature by changing Building Heights of all different Built forms dated on 27.03.2019 at 21:00:01h – Night Time

Source: Author

- According to the Figure 89, Night time Air temperature also decreased when increasing the building heights for each location.
- The Lowest Air temperature was observed in the case 03- East West Urban Canyon.

02. Green Scenario (Case 05)

a.) Increasing existing Tree canopy width two times from the existing tree canopy in Location 01- An Urban Plaza.

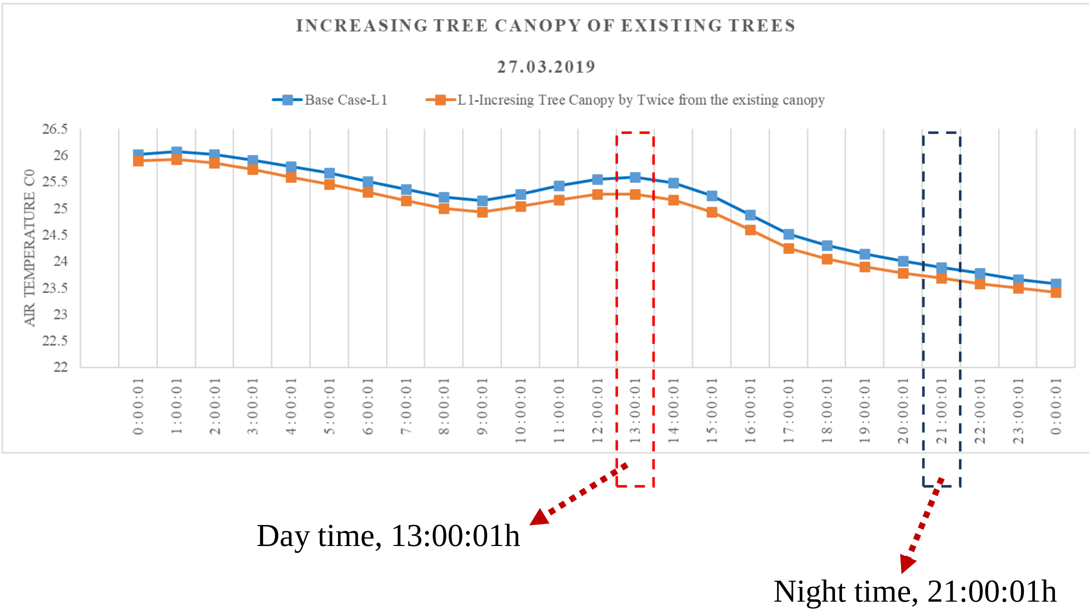


Figure 90: Case 05 – Green – Increasing existing Tree Canopy width two times for the Location 01 – An Urban Plaza

Source: Author

- According to the Figure 90, both Day time and the Night time simulated Air temperature for the case 05 – Green – Increasing Tree canopy width in two times scenario were decreased comparing with the Existing scenario.

- The simulated Air temperature of the day time is higher than the Night time at the Location 01- An Urban Plaza as shown in the Figure 90.

b.) Increasing existing Tree canopy width two times from the existing tree canopy in Location 05- A Parking Precinct.

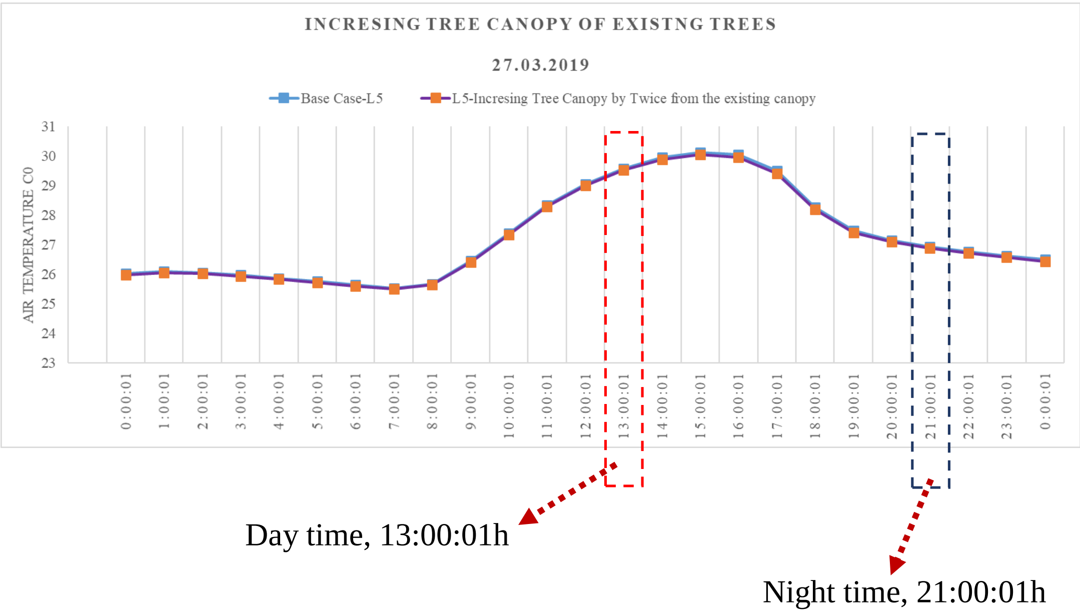
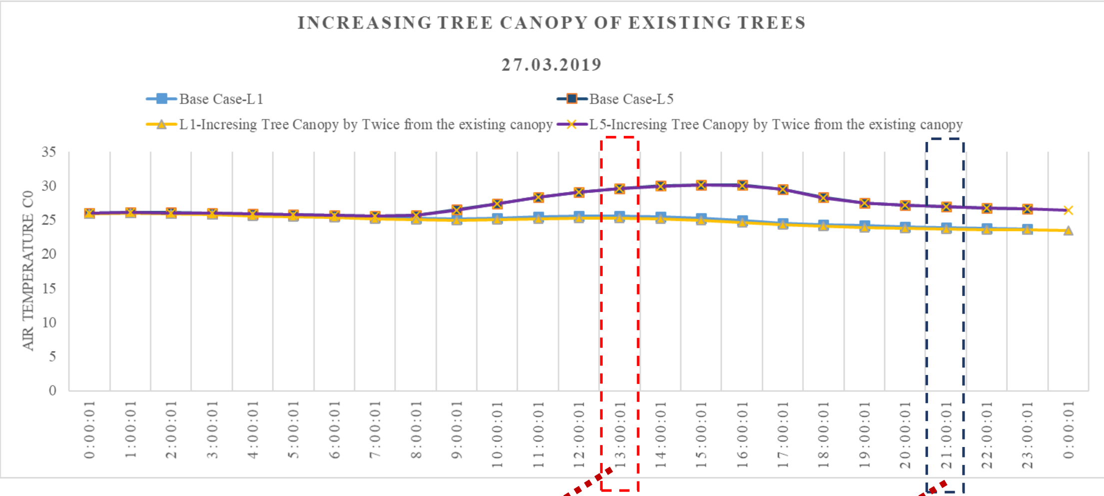


Figure 91: Case 05 – Green – Increasing existing Tree Canopy width by twice for the Location 05 – A Parking Precinct.

Source: Author

- According to the Figure 91, both Day time and the Night time simulated Air temperature for the case 05 – Green – Increasing Tree canopy width in two times scenario done for the Location 05 – a parking Precinct were slightly decreased comparing with the Existing scenario.
- The simulated Air temperature of the day time is higher than the Night time at the Location 05- A Parking precinct.
- As per the Figure 92, the simulated Air temperature on Location 01 and Location 05 were decreased comparing with their existing scenarios.
- Hence there have a considerable effect when increasing existing Tree canopy width case which carried out under the Green scenario.

<u>Comparison of impact of Increasing Tree canopy width in two times of existing trees for the L1- Location 01- An Urban Plaza and L5- Location 05- A Parking Precinct</u>

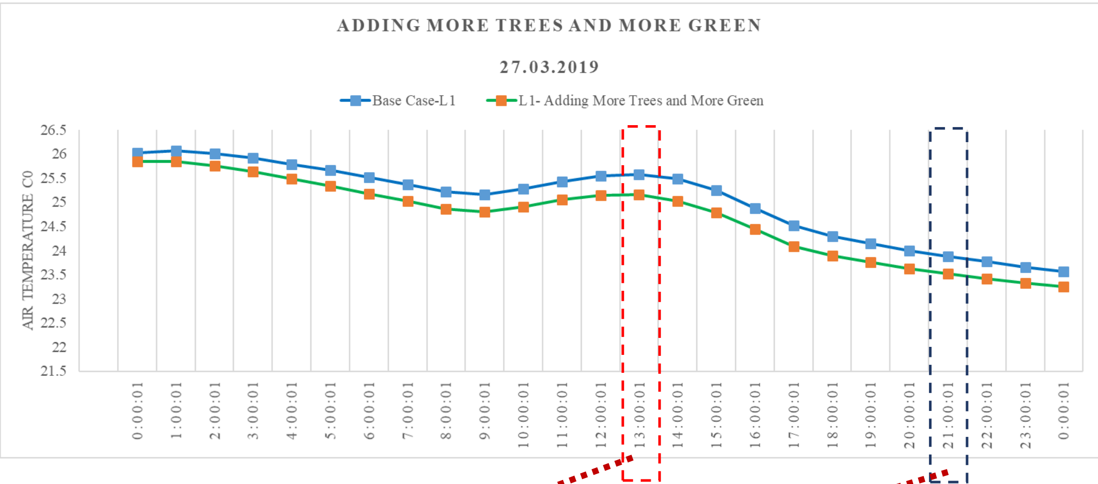


Day time, 13:00:01h　　　　Night time, 21:00:01h

Figure 92: Case 05 – Green – Increasing existing Tree Canopy by twice for the both Location 01 and Location 05

Source: Author

c.) Adding More Trees and More Green for the Location 01- An Urban Plaza



Day time, 13:00:01h　　　　Night time, 21:00:01h

Figure 93: Case 05 – Green – Adding More Trees and More green for the Location 01- An Urban Plaza

Source: Author

d.) Adding More Trees and More Green for the Location 05- A Parking Precinct.

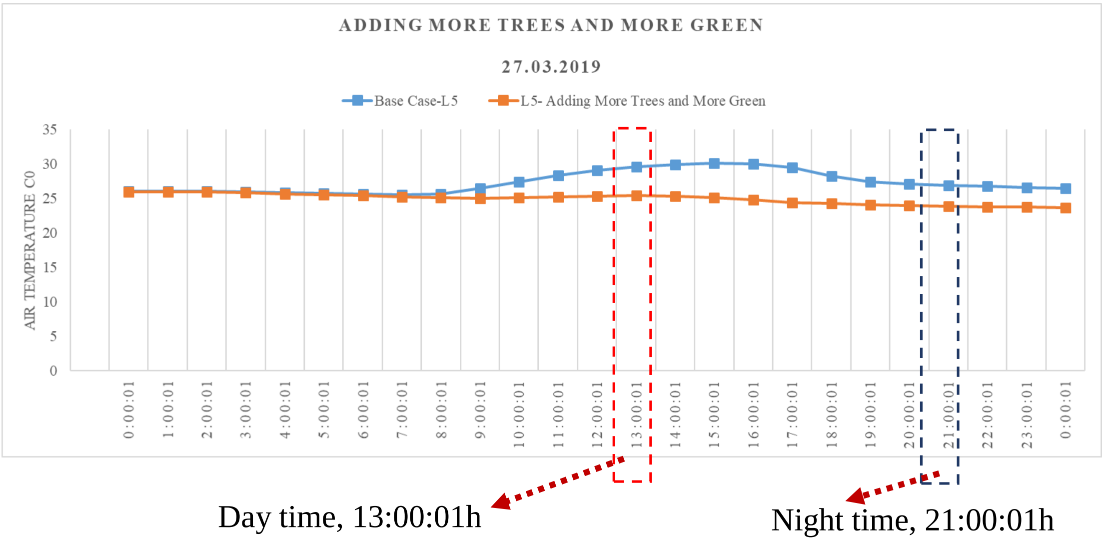


Figure 94: Case 05 – Green – Adding More Trees and More Green for the Location 05- A Parking Precinct

Source: Author

<u>Comparison of impact of Adding Trees and More Green for the L1- Location 01- An Urban Plaza and L5- Location 05- A Parking Precinct.</u>

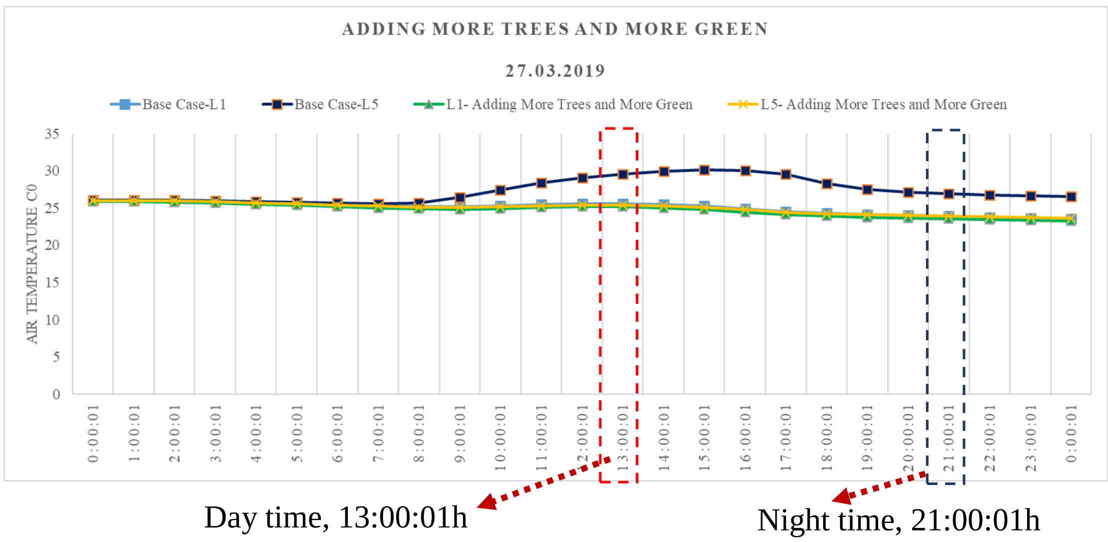


Figure 95: Case 05 – Green – Adding More Trees and More green for the Location 01- An Urban Plaza and the Location 05- A Parking Precinct

Source: Author

- According to the Figure 93, both Day time and the Night time simulated Air temperature for the case 05 – Green – Adding More Trees and More Green scenarios for the Location 01 of an Urban Plaza were decreased comparing with its Existing scenario.
- The simulated Air temperature of the day time is higher than the Night time at the Location 01- An Urban Plaza
- As per the Figure 94, at the Location 05 – A Parking Precinct the simulated Air Temperature is slightly less than the existing scenario.
- According to the Figure 95, Adding More Trees and More Green scenario is most effective for the Location 05, A parking Precinct.

e.) Adding a Tree Line for the L4- Location 04 - Along the Main Street.

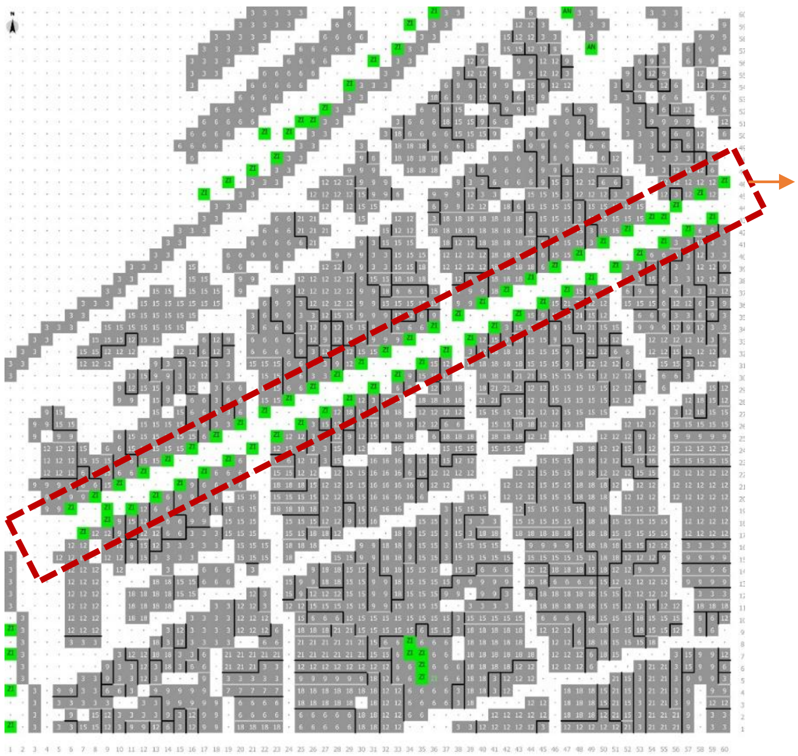


Figure 96: Case 05 – Green – Adding a Tree Line for the both sides of Location 04 – Along the main Street.

Source: Author

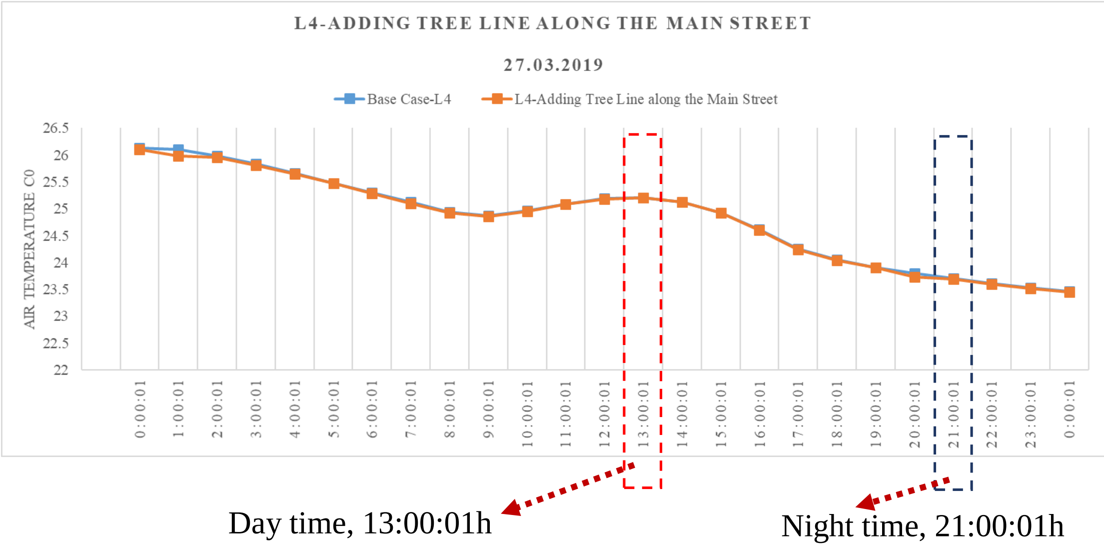


Figure 97: Case 05 – Green – Adding Tree Line for the both sides of Location 04 – Along the main Street.

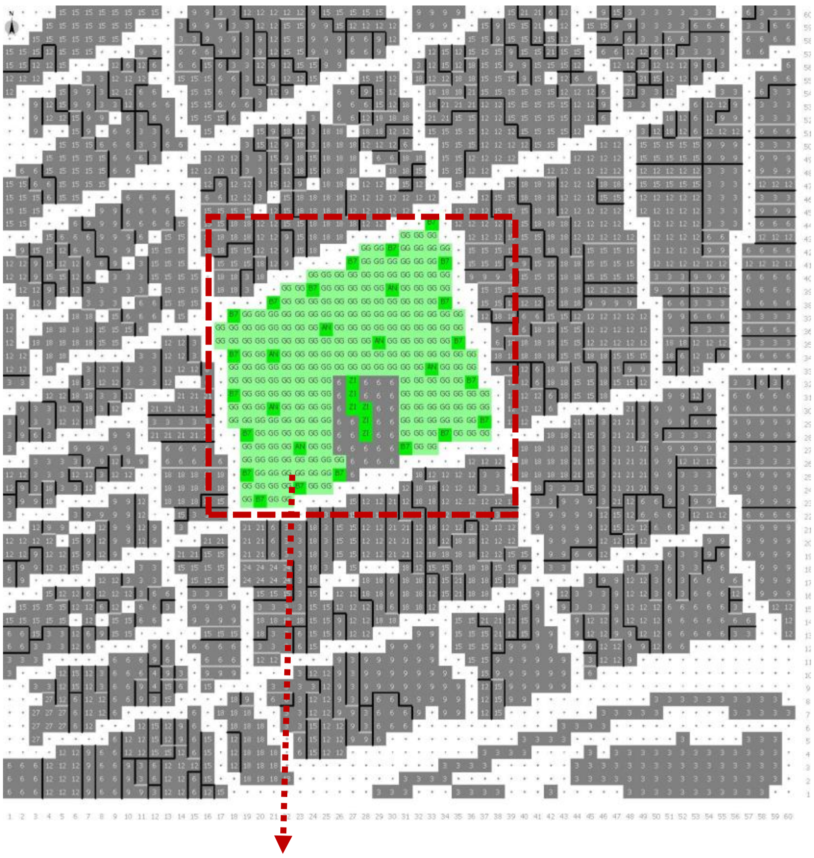
Source: Author

- According to the Figure 97, both Day time and the Night time simulated Air temperature for the case 05 – Green – Adding a Tree Line along the Main Street scenario were slightly decreased comparing with the Existing scenario. But the impact of this scenario is very less comparing with the existing scenario.

- The simulated Air Temperature distribution shown in the Appendix III for All cases in Green scenario.

03. Create Open Spaces (Case 06)

Create an Open space as a Public Plaza at the surrounding area of the existing Dutch Museum Area which is located at the Prince street in Pettah.



Create an Open space as a Dutch Museum Plaza

Figure 98: Case 06 – Create Open Spaces (Case 06) scenario

Source: Author

Data were taken from the **Receptor Point EW** and the **Receptor Pont NS** in the Location 02 and the Location 03.

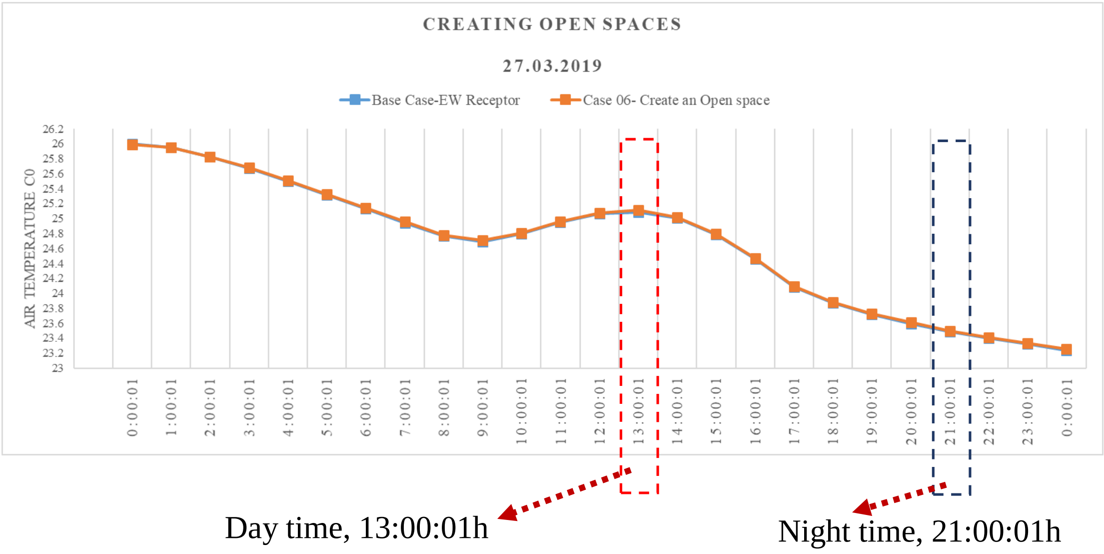


Figure 99: Simulated Air Temperature Comparison at the Case 06, Create an Open space with the Base Case – Existing Situation considering Data at the Location 02 and Location 03, on the Receptor EW.

Source: Author

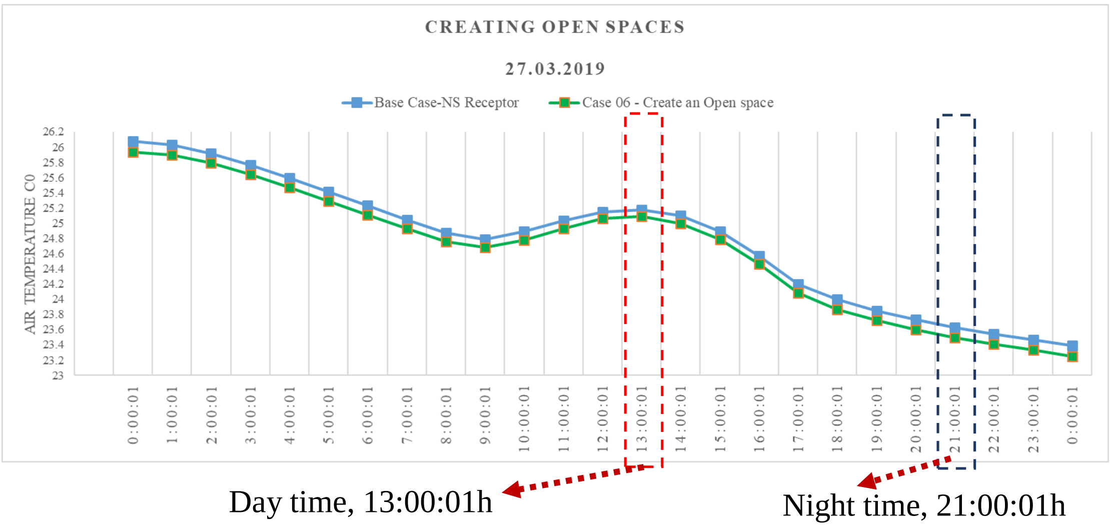


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Figure 100: Simulated Air Temperature Comparison at the Case 06, Create an Open space with the Base Case – Existing Situation considering Data at the Location 02 and Location 03, on the Receptor NS

Source: Author

- According to the Figure 99 , Figure 100 and the Appendix IV both Day time and the Night time simulated Air temperature for the case 06 – Create an Open Space scenario were decreased comparing with the Existing scenario. But the impact of day time, 13:00:01h is very less comparing with the existing scenario.

04. Creating Wind Corridors (Case 07)

a.) Creating Openings at Existing Harbor wall.

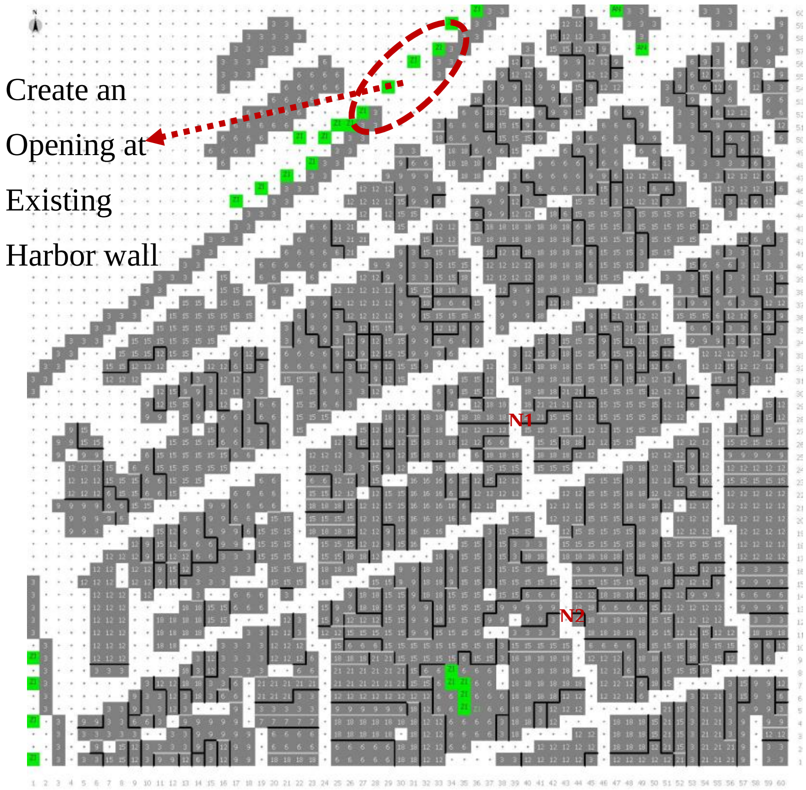


Figure 101: Creating Wind Corridors Scenario- Case 07 – a.) Creating Openings at Existing Harbor wall.

Source: Author

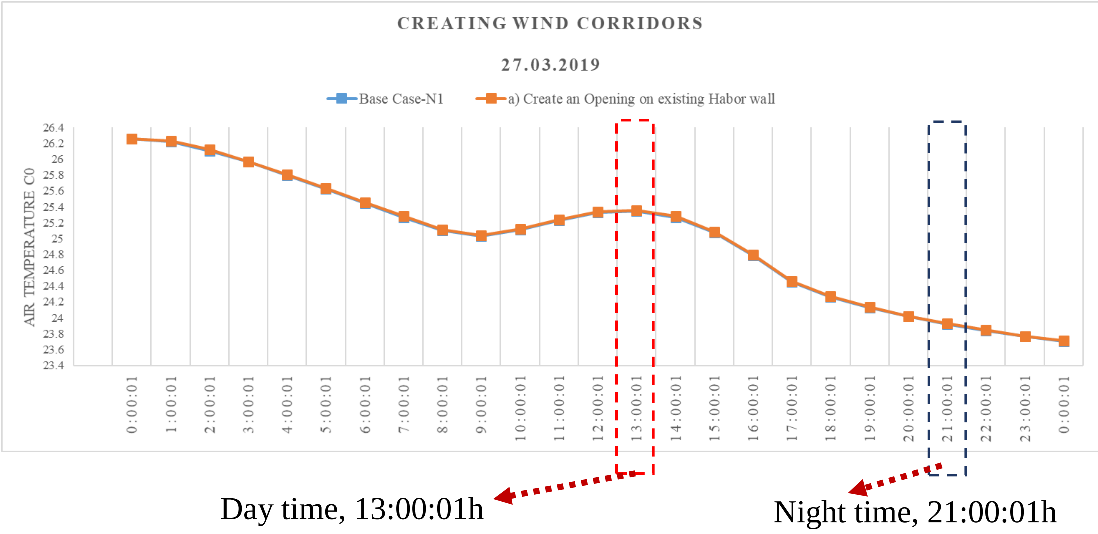


Figure 103: Air Temperature Analysis on a) creating an opening on the existing harbor wall for creating wind corridors. Data were taken on Receptor point N1.

Source: Author

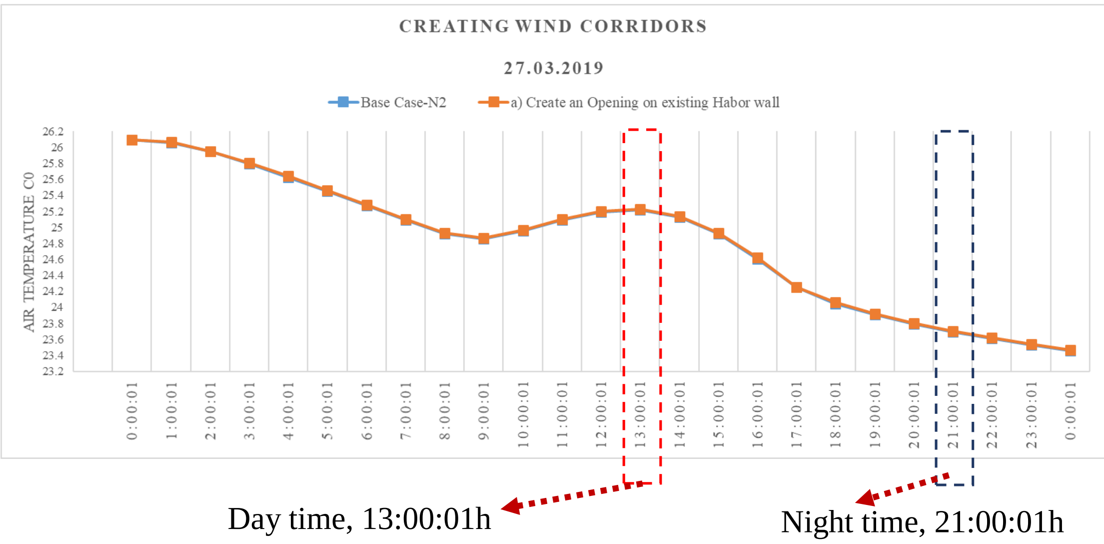


Figure 102: Air Temperature Analysis on a) creating an opening on the existing harbor wall for creating wind corridors. Data were taken on Receptor point N2

Source: Author

- According to the Figure 102 , Figure 103 and the Appendix V both Day time and the Night time simulated Air temperature for the Creating Wind Corridors Scenario- Case 07 – a.) Creating Openings at Existing Harbor wall were indicated the less difference of the Air Temperature comparing to the Base Case of Existing scenario.

b.) Removing existing Harbor wall.

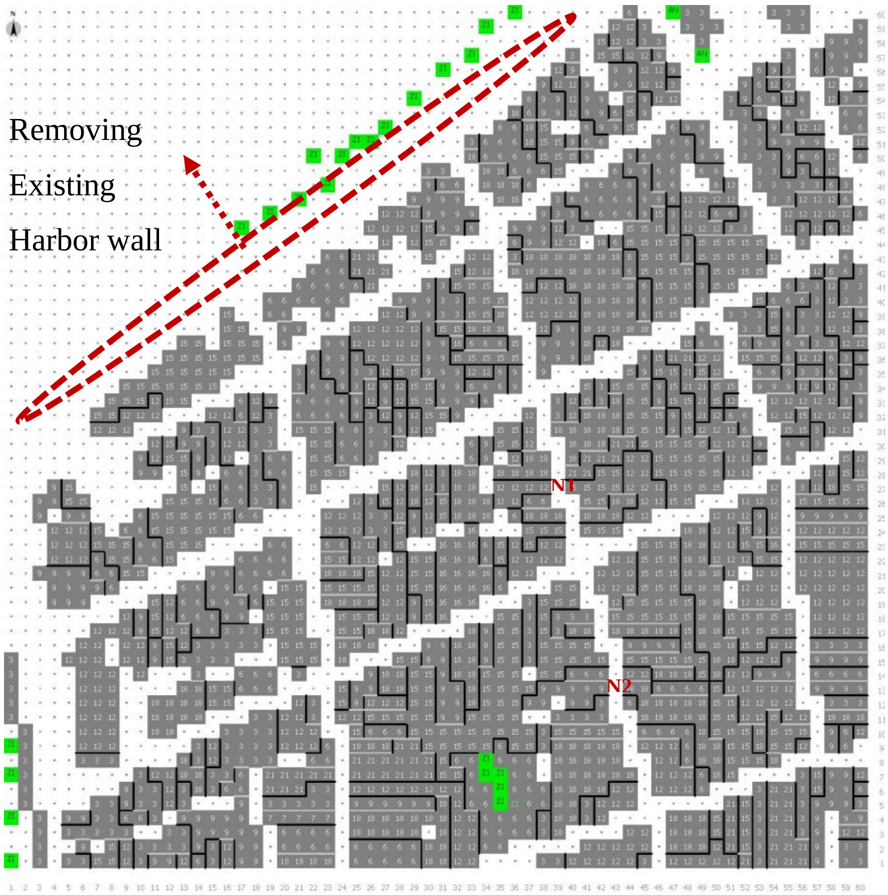


Figure 104: Creating Wind Corridors Scenario- Case 07 – b.) Removing existing Harbor wall.

Source: Author

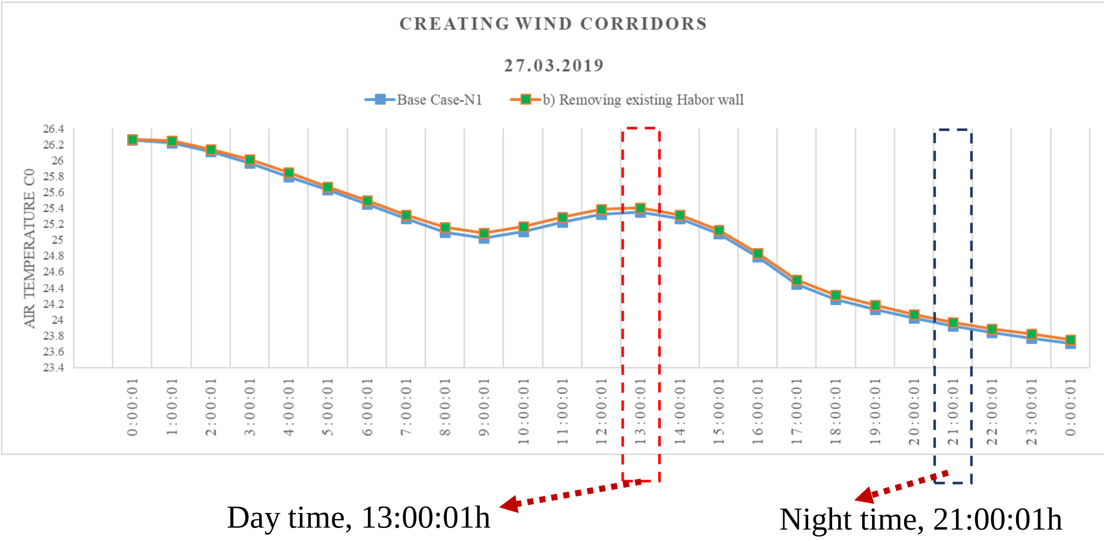


Figure 105: Air Temperature Analysis on b) Removing the existing harbor wall for creating wind corridors. Data were taken on Receptor point N1.

Source: Author

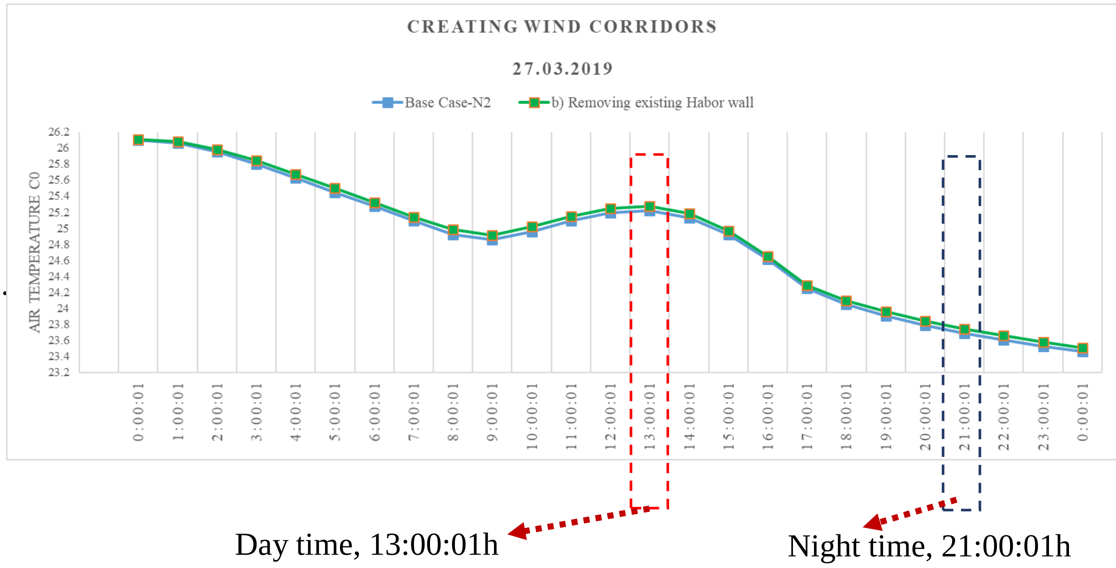


Figure 106: Air Temperature Analysis on b.) Removing the existing harbor wall for creating wind corridors. Data were taken on Receptor point N2.

Source: Author

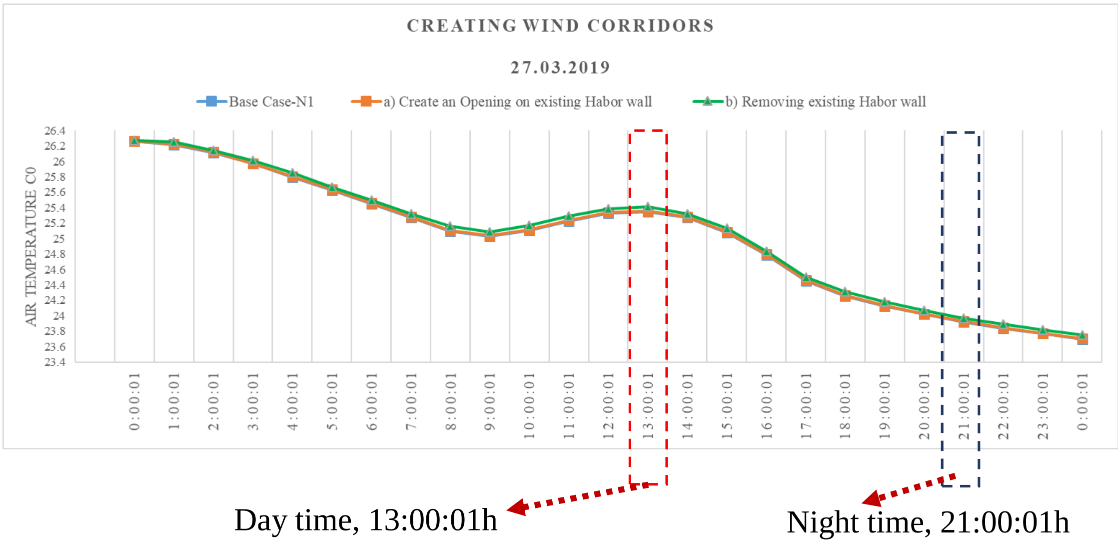


Figure 107: Air Temperature Analysis on both a and b options for creating wind corridors on Receptor point N1

Source: Author

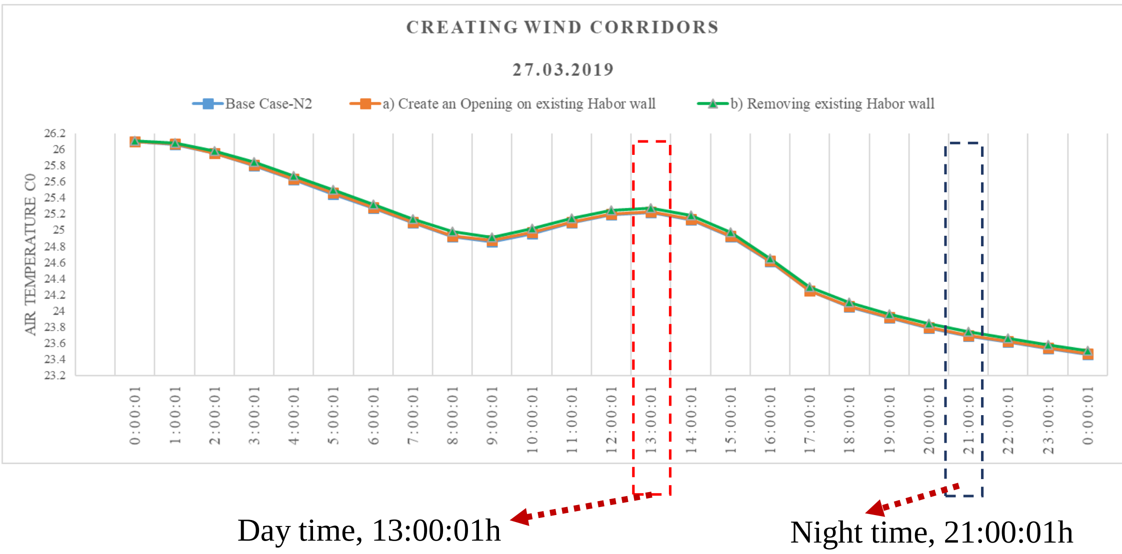


Figure 108: Air Temperature Analysis on both a and b options for creating wind corridors on Receptor point N2

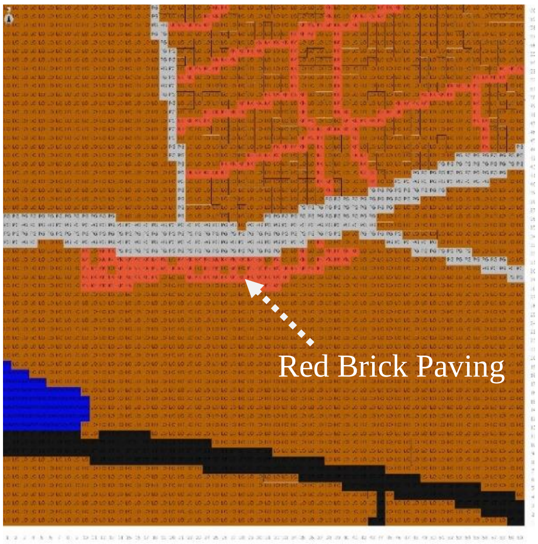
Source: Author

- Removing of existing harbor wall scenario were increased the Air Temperature comparing to the Existing scenario (Base case) due to expose the sea breeze which directly come to the created wind corridor at the Day time as well as the night time. This can clearly as have shown in Figure 105, Figure 106, Figure 107, Figure 108 and the Appendix V.

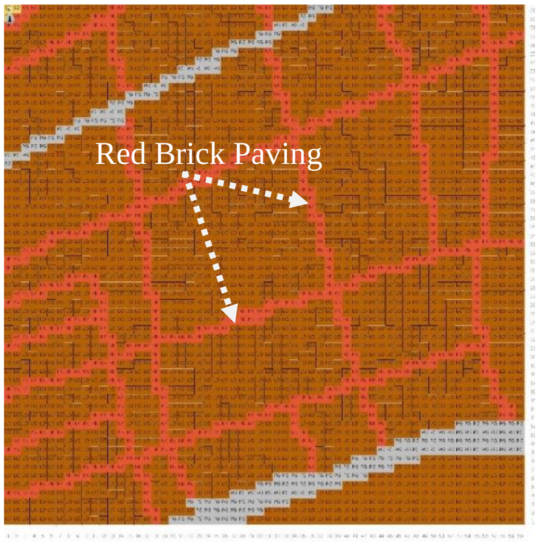
- Accordingly, when comparing the both a) Creating Openings at Existing Harbor wall case and b.) Removing existing Harbor wall Case, the Case (a) Creating Openings at Existing Harbor can be introduce as the best option when create wind corridors at the selected area.

05. Changing Surface Materials (Case 08)

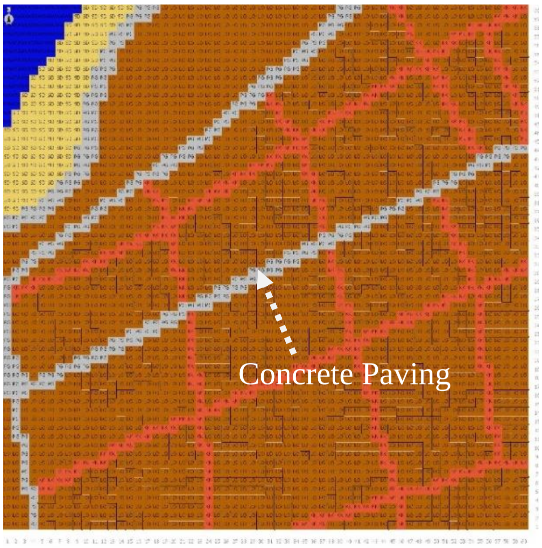
In this case, change the surface material of selected different built forms and analyzed of their air temperature variations.



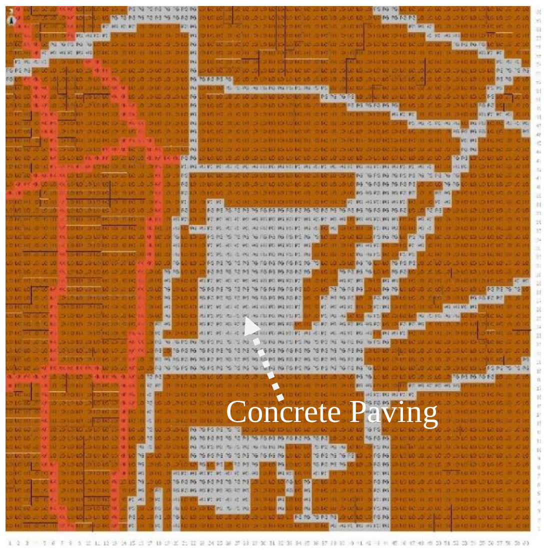
Location 01 – An Urban Plaza



Location 02&03 – EW and NS Urban Canyons



Location 04 – EW Urban Canyons



Location 05 – A Parking Precinct

Figure 109: Changing Surface Materials scenario (Case 08)

Source: Author

All internal roads which were indicated on Location 01, Location 02 and 03, Location 04 and Location 05 were paved using with red brick material and some roads (such as the Main street), Parking Precinct and its surrounding roads in Location 05 laid with concrete paving.

Different Surface Materials have the different level of absorption and reflectivity.

(Albedo) Depend on that the Surface Temperature will be vary for each different location.

Material	**Albedo**	**Emissivity**
Concrete	0.3	0.94
Red Brick	0.3	0.90

Table 22: The albedo of applied materials for all Five locations

Source: (M.Santamouris, 2001)

Data were taken on 13:00:01 h on relevant receptor points of each locations of different built forms.

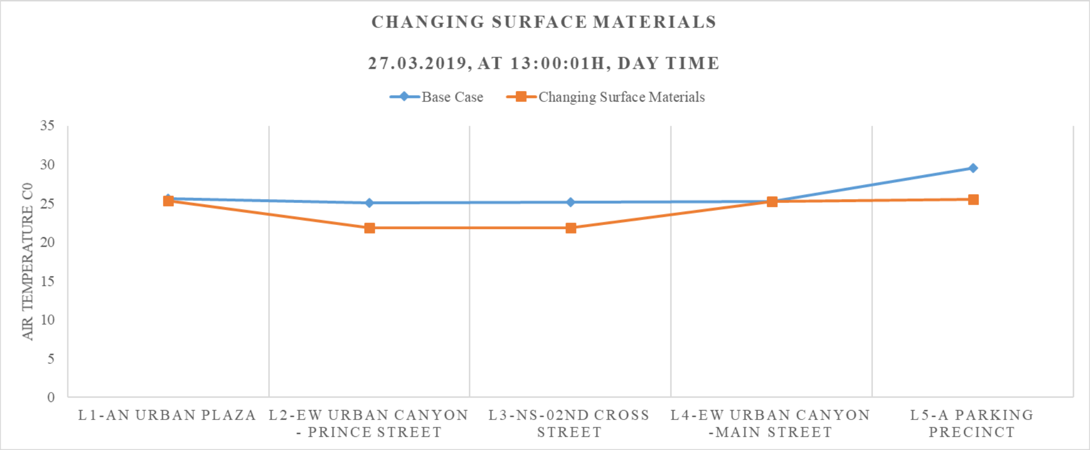


Figure 110: Changing Surface Materials scenario (Case 08) at Day time, 13:00:01h

Source: Author

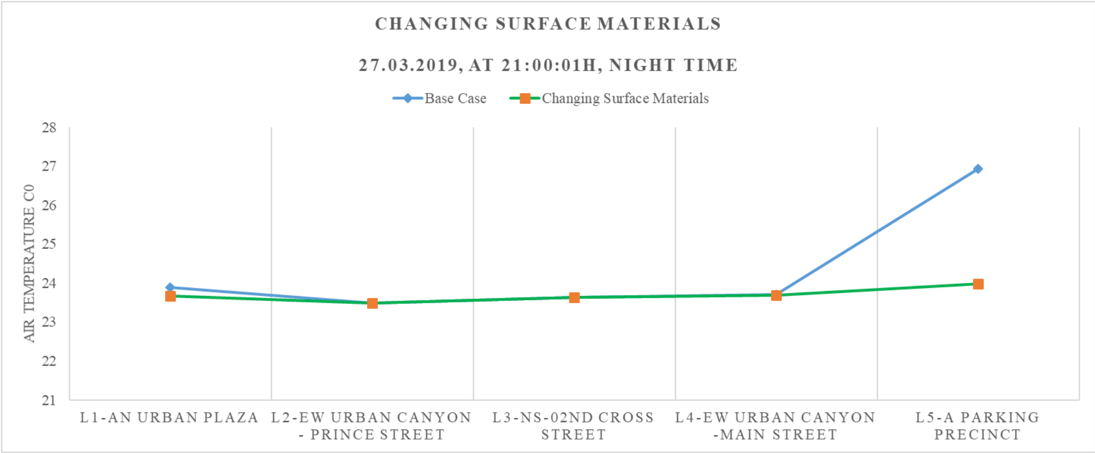


Figure 111: Changing Surface Materials scenario (Case 08) at the Night Time, 21:00:01h.

Source: Author

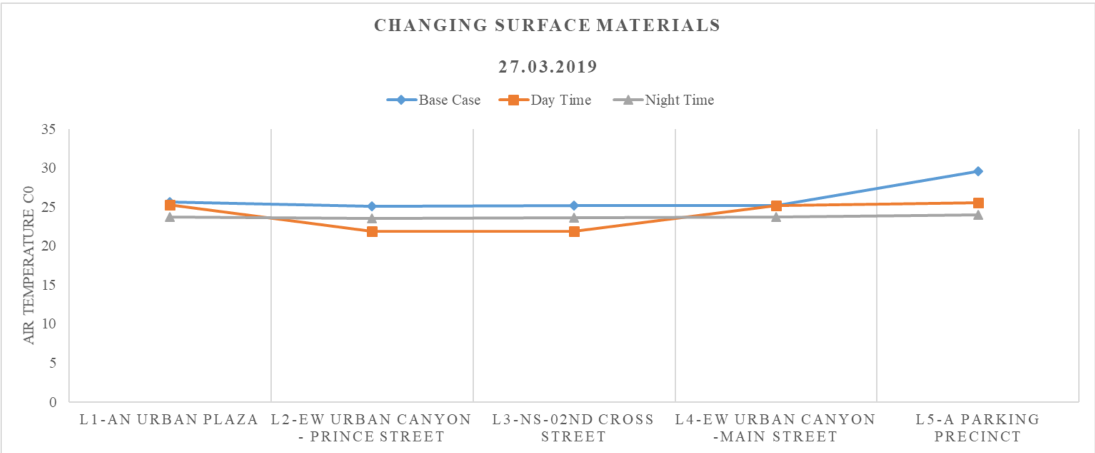


Figure 112: Changing Surface Materials scenario (Case 08) at both Day time, 13:00:01h and the Night Time, 21:00:01h

Source: Author

- As per the Figure 110 and Appendix VI, the Air temperature is more decreased at the Location 02 – East West canyon – Prince Street and Location 03- North South Canyon - 02nd Cross Street which were used red brick paving as their surface materials.

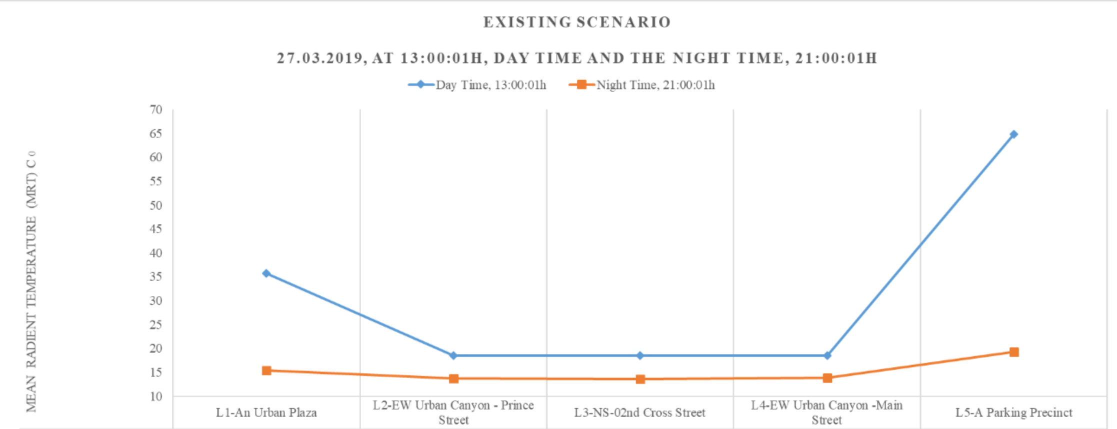
- The highest Air temperature indicated from the Location 05 – A Parking Precinct which was used the concrete paving as their surface materials.
- As per the Figure 111, Figure 112 and Appendix VI the Location 05 – A Parking Precinct identified as the most impacted location for the Air Temperature.

4.3.2 Mean Radiant Temperature Analysis (MRT)

Mean Radiant Temperature were simulated for all different built forms using with Leonardo 2014 and discussed its variations and differences. MRT values were taken at the level of 1.5m for the Day time 13:00:01h and the Night Time 21:00:01h respectively.

4.3.2.1 Existing scenario (Base case)

Simulated Mean Radiant Temperature on, Base Case- existing situation for all Locations at the Day Time 13:00:01h and the Night Time, 21:00:01h respectively.



	L1-An Urban Plaza	L2-EW Urban Canyon - Prince Street	L3-NS-02nd Cross Street	L4-EW Urban Canyon -Main Street	L5-A Parking Precinct
Day Time, 13:00:01h	35.73	18.49	18.44	18.53	64.91
Night Time, 21:00:01h	15.36	13.69	13.58	13.79	19.31

Figure 113: Simulated Mean Radiant Temperature on, Base Case for all Locations at the Day Time 13:00:01h and the Night Time 21:00:01h.

Source: Author

- Considering the Base case, the highest Mean Radiant Temperature was indicated from the Location 05 – A Parking Precinct at The Day time, 13:00:01h.
- As per the Figure 113 and the Appendix VII it was indicated the lowest Mean Radiant Temperature from the Location 03 – North South Urban Canyon - 02nd Cross Street at the Day time.
- As per the Figure 113 and the Appendix VII the highest Mean radiant temperature indicated from the Location 05- a parking precinct and the Lowest Mean temperature was indicated from the Location 03 – North South Urban Canyon at the Night time also.
- At the Night Time Mean Radiant Temperature is more less than the Day time Mean Radiant temperature as shown in the Figure 113 and the Appendix VII.

4.3.2.2 Simulated Mean Radiant Temperature (MRT) of Envisaged Scenarios.

Simulated Mean Radiant Temperature (MRT) Distribution by using Leonardo 2014 at the 1.5 m level at the date of 27th March 2019 of all different built forms special relevant to their receptors of All Locations.

01.) Increasing Building Heights (Case 01, Case 02, Case 03 and Case 04)

Simulated Mean Radiant Temperature distributions of the Case 01 – Low Rise (03 storied height), Case 02 – Intermediate Rise (08 storied height), Case 03 – Medium Rise (12 storied height) and Case 04 – High Rise (14 storied height) for each Locations at the day time 13:00:01h is shown in the Figure 114 and the MRT distribution of the Night time shows in the Figure 115 and the Appendix VIII.

- Accordingly, when increasing the heights of the buildings it was observed that the Mean Radiant temperature of all Locations were decreased.
- It was happened for both Day time and the Night Time.

	L1-An Urban Plaza	L2-EW Urban Canyon - Prince Street	L3-NS-02nd Cross Street	L4-EW Urban Canyon -Main Street	L5-A Parking Precinct
Base Case	35.73	18.49	18.44	18.53	64.91
Case 01-Low Rise (03 storied)	19.47	18.12	18.03	18.2	60
Case 02-Intermediate Rise (08 storied)	18.59	16.96	16.85	16.97	18.5
Case 03- Medium Rise (12 storied)	18.2	16.28	16.17	16.48	17.95
Case 04- High Rise (14 storied)	18.1	16.12	16	16.3	17.77

Figure 114: Simulated Mean Radiant Temperature for increasing Building Height Scenario at the Day Time 13:00:01h.

Source: Author

	L1-An Urban Plaza	L2-EW Urban Canyon - Prince Street	L3-NS-02nd Cross Street	L4-EW Urban Canyon -Main Street	L5-A Parking Precinct
Base Case	15.36	13.69	13.58	13.79	19.31
Case 01-Low Rise (03 storied)	14.83	13.85	13.75	13.79	17.38
Case 02-Intermediate Rise (08 storied)	14.24	12.88	12.76	12.88	14.22
Case 03- Medium Rise (12 storied)	13.99	12.37	12.25	12.35	13.69
Case 04- High Rise (14 storied)	13.9	12.12	12.04	12.15	13.47

Figure 115 : Simulated Mean Radiant Temperature for increasing Building Height Scenario at the Day Time 21:00:01h.

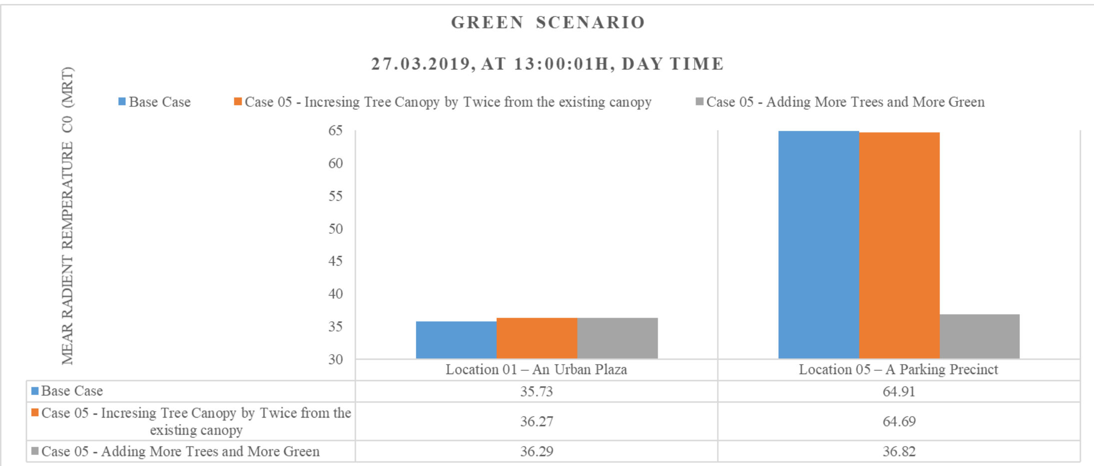
Source: Author

02. Green Scenario (Case 05)

Simulated Mean Radiant Temperature (MRT) distribution were analyzed for following Green Scenarios for only Location 01 – An Urban Plaza and Location 05- A Parking Precinct which already have Green in the existing situation and Location 04 – EW Canyon -Main Street which proposed a Tree line along the Main street at the Day time and for the Night Time.

a.) Increasing Existing Tree Canopy width in two times Scenario
b.) Adding More Trees and More green
c.) Adding Tree Line Along the Main Street.

a) and b) Increasing Existing Tree Canopy by twice Scenario and Adding More Trees and More green.



	Location 01 – An Urban Plaza	Location 05 – A Parking Precinct
Base Case	35.73	64.91
Case 05 - Incresing Tree Canopy by Twice from the existing canopy	36.27	64.69
Case 05 - Adding More Trees and More Green	36.29	36.82

Figure 116: Simulated Mean Radiant Temperature for increasing Existing Tree Canopy by twice Scenario at the Day Time 13:00:01h.

Source: Author

- As per the Figure 116, the Location 05 – A Parking Precinct was indicated the Lower Mean Radiant Temperature (MRT) values for the both Increasing Tree Canopy and the Adding More Trees and More Green scenarios' comparing to the Existing scenario.

- At the Location 01,which consists with an Urban Plaza was observed the higher MRT values comparing to the base Case – Existing scenario for the Day time.
- But considering the both Locations the Highest simulated MRT value can be seen from the Location 05, which have the Parking Precinct for both scenarios at the Day time.

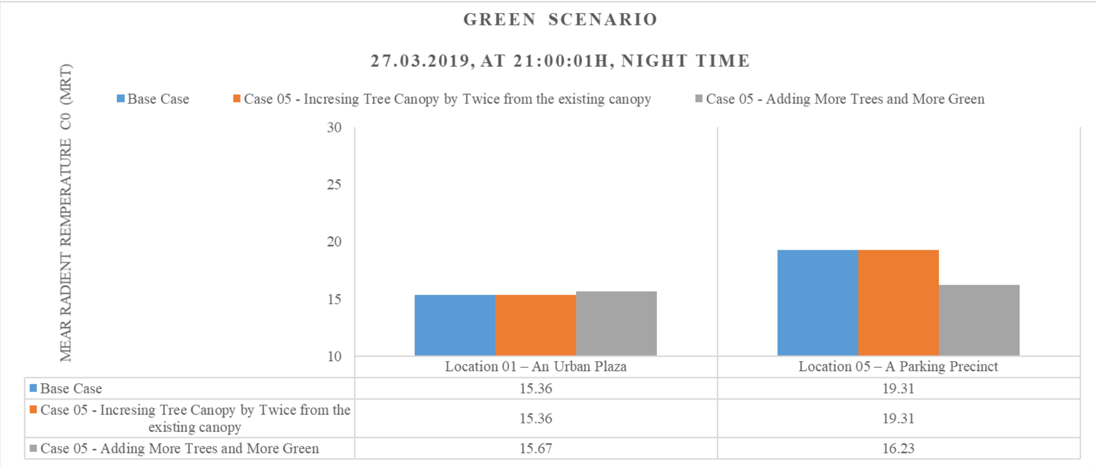


Figure 117: Simulated Mean Radiant Temperature for increasing Existing Tree Canopy by twice Scenario and Adding More Trees and More Green scenarios at the Night Time 21:00:01h.

Source: Author

- As per the Figure 117, the simulated Mean Radiant Temperature (MRT) values were increased at the Location 01 for the Adding More Trees and More Green Scenario at the Night Time.
- At the Location 05 – a Parking Precinct, the MRT value was decreased of the adding More Trees and More Green scenario.
- At the Night Time MRT values for the Both Location 01 and the Location 05 were decreased than the Day Time.
- When comparing the Two Locations, the Location 05 with a parking precinct shows the higher increment of the MRT value than the Location 01 have with the Urban Plaza.
- The pattern of MRT distribution shows from the MRT Distribution maps in Figure 118, Figure 119, Figure 120 and Figure 121.

Figure 118: Simulated Mean Radiant Temperature distribution for a.) Increasing Existing Tree canopy width by twice from the existing Location 01- An Urban Plaza and b.) Adding More Trees and More green for the Location 01- An Urban Plaza at the Day time ,13:00:01h.

Source: Author

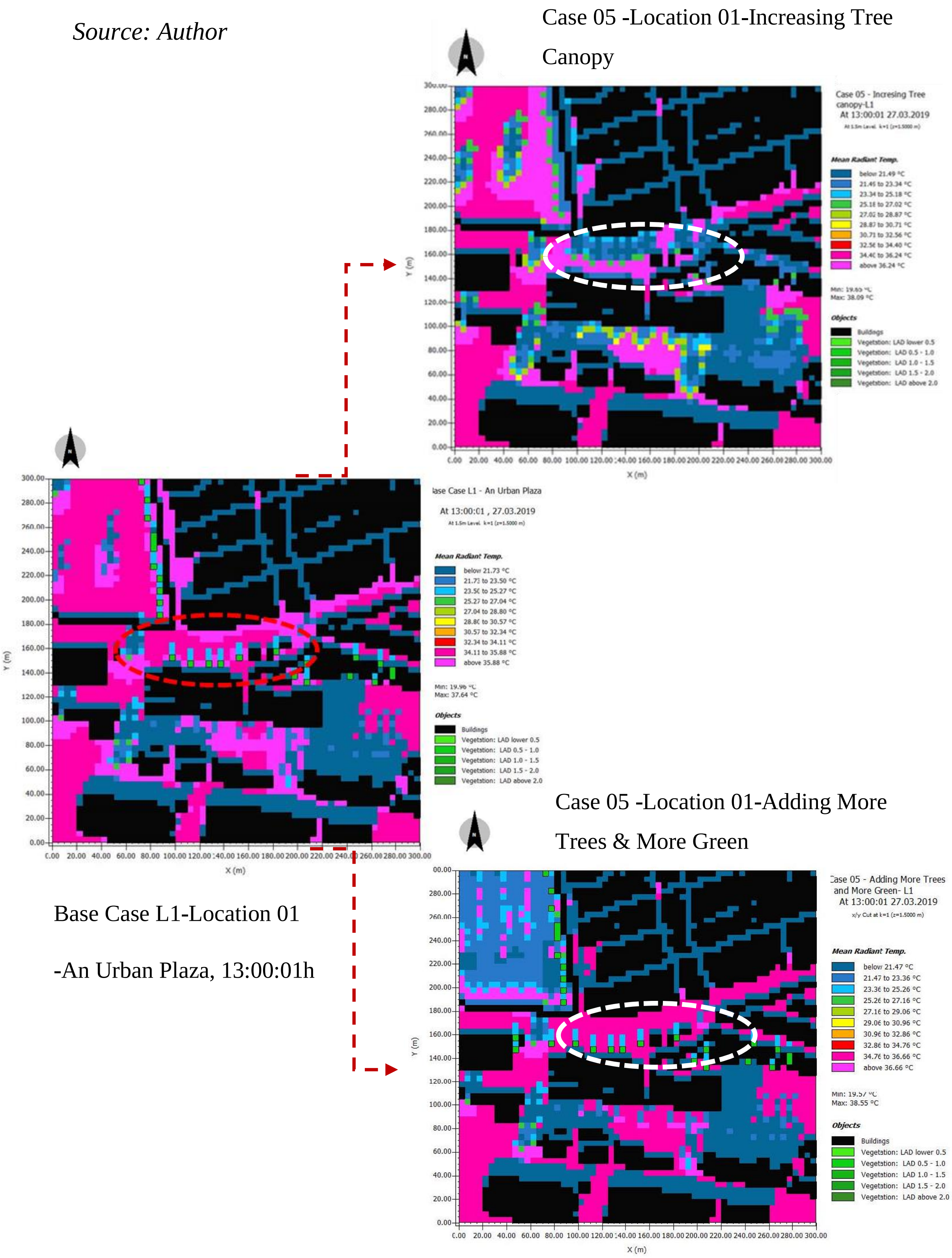


Figure 119: Simulated Mean Radiant Temperature distribution for a.) Increasing Existing Tree canopy width by twice from the existing Location 01- An Urban Plaza and b.) Adding More Trees and More green for the Location 01- An Urban Plaza at the Night Time, 21:00:01h.

Source: Author

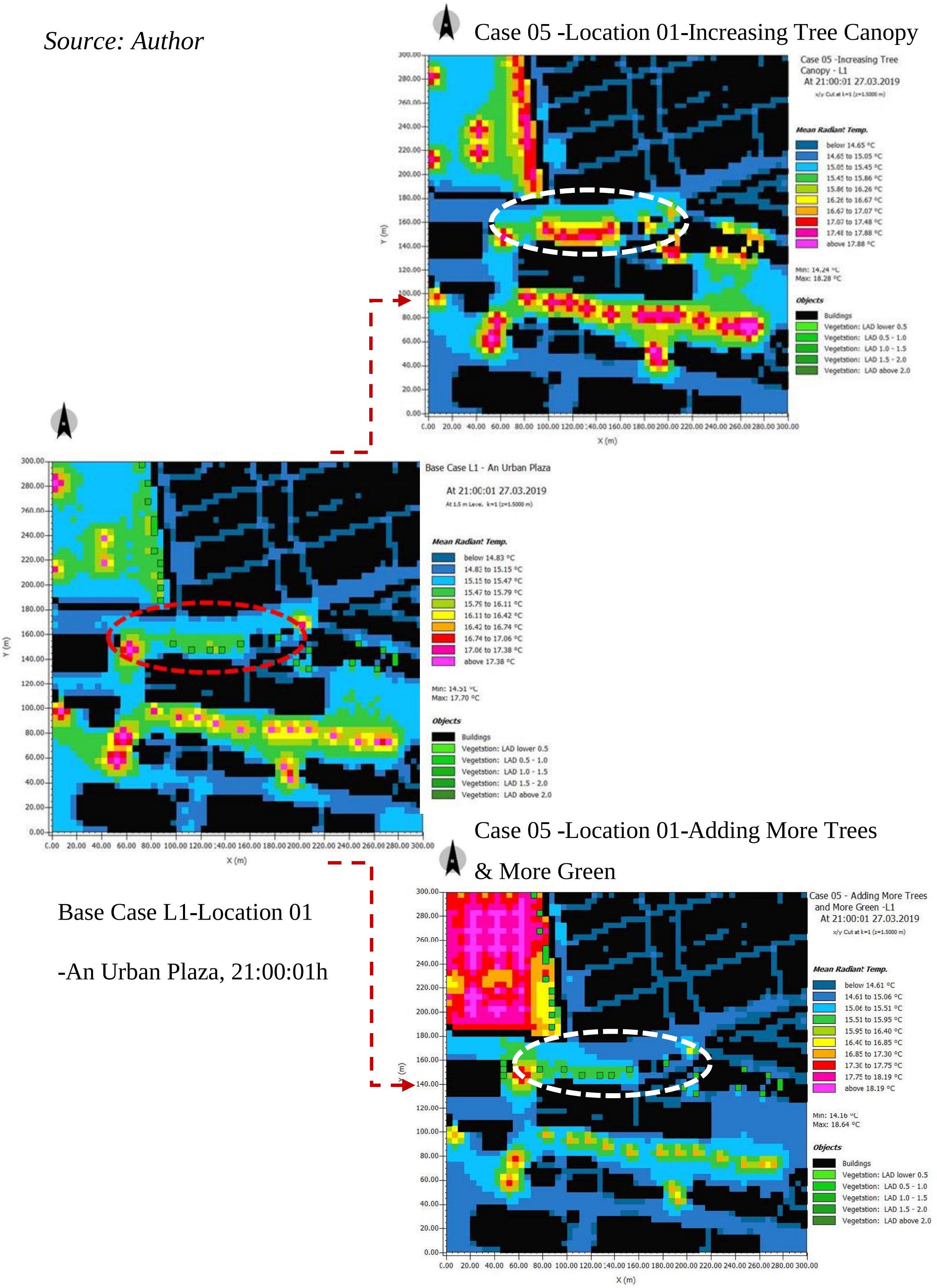
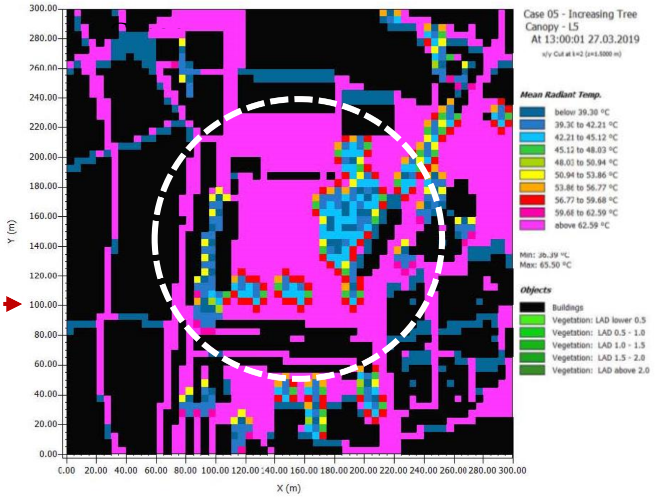
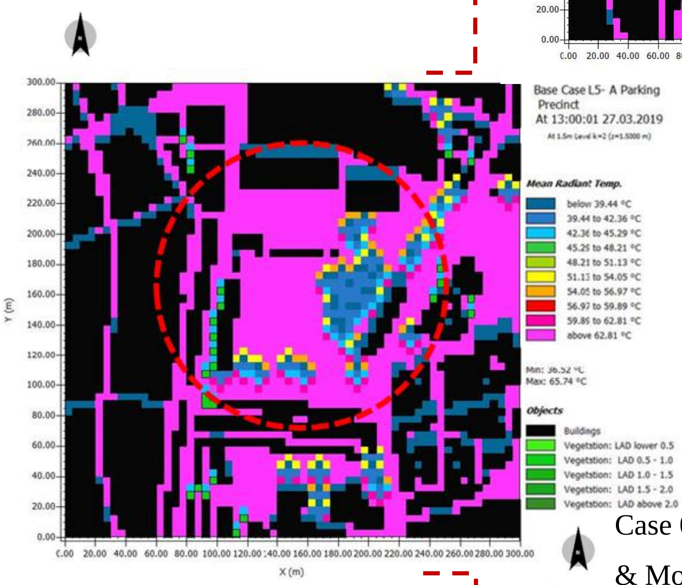


Figure 120: Simulated Mean Radiant Temperature distribution for a.) Increasing Existing Tree canopy width by twice from the existing Location 05- An Urban Plaza and b.) Adding More Trees and More green for the Location 05- An Urban Plaza at the Day time ,13:00:01h.

Source: Author

Case 05 -Location 05-Increasing Tree





Base Case L1-Location 05

-A Parking Precinct, 13:00:01h

Case 05 -Location 05-Adding More Trees

& More Green

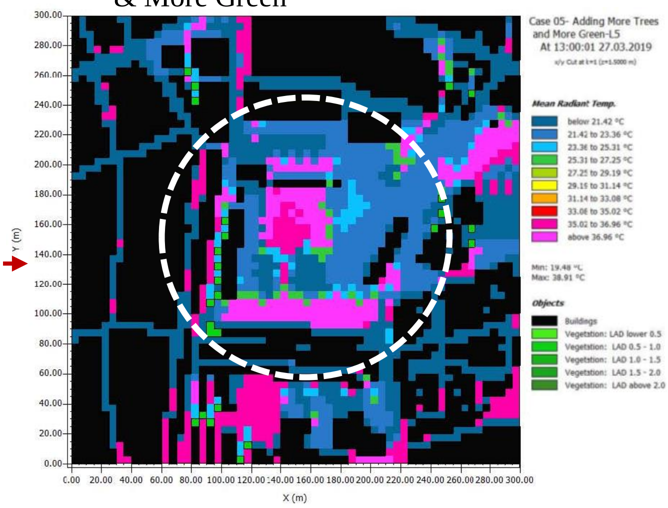
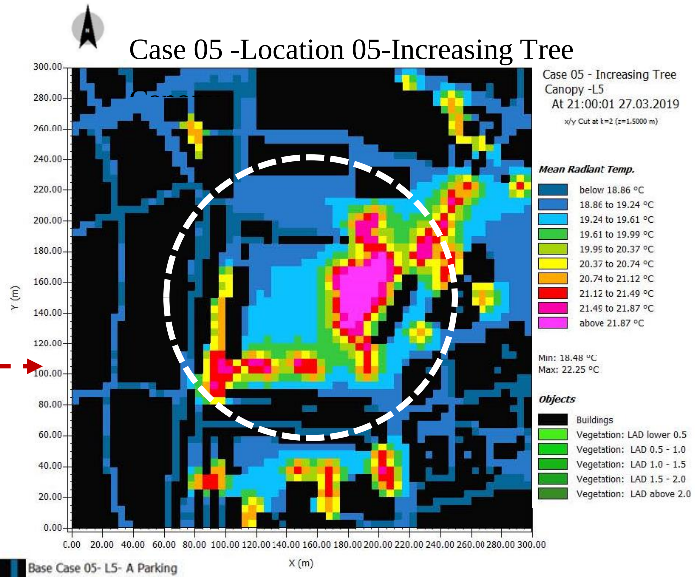
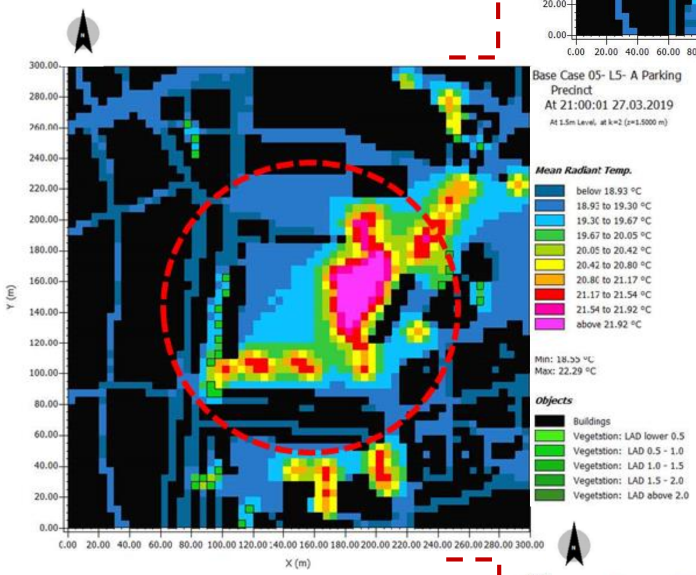


Figure 121 : Simulated Mean Radiant Temperature distribution for a.) Increasing Existing Tree canopy width by twice from the existing Location 05- An Urban Plaza and b.) Adding More Trees and More green for the Location 05- An Urban Plaza at the Night time , 21:00:01h.

Source: Author

Case 05 -Location 05-Increasing Tree

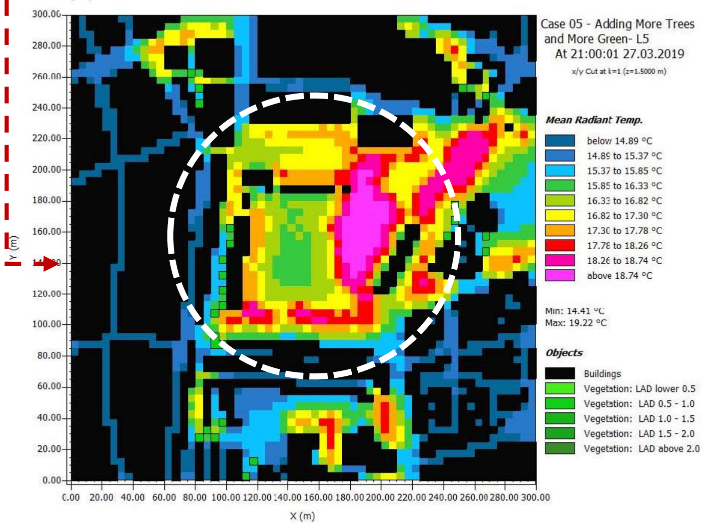




Case 05 -Location 05-Adding More Trees & More Green

Base Case L5-Location 05

-A Parking Precinct, 21:00:01h



c.) Adding a Tree Line for both sides along the Main Street..

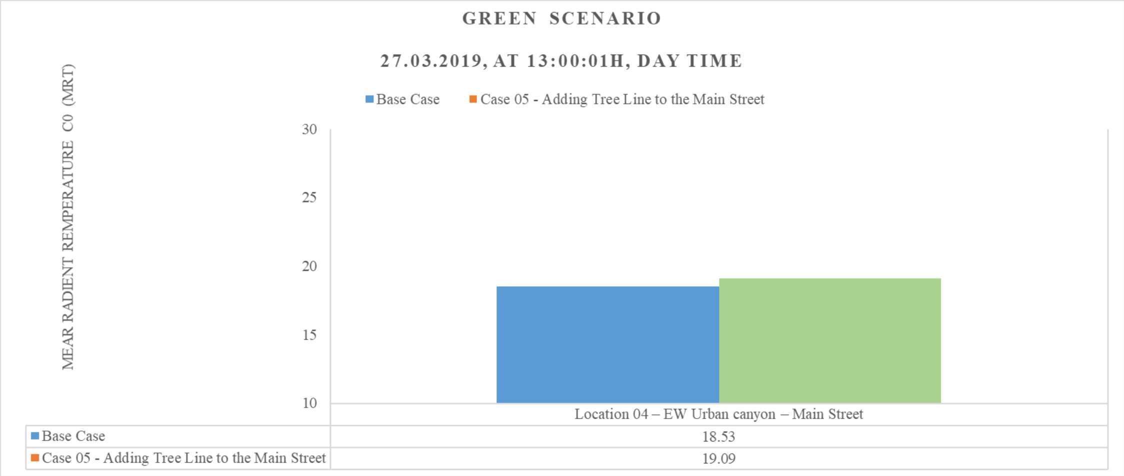


Figure 122 : Simulated Mean Radiant Temperature for the Case 05 – Adding Tree Line along the Main Street at the Day Time13:00:01h.

Source: Author

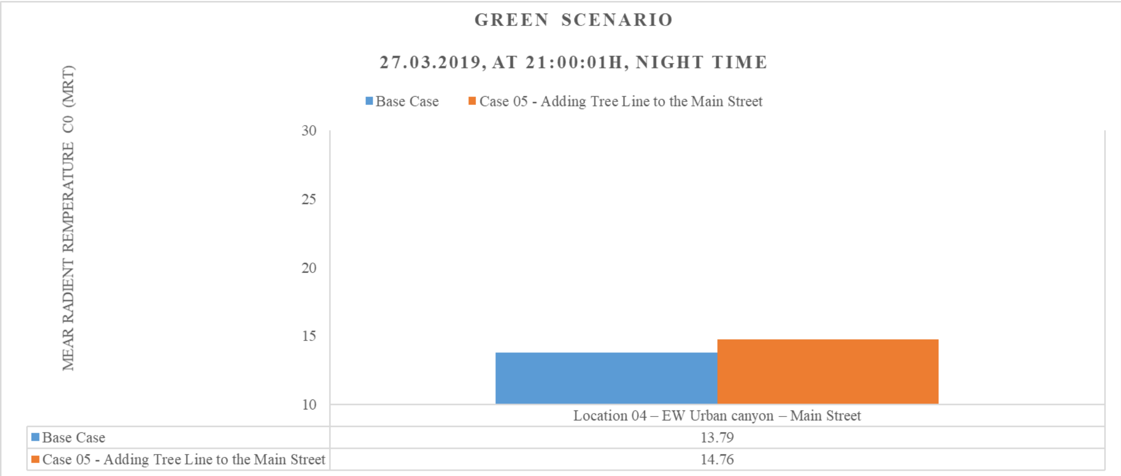


Figure 123: Simulated Mean Radiant Temperature for the Case 05 – Adding Tree Line along the Main Street at the Night Time 21:00:01h.

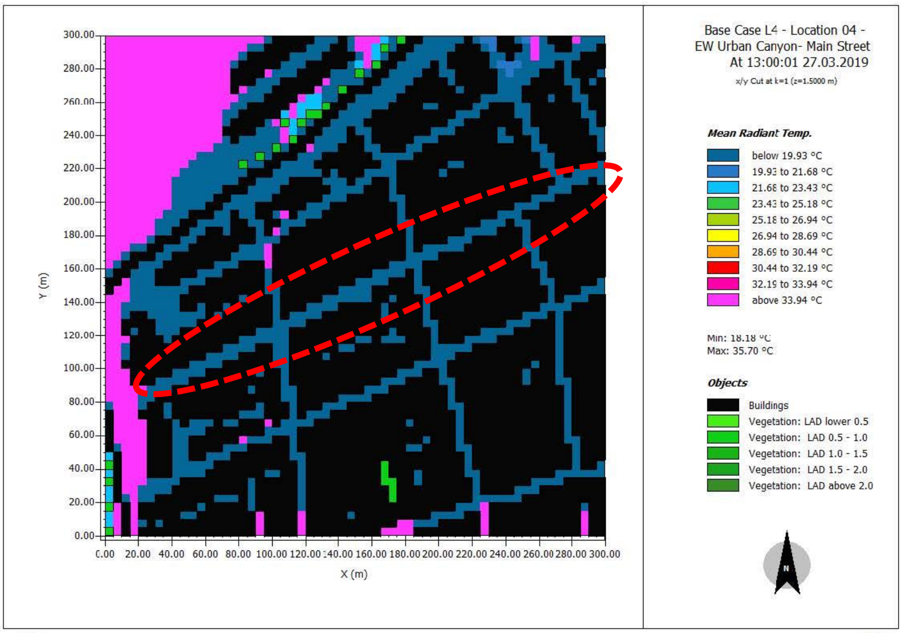
Source: Author

- According to the Figure 122, Figure 123, Figure 124 and Figure 125 it was observed that the MRT was slightly increased for the Adding a Tree Line for the Main Street Scenario at the both Day time and the Night time.

Figure 124: Simulated Mean Radiant Temperature distributions of the Case 05 – Adding Tree Line for the L4- Location 04 - Along the Main Street at the Day time 13:00:01h.

Source: Author

- Simulated MRT distribution of Base Case for the Location 04- EW Urban canyon- Main Street at the Day time, 13:00:01h.



- Simulated MRT distribution of Case 05 – Green – Adding Tree Line along the Main Street at the Day time, 13:00:01h.

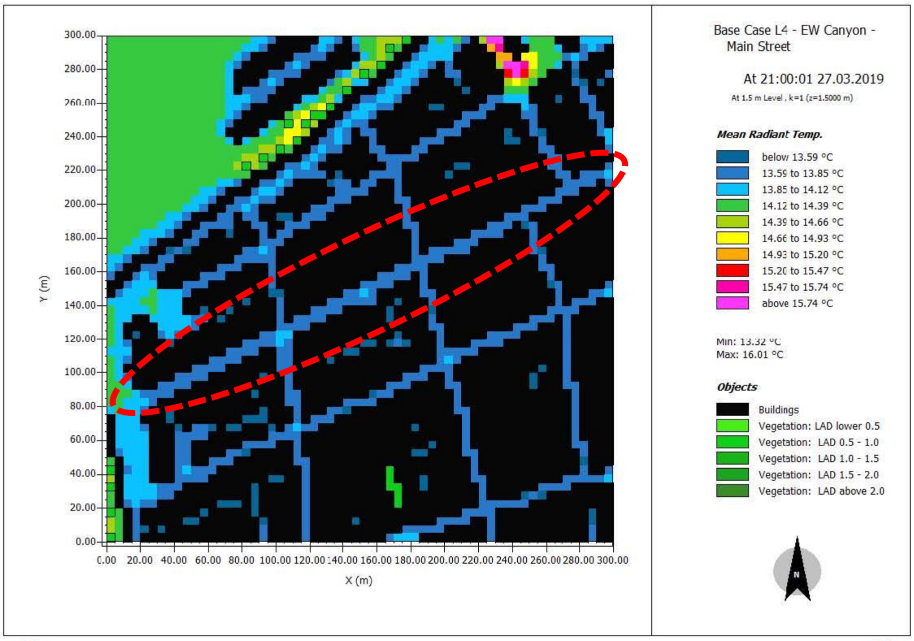
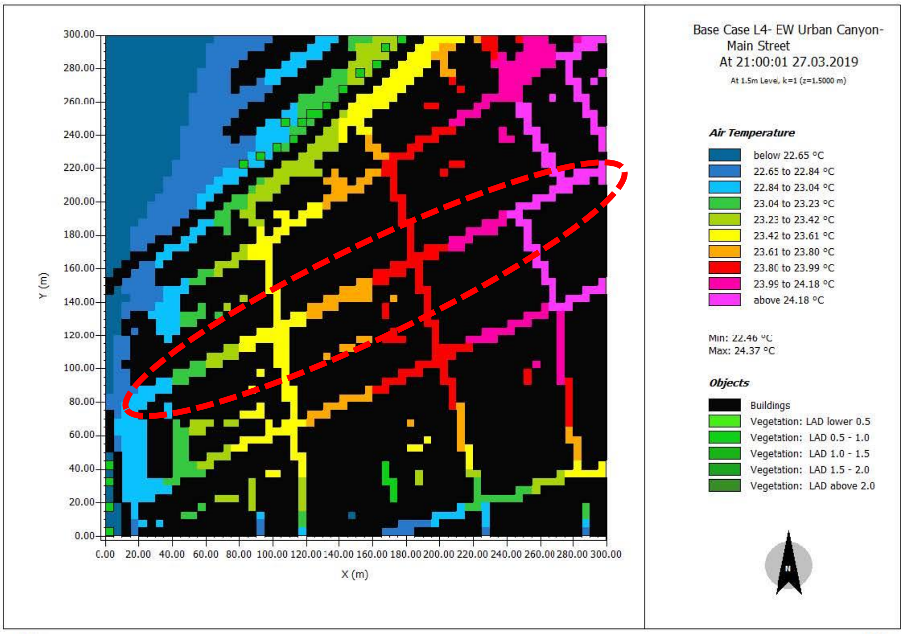


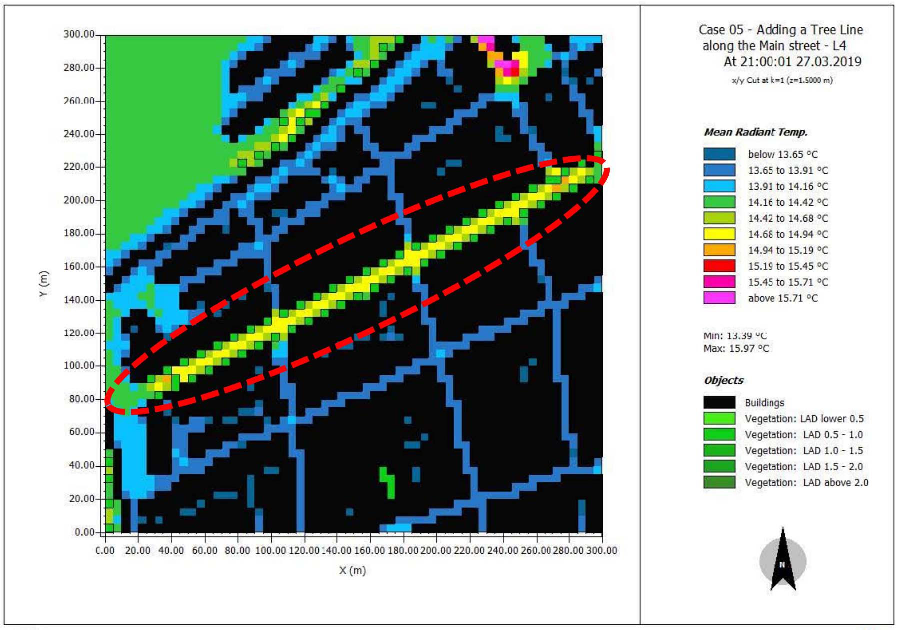
Figure 125: Simulated Mean Radiant Temperature distributions of the Case 05 – Adding Tree Line for the L4- Location 04 - Along the Main Street at the Night time 21:00:01h.

Source: Author

- Simulated MRT distribution of Base Case L4 – Location 04 – EW Canyon – Main Street at the Night time, 21:00:01h



- Simulated MRT distribution of Case 05 – Green – Adding Tree Line along the Main Street at the Night time,21:00:01h.



- Considering the simulated Mean Radiant Temperature (MRT) distribution values it was observed that Case 05- Green- Adding Tree Line for the L4- Location 04 - Along the Main Street shows the less difference of Mean Radiant Temperature (MRT) distribution values comparing to the MRT distribution values of the Base case L4 – Location 04 at the Day time as well as the Night time.

03. Create an Open Space Scenario (Case 06)

Case 06 – Create an Open Space – Location 02 & Location 03 – EW Canyon (Prince Street) and the NS Canyon (02nd Cross Street)

Simulated Mean Radiant Temperature distributions of the Case 06 – Create an Open space- Location 02 and Location 03 at the day time 13:00:01h is shown in the Figure 126 and at the Night time 21:00:01h is shown in the Figure 127.

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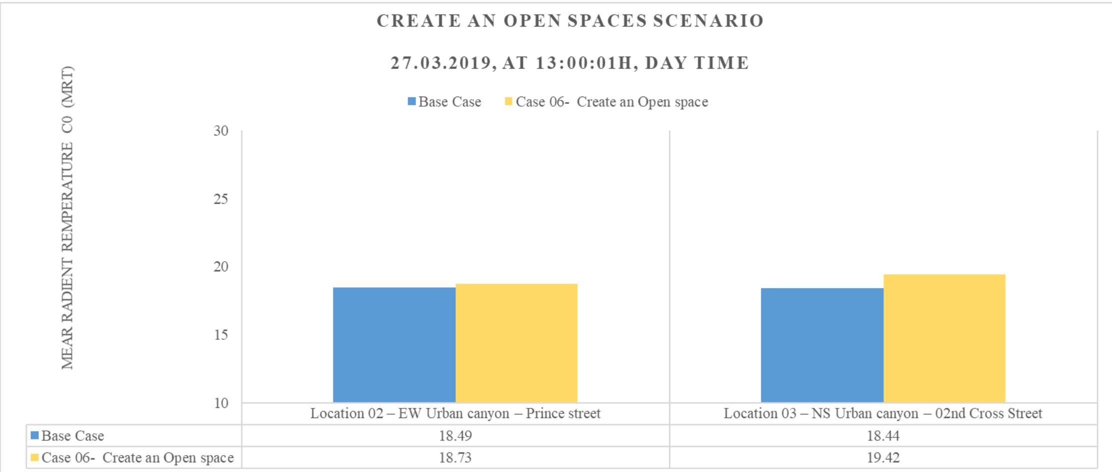


Figure 126: Simulated Mean Radiant Temperature for the Case 06 – Create an Open Space scenario at the Day Time 13:00:01h.

Source: Author

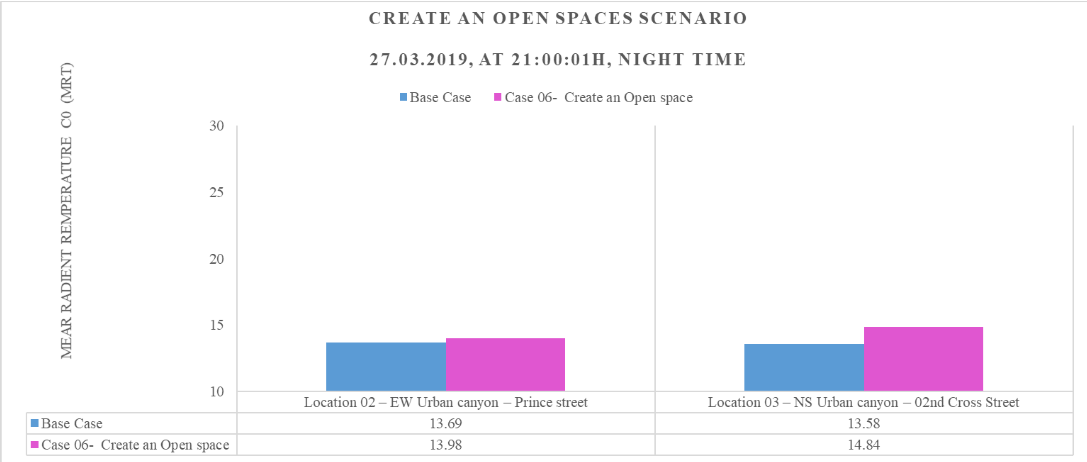


Figure 127 : Simulated Mean Radiant Temperature for the Case 06 – Create an Open Space scenario at the Night Time 21:00:01h.

Source: Author

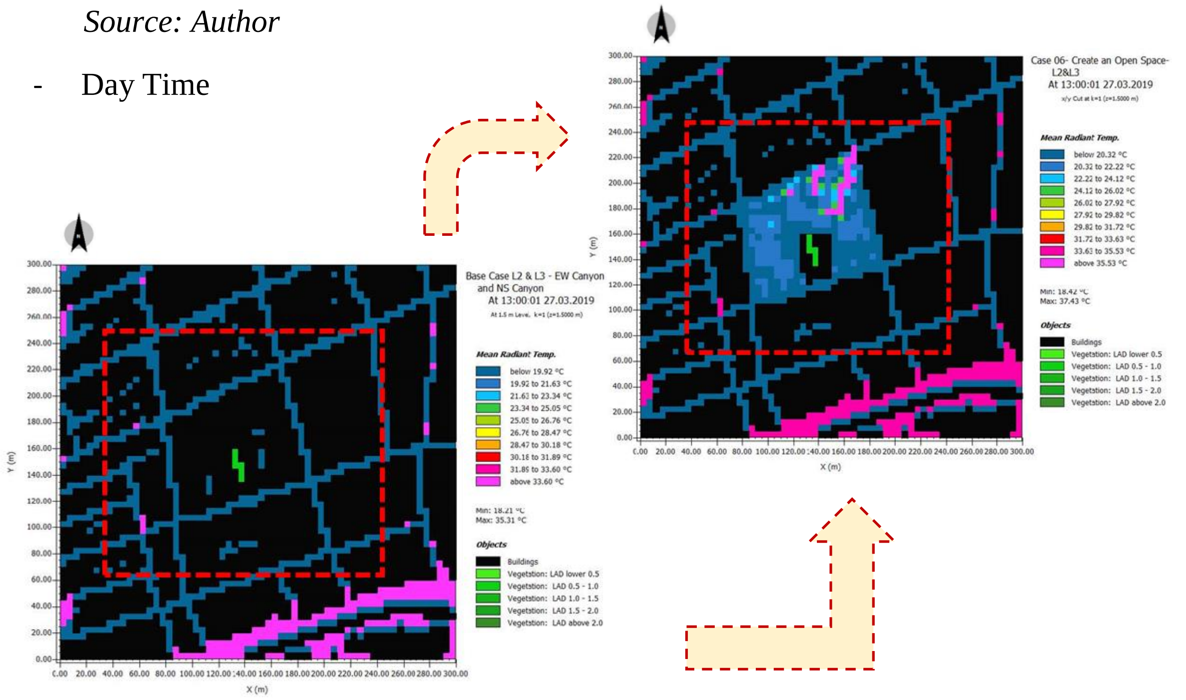
- According to the Figure 126 and the Figure 127, it was observed that the Mean Radiant Temperature (MRT) values were increased at the Location 02 – East West canyon- Prince Street and the Location 03 – North South Street – 02nd Cross Street at the Day time as well as the Night time for the Case 07 – Create Open spaces.

- At the Day time the difference of the increasing the MRT values for both Location 02 and Location 03 is very less compared with the Base case – Existing Scenario at the Day time than to the Night Time.

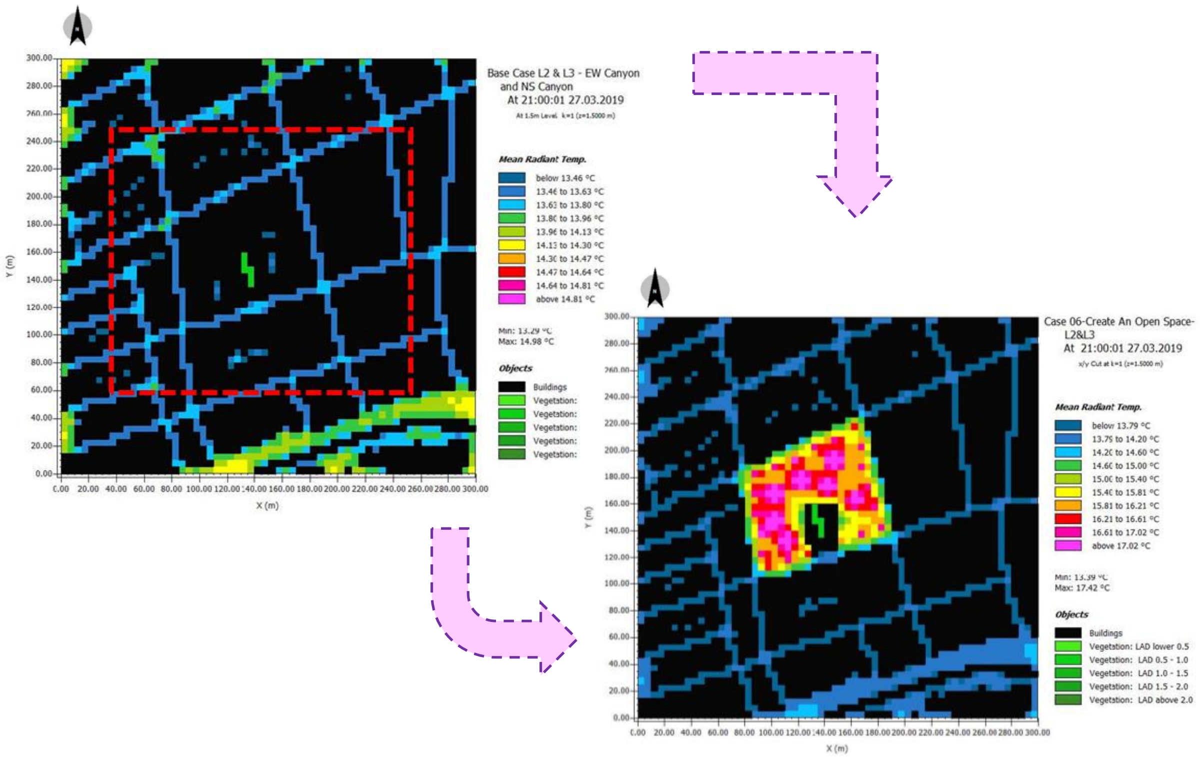
Figure 128: Simulated MRT distribution of Base Case L2 and L3 -Location 02 and Location 03 – EW Canyon (Prince Street) and the NS Canyon (02nd Cross Street) at the Day time, 13:00:01h and the Night Time, 21:00:01h Day Time.

Source: Author

- Day Time

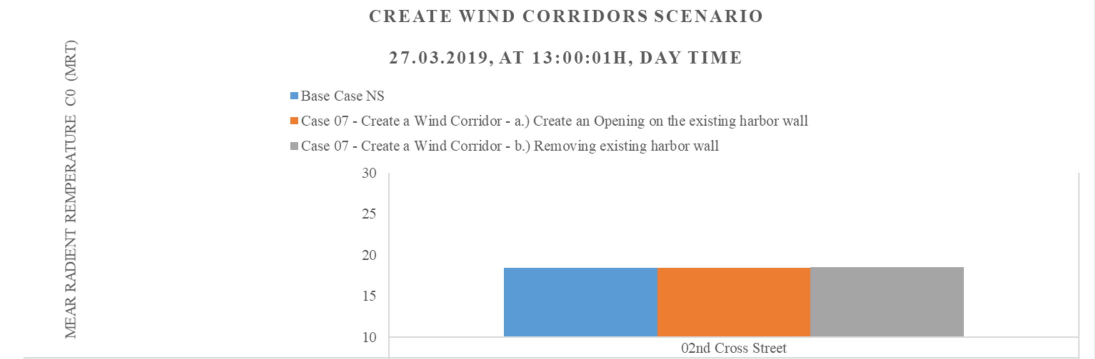


- Night Time



.04. Creating Wind Corridors Scenario (Case 07)

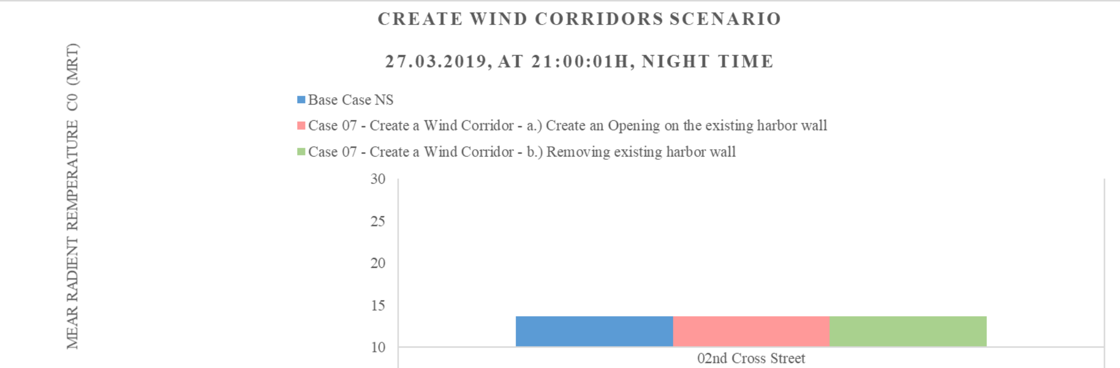
Simulated Mean Radiant Temperature distributions of the Case 07 – Creating Wind Corridors- L4 at the day time 13:00:01h is shown in the Figure 129 and Figure 131 and at the Night time 21:00:01h is shown in the Figure 130 and Figure 132.



	02nd Cross Street
Base Case NS	18.42
Case 07 - Create a Wind Corridor - a.) Create an Opening on the existing harbor wall	18.44
Case 07 - Create a Wind Corridor - b.) Removing existing harbor wall	18.49

Figure 129: Simulated Mean Radiant Temperature for the Case 07 – Create Wind Corridors scenario at the Day Time 13:00:01h

Source: Author



	02nd Cross Street
Base Case NS	13.63
Case 07 - Create a Wind Corridor - a.) Create an Opening on the existing harbor wall	13.63
Case 07 - Create a Wind Corridor - b.) Removing existing harbor wall	13.67

Figure 130 : Simulated Mean Radiant Temperature for the Case 07 – Create Wind Corridors scenario at the Night Time 21:00:01h.

Source: Author

Figure 131: Simulated Mean Radiant Temperature distribution for the Case 07 – Create wind corridors, a.) Create an Opening on Existing Harbor wall and b.) Removing Existing Harbor wall at the Day time ,13:00:01h.

Source: Author

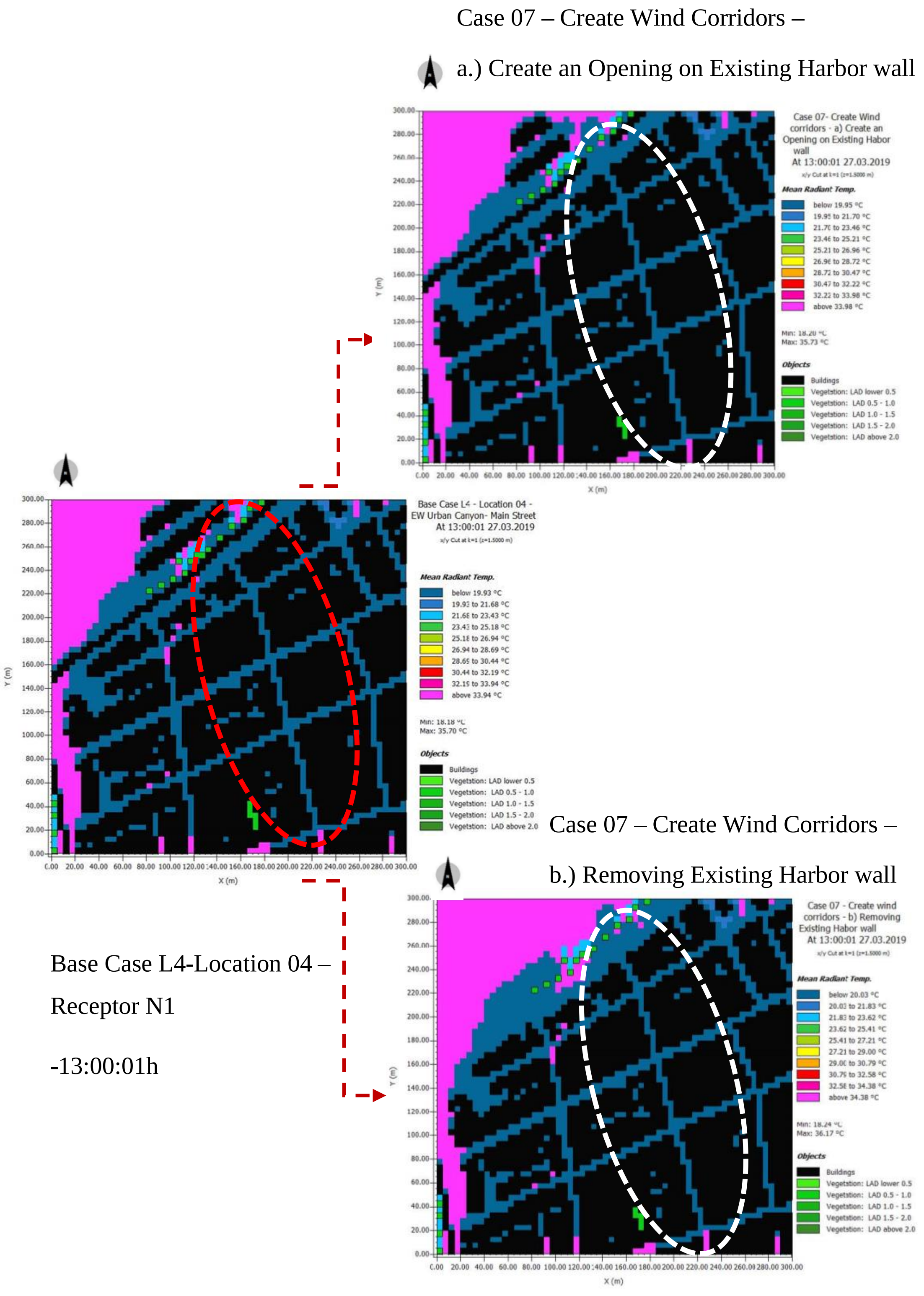
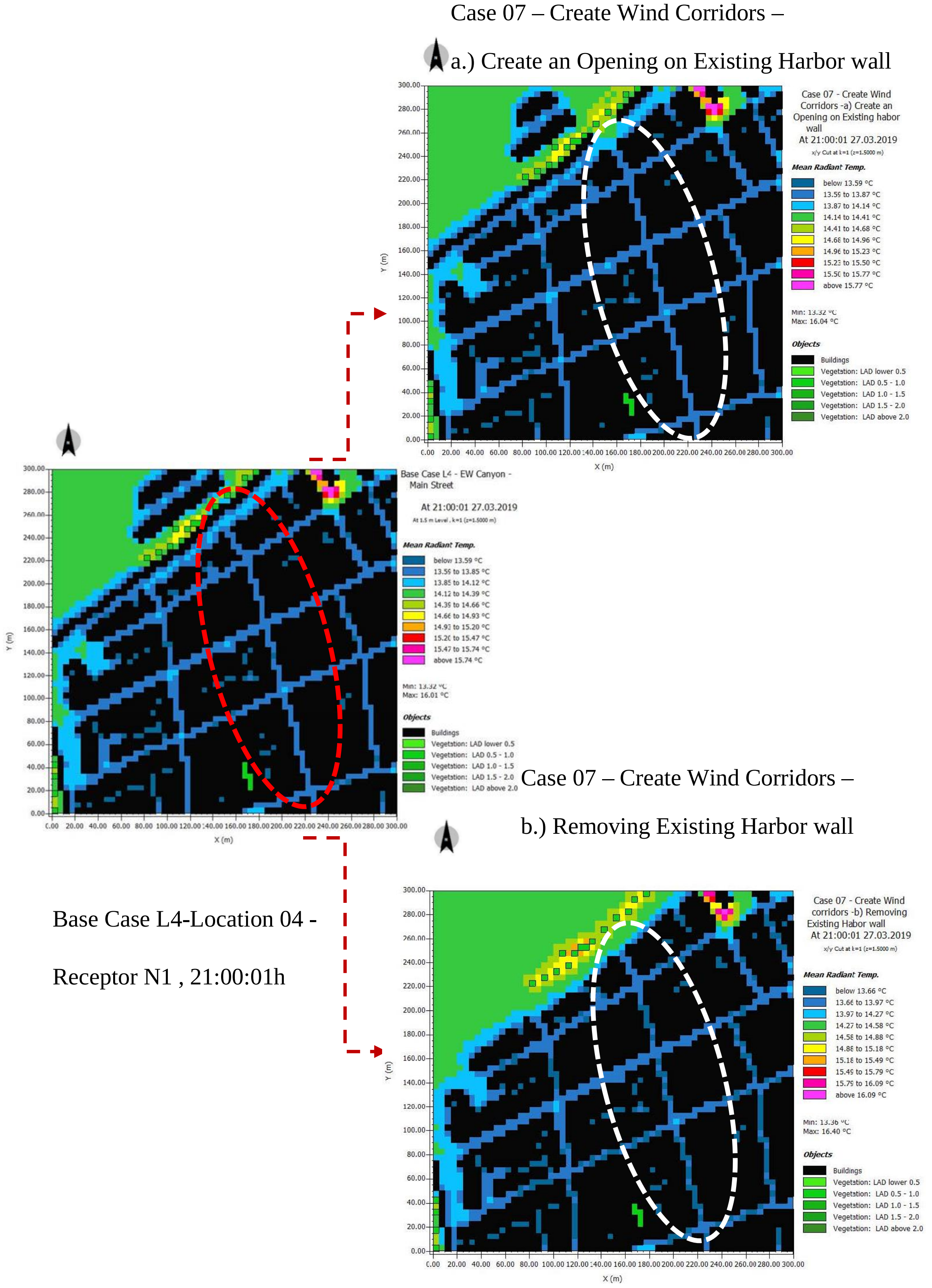


Figure 132 : Simulated Mean Radiant Temperature distribution for the Case 07 – Create wind corridors, a.) Create an Opening on Existing Harbor wall and b.) Removing Existing Harbor wall at the Night time ,21:00:01h

Source : Author



- At the both Day time and the Night time shows the very less difference of the Simulated MRT values taken at the North South direction Receptor Point.
- The Simulated MRT was highest than the existing scenario at the Base case for the both Day and Time.
- Behavior of Create Open spaces were Cleary shown in the Figure 129, Figure 130, Figure 131 and Figure 132.

05. Changing Surface Material. (Case 08)

Simulated Mean Radiant Temperature distributions of the Case 08 – Creating Wind Corridors- L4 at the day time 13:00:01h and at the Night time 21:00:01h is shown in the Figure 133, Figure 134 and the Appendix IX.

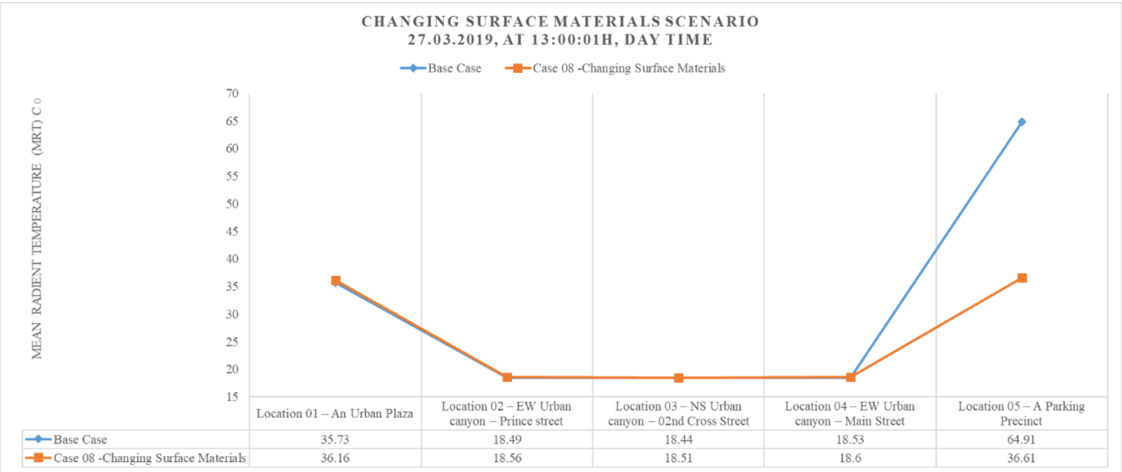


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Figure 133 : Simulated Mean Radiant Temperature for the Case 08 – Changing Surface Materials scenario at the Day Time 13 :00:01h

Source: Author

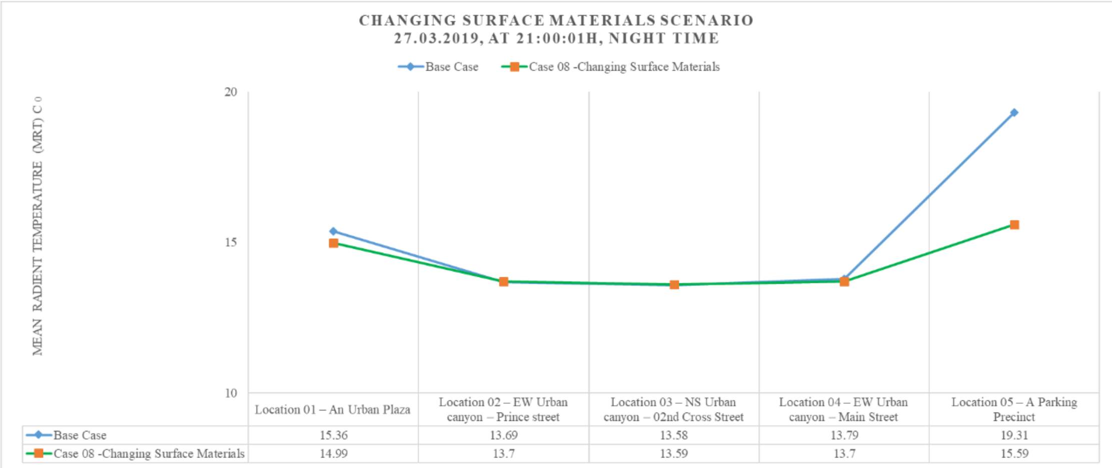


Figure 134 : Simulated Mean Radiant Temperature for the Case 08 – Changing Surface Materials scenario at the Night Time 21:00:01h.

Source: Author

- According to the Figure 133, Figure 134 and Appendix IX , the Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 01 – An Urban Plaza was slightly increased than the MRT value of the Existing situation, the Base Case of - Location 01 – An Urban Plaza at the Day time. Therefore, although change the surface materials of the Urban Plaza the difference of the MRT value change is very less due to the direct sunlight dipping to the particular Location.
- The Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 02– EW Canyon, Prince Street at the Day time, 13:00:01h was slightly increased than the MRT value of the Existing situation, the Base Case of - Location 02 – EW Canyon at the Day time. At the Location 03 – NS Canyon the MRT values of Case 08 is higher than the Base case of Location 03 at Day time, 13;00;01h.
- The Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 04– EW Canyon – Main Street was slightly decreased than the MRT value of the Existing situation, the Base Case of - Location 04 – EW Canyon at the Day time.

- The Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 05– A Parking Precinct was decreased at the Day time and the Night Time.

- The Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 01 – An Urban Plaza at the Night Time, 21:00:01h was slightly reduced than the MRT of the Existing situation, the Base Case of - Location 01 – An Urban Plaza at the Night time. When comparing to the MRT value of Day time and the Night time it was observed the MRT values of the Night time is very less than the Day time.

- The Simulated Mean Radiant Temperature of the Case 08 – Changing Surface Materials in Location 02– EW Canyon, Prince Street at the Night Time, 21:00:01h was slightly reduced than the MRT value of the Existing situation, the Base Case of - Location 02 – EW Canyon at the Night time. When comparing to the MRT value of Day time and the Night time at the Location 02 it was observed the MRT values of the Night time is very less than the Day time. At the Location 03 – NS Canyon the MRT values of Case 08 is much higher than the Base case of L03 at both Day time and the Night Time. The MRT values of the Case 08 for the Location 02 – EW Canyon is less than the MRT values of Location 03 – NS Canyon at the Night time.

- The Simulated Mean Radiant Temperature value of the Case 08 – Changing Surface Materials in Location 04– EW Canyon – Main Street mostly indicated the same MRT value comparing with the Existing situation, the Base Case of - Location 04 – EW Canyon at the Night time. Comparing the MRT values of the Day time and the night time it was observed that the MRT values of the day time is higher than the Night time both Base case and the Case 08.

4.3.3 Predicted Mean Vote Analysis (PMV)

Predicted Mean Vote Values were obtained from the ENVI –met 4 BIOMET V1.01 and relevant graphs were prepared by using the Leonardo 2014, of all different Five built forms and discussed its variations and differences of thermal stress. PMV values were taken at the level of 1.5m for the Day time 13:00:00h and the Night Time 21:00:00h respectively.

Predicted Mean Vote (PMV) is an index to predict the average vote of a huge set of people on the seven –point thermal Sensation /feeling scale.

Thermal Sensation Scale;	
Scale	***Comments***
+3 = Hot	intolerably warm
+2 = Warm	tolerably uncomfortable, warm
+1 = Slightly Warm	too warm
0 = Normal	Comfortable
-1 = Slightly Cool	tolerably un comfortable, cool
-2 = Cool	too cool
-3 = Cold	intolerably cool

Table 23: Thermal Sensation Scale

Source: Franger's comfort Equation

Calculated for the PMV values for the each Locations and also for modification scenarios were graphically graphs at the Day time of 13:00:00 h and the Night time 21:00:00h.

4.3.3.1. Predicted Mean Vote Analysis (PMV) for the Existing Scenario of all Five locations. (Base Case)

- Day Time, 13:00:00h

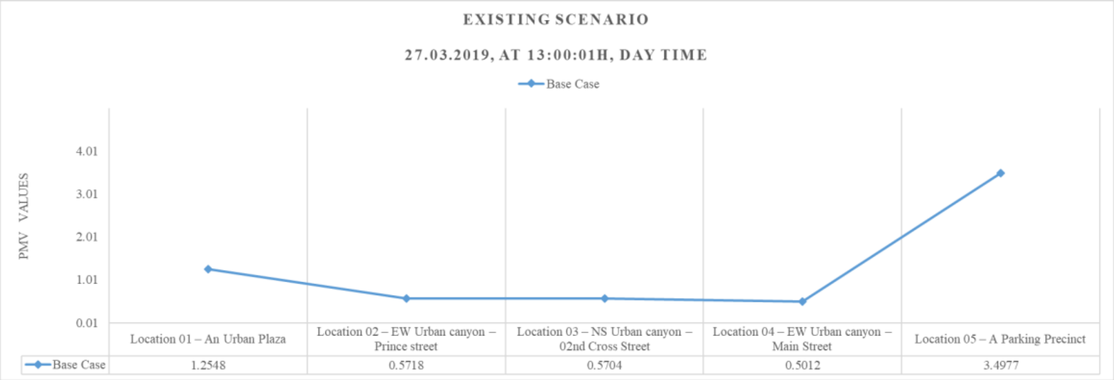


Figure 135: PMV values of the Existing Scenario at the Day time, 13:00:01h

source: Author

- Night time, 21:00:00h

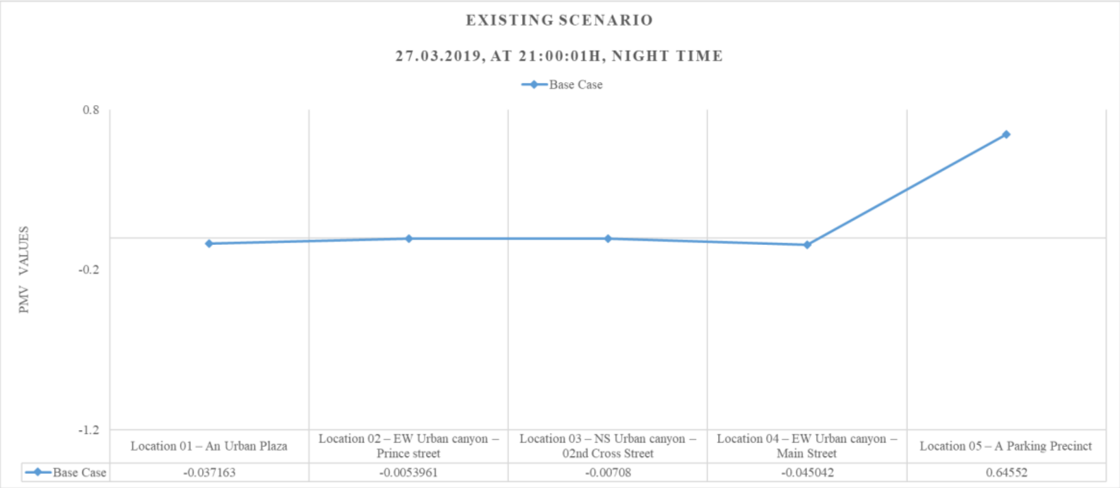


Figure 136 : PMV values of the Existing Scenario at the Day time, 21:00:01h

source: Author

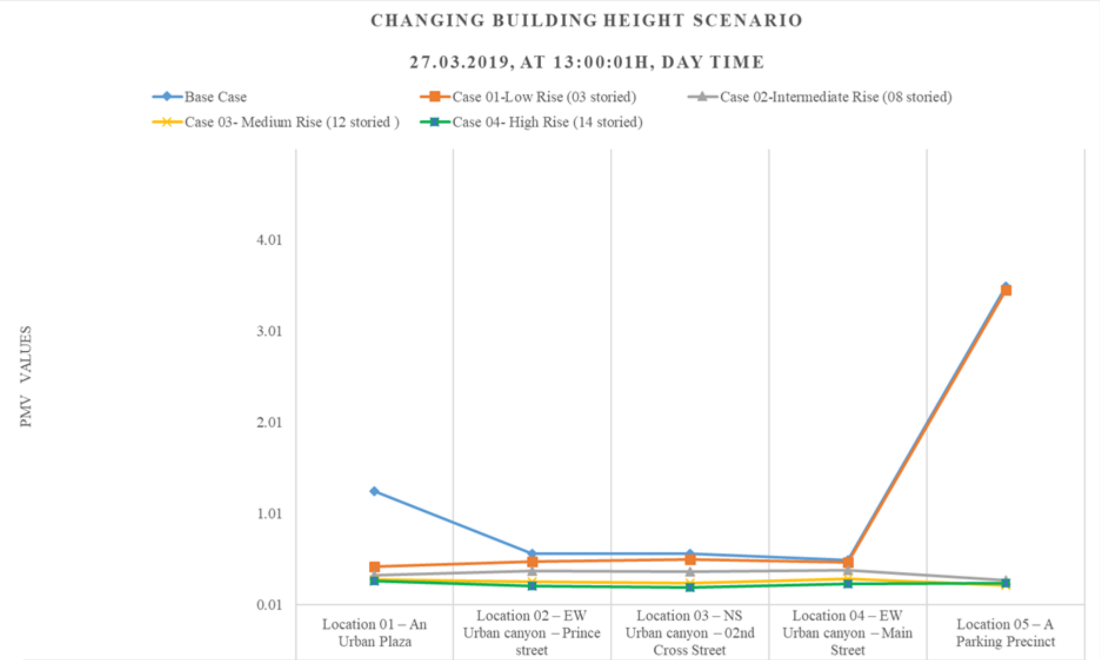
- East- West Canyons and the North -South Canyon shows the lowest PMV values comparing all five locations at the Day time, 13:00:01h.
- As per the Figure 135, PMV values are 0.57 for Receptors of both EW Urban Canyons and NS Urban canyons. When compared with the thermal sensation scale in the Table 23 those EW and NS canyons feel comfortable comparing to other Locations for the day time.

- PMV values of the Receptor for the Location 05 -Parking Precinct shows the highest PMV value for both day and night time of the existing scenario. According to the Thermal sensation scale that location feel intolerably warm at the Day time. Night time its feel comfortable.

4.3.3.2 Predicted Mean Vote Analysis (PMV) for Envisaged Scenarios.

01.) Changing of Building Heights. (Case 01, case 02, case 03 and Case04)

- Day Time, 13:00:00h

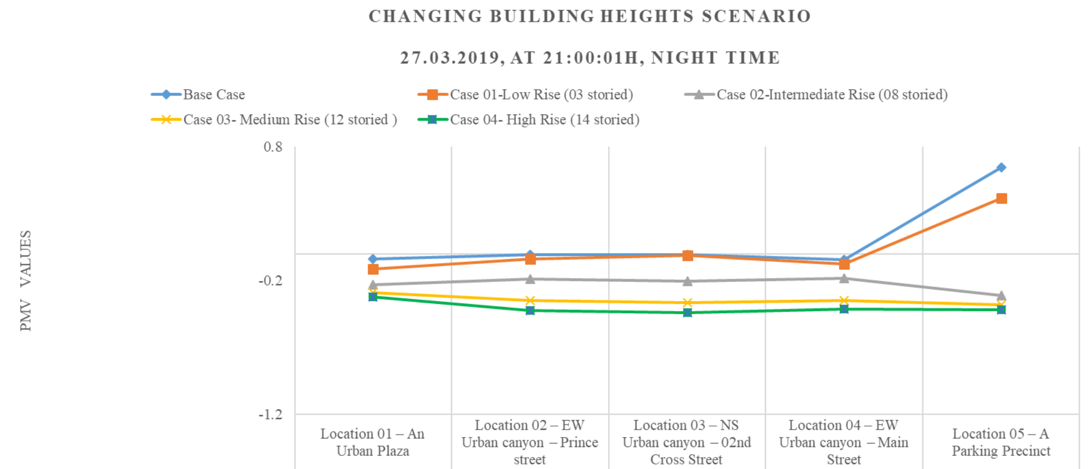


	Location 01 – An Urban Plaza	Location 02 – EW Urban canyon – Prince street	Location 03 – NS Urban canyon – 02nd Cross Street	Location 04 – EW Urban canyon – Main Street	Location 05 – A Parking Precinct
Base Case	1.2548	0.5718	0.5704	0.5012	3.4977
Case 01-Low Rise (03 storied)	0.4296	0.4854	0.5101	0.4739	3.456
Case 02-Intermediate Rise (08 storied)	0.3333	0.3858	0.3722	0.3941	0.2775
Case 03- Medium Rise (12 storied)	0.2863	0.2637	0.2499	0.2958	0.2216
Case 04- High Rise (14 storied)	0.2713	0.2155	0.2024	0.2423	0.2473

Figure 137 : PMV values of Changing Building Height Scenario at the Day time, 13:00:00h

source: Author

- Night Time, 21:00:00h



	Location 01 – An Urban Plaza	Location 02 – EW Urban canyon – Prince street	Location 03 – NS Urban canyon – 02nd Cross Street	Location 04 – EW Urban canyon – Main Street	Location 05 – A Parking Precinct
Base Case	-0.037163	-0.0053961	-0.00708	-0.045042	0.64552
Case 01-Low Rise (03 storied)	-0.11217	-0.041429	-0.015021	-0.076576	0.41407
Case 02-Intermediate Rise (08 storied)	-0.23161	-0.19076	-0.20698	-0.18586	-0.31408
Case 03- Medium Rise (12 storied)	-0.28819	-0.34904	-0.36809	-0.34722	-0.38084
Case 04- High Rise (14 storied)	-0.32058	-0.42358	-0.44249	-0.41574	-0.41648

Figure 138: PMV values of Changing Building Height Scenario at the Night time, 21:00:00h

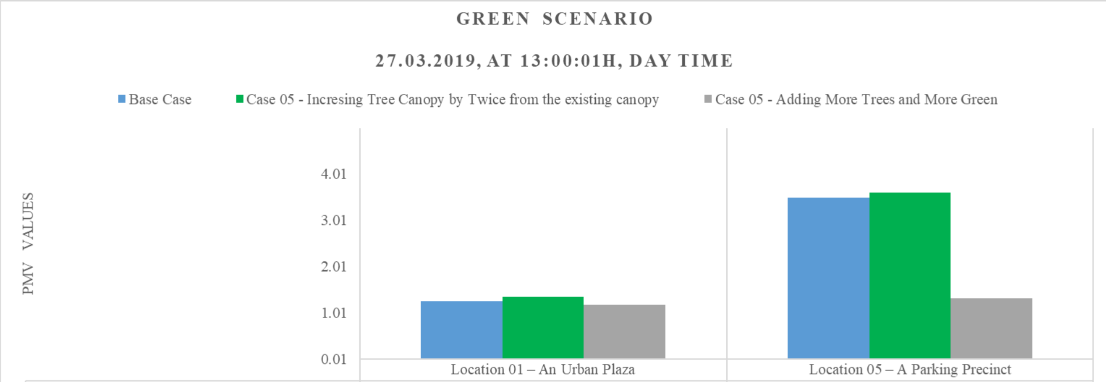
Source: Author

- As per the Figure 137 and the Figure 138 the High Rise scenario indicated the lowest PMV values for the all Locations at the Day time as well as the Night time.
- Therefore, increasing the Building heights as per the regulation is the most suitable option to create a comfortable environment.
- EW and NS Urban Canyons shows the lowest PMV values comparing all Locations due to the Shade at the Day time.
- According to the Thermal sensation scale in Table 23 all the Location at the Night time were feel comfortable.

2.0) Green Scenario (Case 05)

PMV Value were calculated according to the cases for Increasing Tree Canopy by twice from the existing canopy and the Adding more trees and more green for the Location 01 – An Urban Plaza and the Location 05 – A Parking precinct.

- Day Time , At 13:00:00h

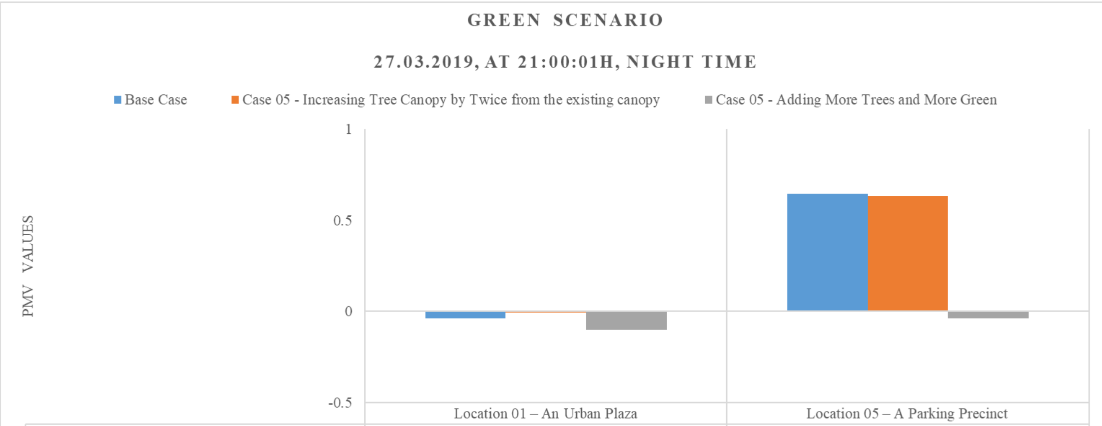


	Location 01 – An Urban Plaza	Location 05 – A Parking Precinct
Base Case	1.2548	3.4977
Case 05 - Incresing Tree Canopy by Twice from the existing canopy	1.3585	3.6112
Case 05 - Adding More Trees and More Green	1.1818	1.326

Figure 139 : PMV values of Green Scenario at the Day time, 13:00:00h

source: Author

- Night Time, At 21:00:00h



	Location 01 – An Urban Plaza	Location 05 – A Parking Precinct
Base Case	-0.037163	0.64552
Case 05 - Increasing Tree Canopy by Twice from the existing canopy	-0.0072382	0.63198
Case 05 - Adding More Trees and More Green	-0.10174	-0.038768

Figure 140 : PMV values of Green Scenario at the Night time, 21:00:00h

source: Author

- As per the Figure 139 the Location 01 – An Urban Plaza indicated the lesser PMV values than Location 05 – A Parking Precinct for the Day time. According to the Thermal Sensation Scale all Locations feel more than too warm due to the PMV values increased more than +1 for the Day time.
- For the Night Time Location 01 feel comfortable due to PMV values were lesser than the “0”. For the Location 05, calculated PMV values were lesser than the “0” only at the Adding more tress and more green scenario at the night time.
- In the Green scenario, Adding More trees and More Green option shows the considerable impact to reduce the PMV value than the increasing Tree canopy.

PMV Value were calculated according to the case of **Adding a Tree Line** for both sides for the Location 04– EW Canyon – Main Street.

- Day Time, At 13:00:00h

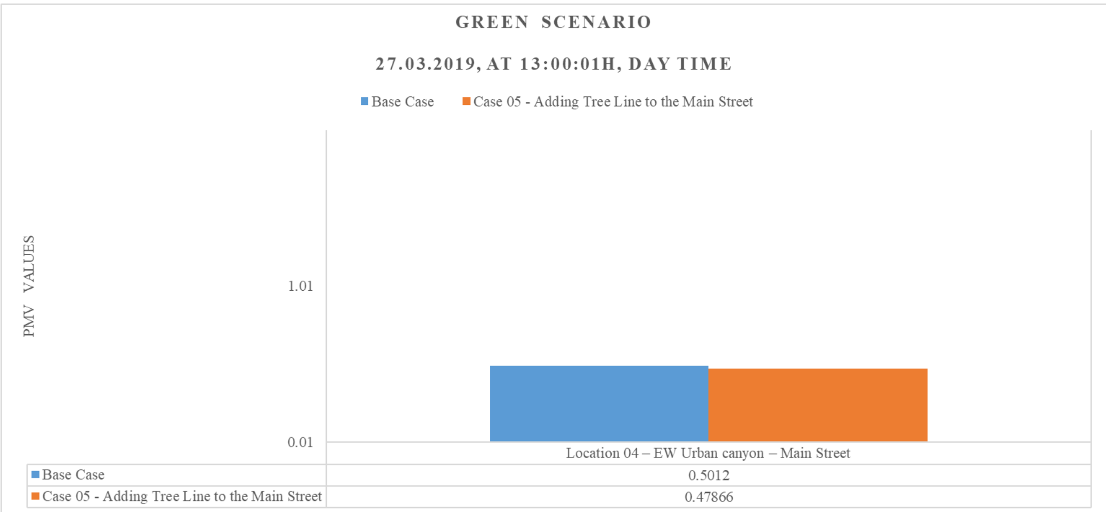


Figure 141 : values of Green Scenario – Adding Tree Line for the Location 04 – EW Canyon – Main Street at the Day time, 13:00:00h

source: Author

- Night Time , At 21:00:00h

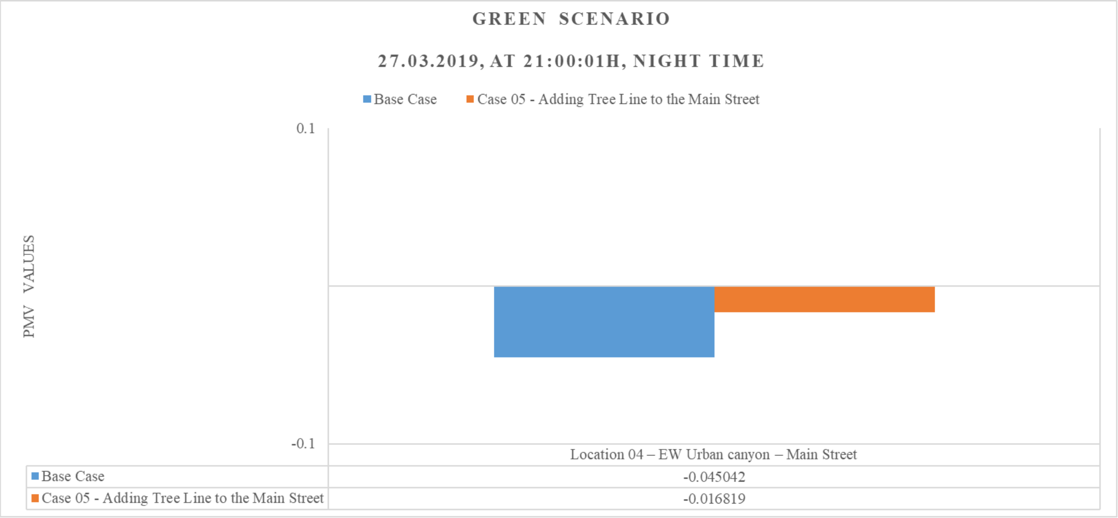


Figure 142 : PMV values of Green Scenario – Adding Tree Line for the Location 04 – EW Canyon – Main Street at the Day time, 21:00:00h

Source: Author

- As per the Figure 141 and the Figure 142 the PMV value was decreased comparing with the existing situation at the same Location when Adding a Tree line for the Location 04- EW Canyon – Main Street both at the Day time and Night Time.

- According to the Sensation Scale the PMV value is Less than the “0”. Therefore, Location feel comfortable at the Night time.

03.) Create Open Spaces Scenario (Case 06)

PMV Value were calculated according to the case 06 – Create an Open Space for the Location 02– EW Urban canyon – Prince Street and Location 03 – NS Urban canyon – 02nd cross Street for the Day time at 13:00:01h and Night Time at 13:00:01h.

- Day Time , At 13:00:01h

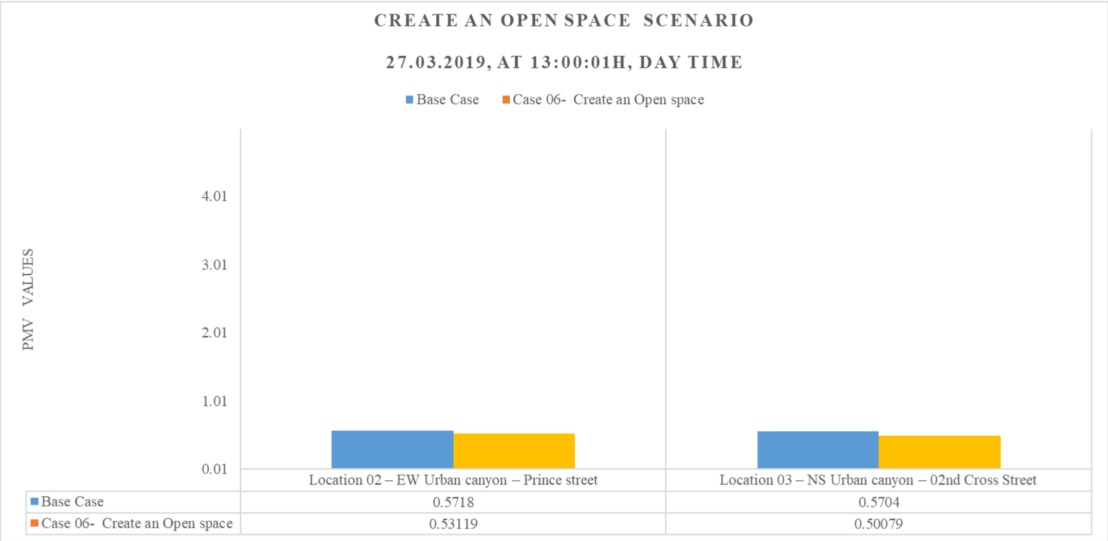


Figure 143 : PMV values of Green Scenario – Case 06 – Create an Open Space at the Day time, 13:00:01h

source: Author

- As per the Figure 143, Figure 144 and Figure 145, the Location 02 – East West (EW) Urban Canyon and the Location 03 – NS Urban canyon shows the nearly similar PMV values. Further, the calculated PMV Value was higher than to the “0”. Therefore, the Location 02 and Location 03 feel slightly warm at the Day time.

- Impact of Create an Open space on Urban canyons/ Urban streets is much lesser due to created open space directly exposed to the sun waves.

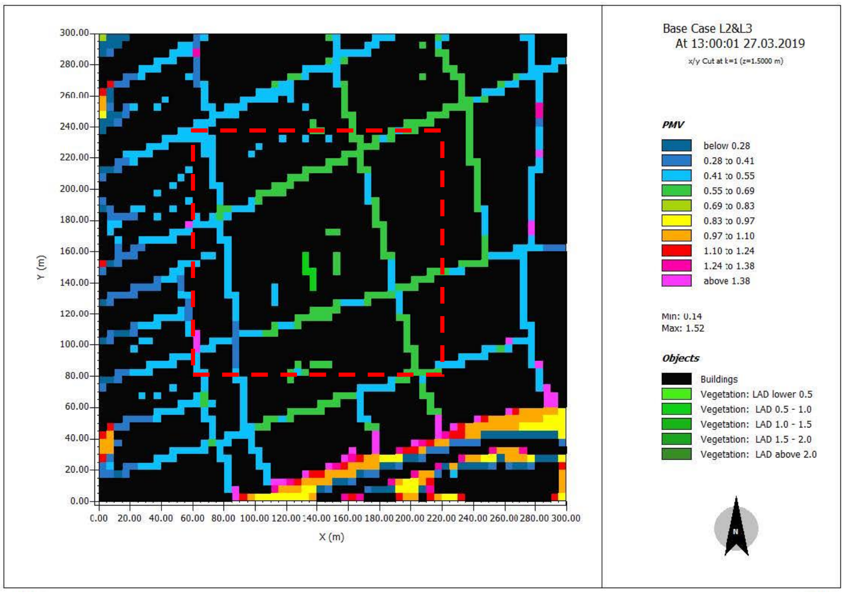


Figure 144 : PMV distribution of Existing Scenario – Base Case L2&L3 at the Day time, 13:00:01h

Source: Author

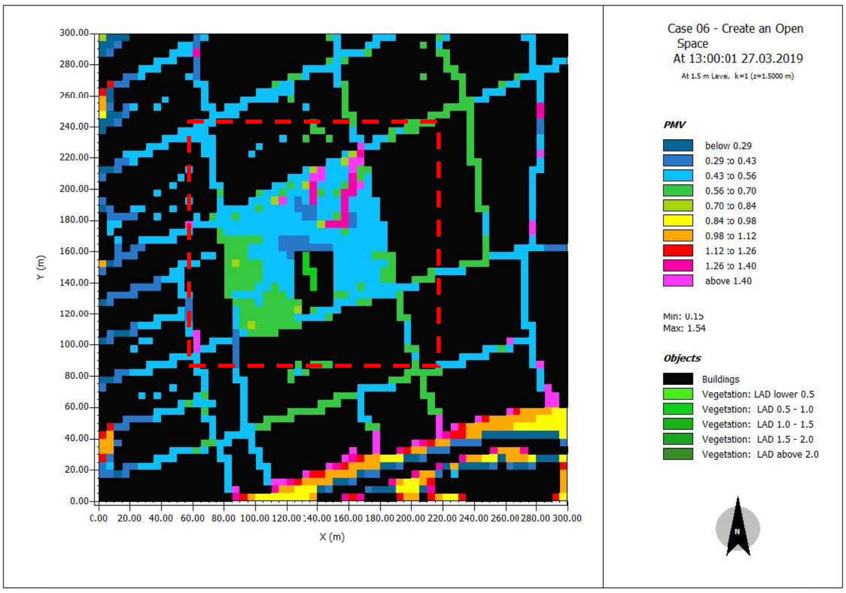


Figure 145: PMV distribution of Green Scenario – Case 06 – Create an Open Space at the Day time, 13:00:01h.

Source: Author

- Night Time , At 21:00:01h

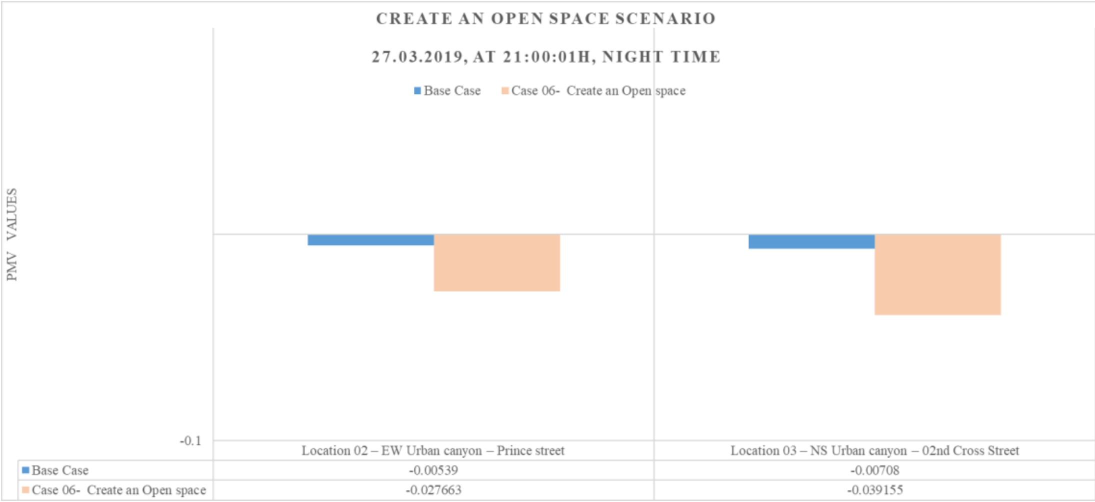


Figure 146: PMV values of Green Scenario – Case 06 – Create an Open Space at the Night time, 21:00:01h

Source: Author

- As per the Figure 146, Figure 147 and the Figure 148 the calculated PMV value of Location 02 – EW Urban Canyon is lesser than the Location 03 – NS Urban canyon and all the calculated PMV Values were less than “0”. Therefore, the Location 02 and Location 03 feel comfortable at the Night time also.

- But comparing with the existing situation, Base Case scenario, Calculated PMV values were increased of both Locations at the Night Time.

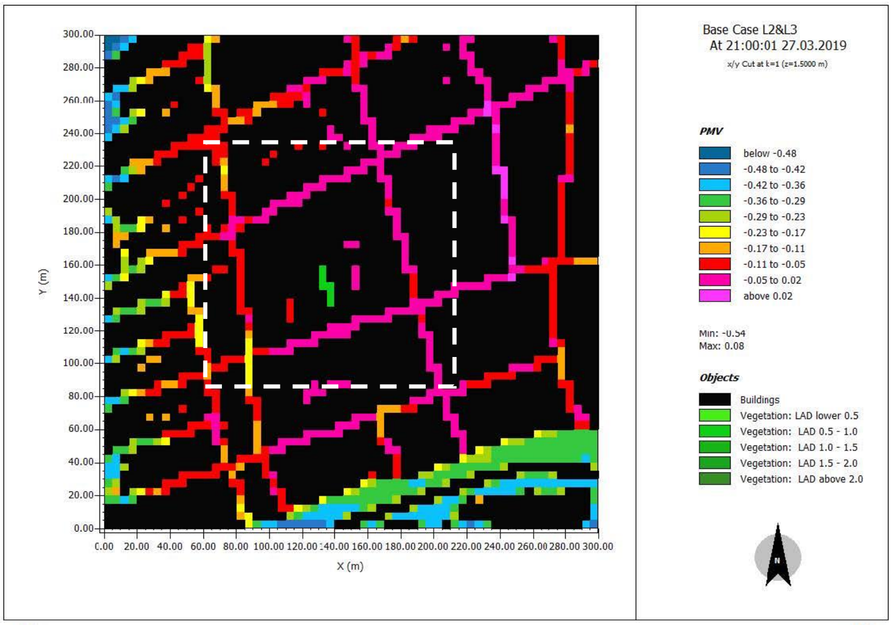


Figure 147 PMV distribution of Existing Scenario – Base Case L2&L3 at the Night time, 21:00:01h

Source: Author

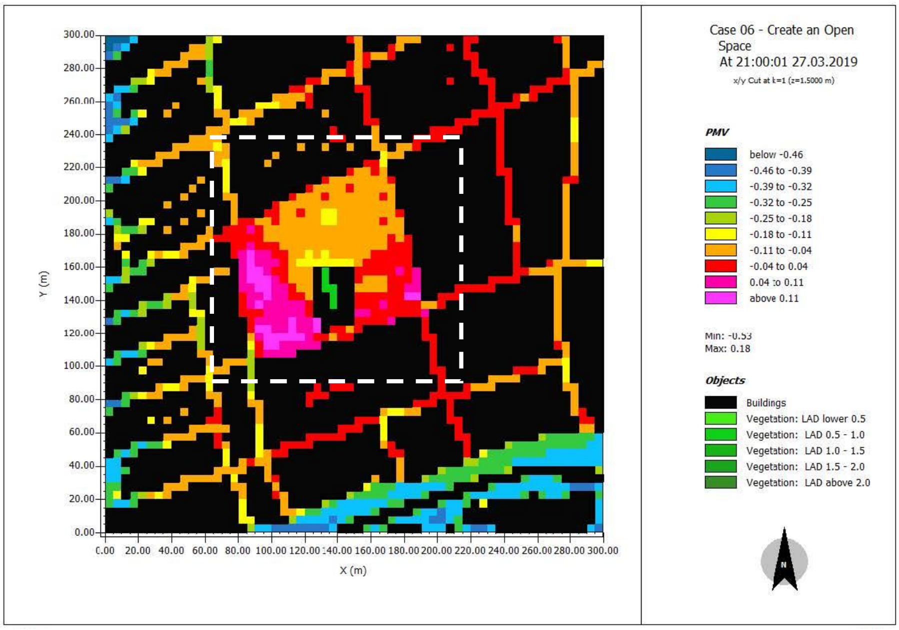


Figure 148 : PMV distribution of Green Scenario – Case 06 – Create an Open Space at the Night time, 21:00:01h.

Source: Author

04.) Create Wind Corridors Scenario (Case 07)

PMV Value were calculated according to the case 07 – Create Wind Corridor Using the Location 04– EW Urban canyon for the Day time at 13:00:01h as well as the Night Time at 21:00:01h. The simulation was done for two scenarios as (a.) Create an Opening on Existing harbor Wall and (b.) Removing Harbor Wall and compared the differences of calculated PMV values.

- Day Time, 13:00:01h

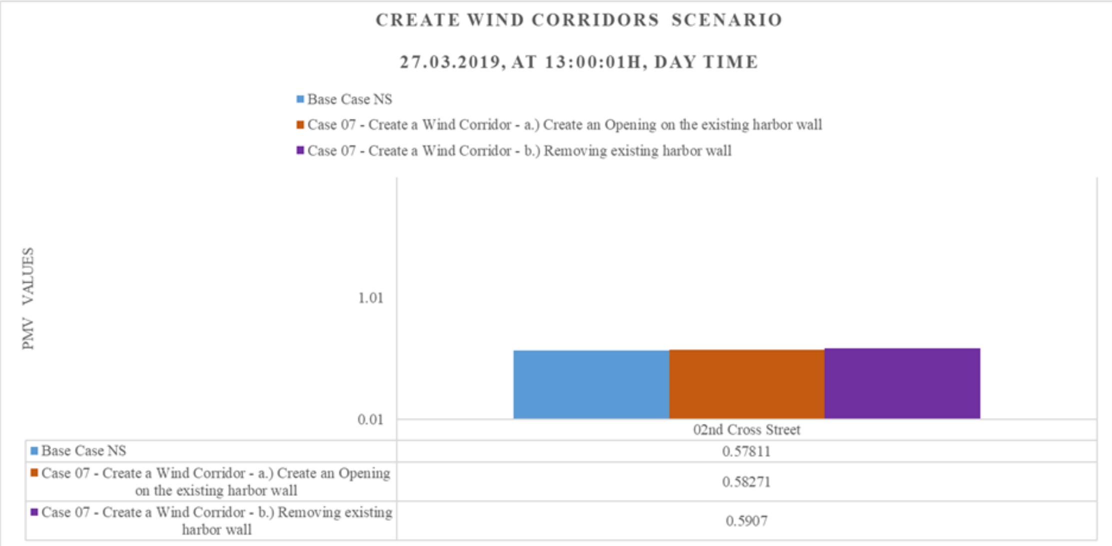


Figure 149 : PMV values of Case 07 – Create wind corridor scenario at the Day time, 13:00:01h

Source: Author

- As per the Figure 149, the PMV value of a.) Removing harbor wall scenario is much higher than the b.) create an Open space on the existing harbor wall scenario at the Day time.
- Removing Harbor wall effect to create wind corridor to the 02nd cross streel directly. Due to the impact of sea breeze which along through the Urban canyon the PMV value increased.

- Night Time, 21:00:01h

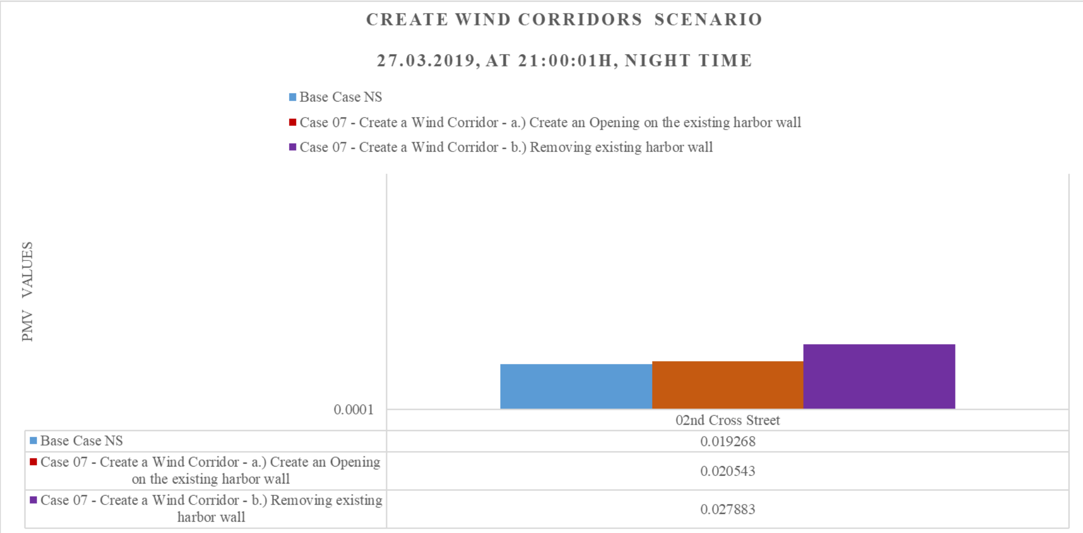


Figure 150 : PMV values of Case 07 – Create wind corridor scenario at the Night time, 21:00:01h..

Source: Author

- As per the Figure 151, for the Night time also happening the same.
- According to the Figure 150 and Figure 151, the calculated PMV values regarding to the Case 07 – Create wind corridors, both (a) Create an Opening on the existing harbor wall and (b.) Removing existing harbor wall were higher than the existing situation/Base Case Scenario at the day time as well as the Night Time.
- Further, considering the comfort of the wind corridors (02nd cross street) it was feel the slightly warm due to the PMV value higher than to the “0” as per the Sensation scale for the both day and night times.
- Therefore, the impact of create wind corridors scenario near the area having sea breeze area is less.

05.) Changing Surface Material Scenario (case 08)

PMV Value were calculated according to the case 08 – Changing Surface Materials for each different Five Locations for the Day time at 13:00:01h as well as the Night Time at 21:00:01h.

- Day time, 13:00:01h

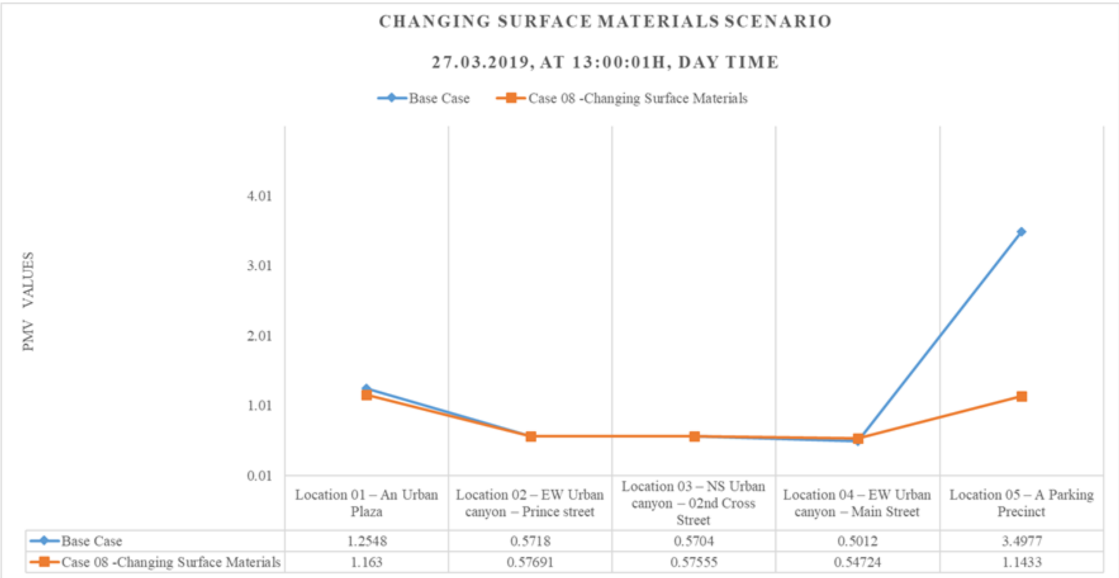


Figure 151 : PMV values of Case 08 – Changing Surface Materials scenario at the Day time, 13:00:01h.

Source: Author

- As per the Figure 151, the calculated PMV values of Location 01 – An Urban Plaza and the Location 05 – Parking Precinct shows considerable decreased than the Location 01 – East West Urban Canyon – Prince Street, Location 03 – North South Urban Canyon and the Location 04 – East West Urban Canyon – Main Street.
- According to the sensation scale all Locations feel slightly warm at the Day time.

- Night time, 21:00:01h

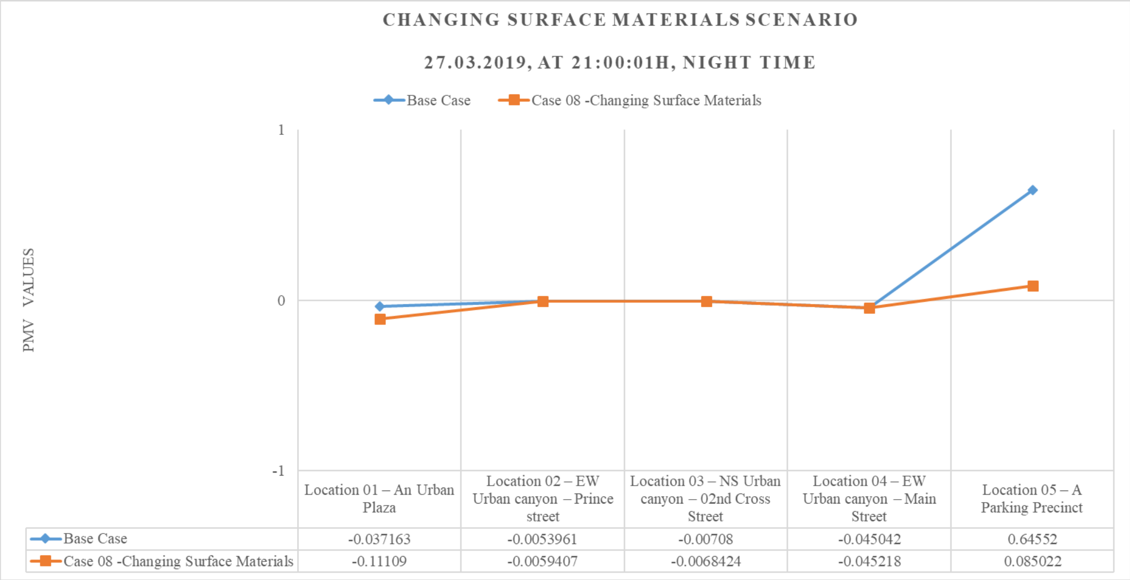


Figure 152: PMV values of Case 08 – Changing Surface Materials scenario at the Night time, 21:00:01h.

Source: Author

- As per the Figure 152, at the Night time, calculated PMV values of Location 01 – An Urban Plaza, Location 02 – East West Urban Canyon – Prince Street , Location 03 – North South Urban Canyon and the Location 04 – East West Urban Canyon – Main Street indicated the **"-"** PMV values. Hence all 04 Locations feel comfortable at the Night time except the Location 05, due to its having the PMV value higher than to the "0".

- Therefore, the Location 05 – A Parking Precinct feel slightly warm at the Night time.

CHAPTER FIVE: CONCLUTION

This Study was clearly highlighted the impact of different urban built forms to the outdoor thermal comfort and importance of create planning strategies to mitigate the Urban heat for pedestrian comfort.

The relevant analysis were carried out with two methods to active objectives as mentioned in the Chapter one at the 27th March 2019 which was the one of the hottest month in Sri Lanka.

5.1 Key findings of the study

The Following Findings were summarized of empirical data Analysis and the ENVI – met Simulation data analysis.

5.1.1. Summary of Findings for Empirical Data Analysis.

5.1.1.1. Average Air Temperature

<u>- 11.00 a.m. to 13.00 p.m.</u>

- The highest Average Air temperature was observed from the Location 05 with a Parking precinct.
- The lowest Average Air temperature was observed from the Location 01 which is an Urban Plaza.
- Average Air Temperature is higher at the Location 04 – East – West Urban canyon (Main Street) which comprises with the wider urban canyon than the Location 02- East-West Urban Canyon (Prince Street) which comprises a narrow urban canyon.

<u>- 16.00 p.m. to 18.00 p.m.</u>

- The highest Average Air temperature was observed from the Location 01 having with an Urban Plaza at the time period of 16.00 p.m. to 18.00 p.m.
- The lowest Average Air temperature indicated from the Location 05 consisting with a Parking Precinct.
- Average Air Temperature of the Location 02– East – West Urban canyon (Prince Street) which comprises with the narrow urban canyon is higher than

the Location 04- East-West Urban Canyon (Main Street) which comprises a wider urban canyon.

5.1.1.2. Thermal Heat Index Value (THI Value)

- 11.00 a.m. to 13.00 p.m.

- The highest THI value was indicated from the Location 05 having with a Parking Precinct.
- The lowest THI value was indicated from the Location 01 which have an Urban Plaza.
- All locations achieved the more than 26 C^o THI value. Therefore, at the time period of 11.00 a.m. to 13.00 p.m. feel uncomfortably hot.

- 16.00 p.m. to 18.00 p.m.

- The highest THI value was indicated from the Location 01 consisting with an Urban Plaza.
- The lowest THI value indicated from the Location 05 having with a Parking Precinct.
- The THI value of Location 05 is less than the 26 C^o . Therefore, it feels 50% of the subjects feel comfortable.
- Other all locations feel uncomfortable due to the THI values were more than the 26 C^o.

5.1.1.3. Thermal Heat Index Difference (THI Difference)

- 11.00 a.m. to 13.00 p.m.

- The Location 05 which have a Parking Precinct indicated the less THI difference comparing all other Locations.
- The heist THI Difference was indicated from the Location 01 which consist an Urban Plaza.

- 16.00 p.m. to 18.00 p.m.

- The less THI difference was observed from the Location 01 which consist an urban Plaza.
- The highest THI difference was observed from the Location 05 which have a Parking precinct.

5.1.1.4. Surface Temperature

- 11.00 a.m. to 13.00 p.m.

- The highest Average Surface Temperature was indicated from the Location 05 which have a parking Precinct.
- The lowest Average Surface temperature was indicated from the Location 02 consist with an East –West Canyon (a) Prince Street.

- 16.00 p.m. to 18.00 p.m.

- The highest Average Surface Temperature was indicated from the Location 01, consist an urban Plaza.
- The lowest Average Surface temperature was indicated from the Location 05 consist a Parking Precinct.

5.1.2. Summary of Findings of ENVI - met Computer based Simulation Data Analysis on envisaged planning interventions.

5.1.2.1. Air Temperature

Increasing Building heights and Changing Surface Materials Scenario

- Changing surface Materials Scenario assists to reduce the Air temperature on both Location 02 – East West Urban canyon and the Location 03 – North South Urban Canyon as shown in the Figure 153 in Appendix X.

- Changing surface material scenario also assists to reduce the Air Temperature on all Locations as shown in Figure 152 in Appendix X. That scenario also most effected to the Location 02-East West urban Canyon and the Location 03-North South urban canyon which applied red brick as their road paving.
- Increasing building heights scenario is the most suitable scenario to reduce the Air temperature of all locations.

Green Scenario

- Considering the Green scenario there were choose only three Locations which already have greeneries at the existing and having any possibilities to apply proposed scenarios.
- As per the Figure 92, Figure 93, Figure 94 and the Figure 95 there have a slightly deduction of simulated Air temperature indicated from the Location 01, An Urban Plaza and the Location 05, A Parking Precinct.
- Therefore, Trees with large tree canopies and adding more trees and more green at urban areas as can use as urban heat mitigation strategies in city planning.
- As per the Appendix X, Figure 160, Adding More Trees and more green scenario applied to the Location 01, An Urban Plaza is more effective in reducing air temperature than the Location 05 which having with a parking precinct.

Create an Open Space Scenario

- According to the Figure 99 , Figure 100 and the Appendix IV both Day time and the Night time simulated Air temperature for Create an Open Space scenario were decreased comparing with the Existing scenario. But the effect of day time, 13:00:01h to the Air temperature variation is very less comparing with the existing scenario.

Creating wind corridors Scenario

- As per the simulated results, creating wind corridors scenario for the 02nd cross street, the effect to the Air temperature variation is very less. The simulated Air temperature was slightly increased than the existing scenario due to effect of hottest sea breeze directly come through the created Urban wind corridor.

5.1.2.2. Mean Radiant Temperature (MRT)

<u>Increasing Building heights and Changing Surface Materials Scenario</u>

- According to the Appendix X and Figure 155 it was clearly identified the simulated MRT values were decreased at the increasing building height scenario than the change the surface temperature scenario at all locations.
- The simulated MRT values of Location 02, East West canyon, the Location 03 , North South Canyon and the Location 04 , EW Canyon (Main Street) which were classified as Urban canyons were comparatively less than the Location 01 , An Urban Plaza and the Location 05 ,A Parking precinct.

<u>Green Scenario</u>

- Considering the Green scenario, adding more trees and more green was the most effective scenario to reduce the MRT at the Location 05, A Parking Precinct. At the Location 01 , An Urban Plaza shows the slightly higher MRT value than the existing scenario at the Day time as well as the Night time at the case of adding more trees and more green scenario.
- As per the Figure 122 and Figure 123 it was observed a very few deductions of simulated MRT value for the Location 04, East- West Urban canyon which is called as the Main street in Pettah as the result of the case, adding a tree line along the Main street for both sides.

<u>Create an Open Space Scenario</u>

- Considering the create an open space scenario done to the Location 02 , East-West canyon (Prince street) and the Location 03 , North -South canyon (02nd cross street) the simulated MRT values were increased comparing its existing scenario. But the difference of the MRT is very less as per the Figure 126 and the Figure 127 for both Day time as well as the Night time. That was happened due to the many reasons such as direct sunlight dipping on the created Urban plaza, sea breeze, wins speed, albedo (Reflection and absorption of materials) of surface materials…. etc.

Creating Wind corridors Scenario

- Considering the creating wind corridor scenario which was applied to the 02nd Cross street at the Pettah, the effect of the MRT difference was very less for the both Day and night times as shown in the Figure 129 and Figure 130.
- The simulated MRT was slightly increased with the base case. It was occurred due to the impact of sea breeze and the wind effect happening at the location.

5.1.2.3. Predicted Mean Vote (PMV)

Increasing Building heights and Changing Surface Materials Scenario

- According to the Figure 157 in Appendix X, it was observed the lowest PMV values indicated from the Case 04 - High Rise under the increasing building heights scenario for all Locations.
- Increasing of Building height scenario most effected to the Location 02 consist with a East – West (EW) urban canyon and the Location 03 consist with a North –South (NS) urban canyon among all five locations.
- According to the thermal sensation scale in the Table 23, Location 02, EW Urban canyon and Location 03, NS Urban canyon simulated under the Case 04 – High rise scenario, feel slightly warm at the Day time and slightly warm at the Night time as shown in Figure 137 and Figure 138.

Green Scenario

- At the green scenario the calculated PMV values at the day time is more than +1 under the adding more trees and more green scenario as shown in Figure 139.
- According to the thermal sensation scale in the Table 23, the Location 01 – An Urban Plaza and Location 05 – Parking Precinct feel slightly warm under the adding More trees and more green scenario at the day time.
- Under the increasing tree canopy scenario, it was observed that only Location 01 – An Urban Plaza feel slightly warm due to its PMV value was indicated as

+1. For the Location 05 – A parking precinct indicated PMV value is more than +3. Accordingly, Location 05, feel intolerably Warm as per the Thermal Sensation scale in the Table 23 for the day time.

- As shown in the Figure 140, the PMV values were under the level of -1 of the Location 01 – An Urban Plaza for both increasing tree canopy and adding more trees and more green scenarios. Hence the Location 01 , get feel slightly cool.
- For the Location 05 – A Parking precinct indicated -1 as the thermal sensation scale for the adding more trees and more green scenario and its feel slightly cool.
- Increasing tree canopy scenario under the Location 05 for the Parking precinct observed that the value of PMV was under +1. Accordingly, that Location 05 consist with a Parking Precinct feel slightly warm at the Day time.
- As shown in Figure 141, it was observed that under the adding Tree line along the main street, the calculated PMV value is less compared to the existing scenario at the Day time. But indicated the considerable difference of PMV value at the Night time under the mentioned scenario as shown in Figure 142.

Create an Open Space Scenario

- Under the create an Open space scenario which was applied only for the Location 02 with an East – West (EW) urban canyon and the Location 03 with a North- South NS) canyon, the calculated PMV values were slightly reduced than the existing scenario. At the Day time as shown in the Figure 143.
- However, the PMV values were within the +1 as per the Sensation scale at both Locations and that Locations were feel slightly warm for the Day time.
- As shown in the Figure 146, it was observed that the calculated PMV value is very less than the existing scenario at the Night time.
- The PMV values obtained for the both existing and create an open space scenario simulated for the Location 02, EW urban canyon and the Location 03, NS urban canyon feel slightly cool at the Night time.

<u>Creating Wind Corridors Scenario</u>

- The calculated PMV values were increased for Creating wind corridor scenario at the Day time as well as the Night time. As per the sensation scale in the Table 23 , the PMV value of Receptor N1 feel slightly warm both Day and Night times.

Narrow Urban Canyon (prince Street) and the Wider Urban Canyon (Main Street)

According to the empirical data and the results of computer simulation it was highlighted as the narrow urban canyon is more sensible to mitigate urban heat than the wider urban canyon which are in the same orientation for the Day time. At the Night time the results show its inverse. Furthermore, the Thermal comfort of the narrow and wider canyons depends on their surface materials (Albedo), orientation, Building height (Sky view factor) etc.

5.2 Significance of the study for Spatial Planning and Design

Considering all above research findings of the following were concluded;

- Built forms with East West and North south oriented streets in a highly urbanized area act as Urban Canyons. Urban Canyon provide shade at the Day time. Accordingly, Urban planners needs to create design guidelines to promote shading in urban areas which people more gathered and areas which have more outdoor activities in City planning to mitigate urban heat and to create comfort environment for people. "Urban Shade" Concept can have introduced for the urban public spaces in tropical countries like Sri Lanka to create comfort environment in an urbanized area.
- The built forms such as an Open plaza, with lots of trees with larger tree canopy, with more green and with cool materials for paving areas also can be introduced as a successful design implications need to include in Guide plans by Spatial planners.

- Parking precinct is an another type of built form which is an essential requirement need to consider in City Planning. When creating parking in an Urban area it is very fruitful to construct with using cool surface material which have less absorption quality. And also it needs to have More trees with wide canopies in parking precincts will helps to mitigate the urban heat further.

Accordingly, it is really important to include the concluded findings of the above study in future spatial planning and it is essential to consider the urban heat and should include the urban heat mitigation strategies in to future city development plans as different environmental guide lines which need to follow by planners in creating sustainable urban settings.

5.3 Limitations of the Study

- Limitations occurred for Measured Data

- The scope of this study is limited to a selected study area of Colombo, Sri Lanka which has a warm humid climate and sea breeze will effect to the accuracy of measuring data. Further within the climatic conditions, there are variations during the year. Therefore, the results will limit for the study area.
- Limitations of the weather data range being limited to a single day. If it is located weather stations on different selected built forms for more than a day will increased the accuracy of the obtained empirical weather data.

-Limitations occurred for Computer Simulation

- When modelling the selected locations using from the ENVI-met computer software a major limitation occurred due to the available grid at the ENVI-met 4.1 software. The available grid version was 100x100x40. Therefore, the model limited to the 100x100x40 grid. Accordingly, the area wanted to simulation was limited for selected Five locations separately. If there have possibilities to model the total area including all five selected built forms, will assist to enhance their accuracy of simulated results.

- There are different measures for Thermal Comfort. But in this study it limited to Air temperature, Thermal Heat Index (THI), Thermal Heat Index Difference (THI Difference), Mean radiant temperature (MRT), Predicted Mean Vote (PMV), Humidity, Wind Speed and wind direction.

- Several technical difficulties which occurred when carrying out the Simulations for the ENVI- met software. (Time period) It possible to occurs a worst scenario.

- Further this research is a hypothetical experimental research. It's not validate the measured data due to the limitations of the software.

5.4 Directions for Future Study

- To explore the impact of different built forms for the user/ pedestrians comfort it is essential to explore the Physiological Equivalent Temperature (PET) from the ENV- met simulation. In this study it couldn't carried out due to the unavailability of Biomet output data key as the limitation of used ENVI – met computer software.
- Implementing a Questioner survey from each location regarding to people feelings of the comfort and analysis with comfort levels will be an interesting study in furthermore.
- If have any possibilities to implement this research for a macroclimatic context it would be more comprehensive research further.

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APPENDICES

APPENDIX I: Building heights were categorized according to the Urban Development Authority Guide Lines. (Appendix I – ‘C’ Form of Building Guide Plan, UDA)

Form "C"

Specification to Lots

1 Class of Building	2 Extent (Square Metres)	3 Max. Number of Floors	4 Max. Height (Metres)	5 Min. Width of Site (Road frontage) (Metres)	6 Min. Road width (Metres)	7 Rear Space (Metres)	8 Space on other Sides (Metres)	9 Space in Front (Metres)	10 Plot Coverage # Res.	10 Plot Coverage # Non Res.	11 Floor Area Ratio Res.	11 Floor Area Ratio Non Res.	12 Other Requirements
Low Rise													
- A	150 - 249	2(G+1)	7.50	6	03	2.3	-	01*	65%	80%	1:1.50	1:1.50	Nil
- B	150 - 249	3(G+2)	11.25	6	06	3.0	-	01*	65%	80%	1:2.00	1:2.25	Nil
Intermediate Rise													
-A	250 - 399	5(G+4)	18.75	8	06	3.5	-	01*	65%	80%	1:3.00	1:3.75	
- B	400 - 749	6(G+5)	22.50	10	09	4.5	-	01*	65%	80%	1:3.75	1:4.50	
- C	750 - 999	8 (G+7)	30.00	15	09	5.0	-	02	65%	80%	1:5.00	1:6.00	
Middle Rise	1000-1999	12(G+11)	45.00	30	12	6.5	6.5	03	65%	70%	1:7.50	1:8.00	Lift and stand by generator
High Rise	2000 & above	13 & above	46.00 & above	40	12	10.0	10.0	03	50%	50%	To be issued with Preliminary Planning Clearance		

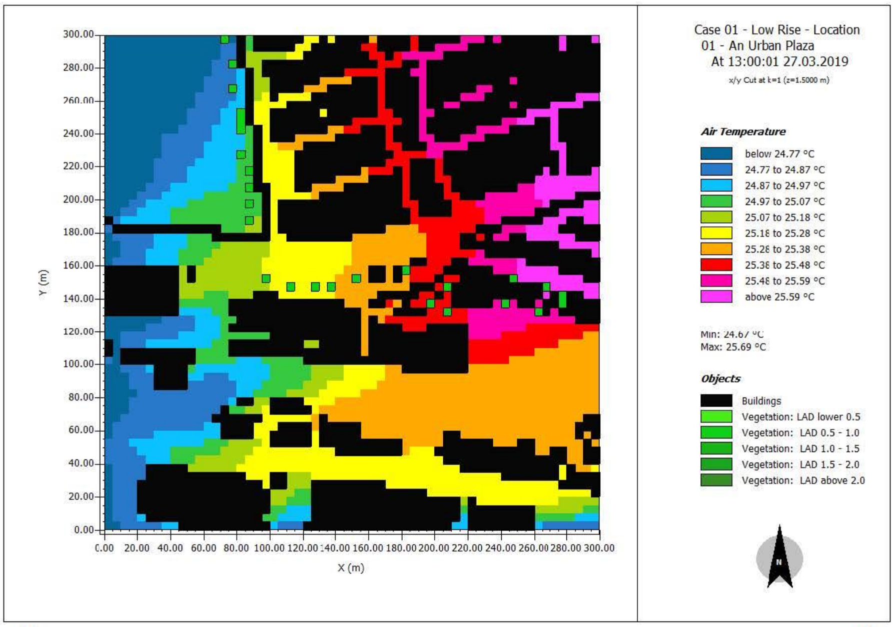
Note: *The Urban built form, character of the street and the natural environment within the context of local areas may have a continuity & harmony with the built and natural environment when the Development Guide Plans (DGP's) are enforced until such time the Authority may decide and instruct on open spaces around the buildings, Architectural form and the character of the street and the building etc.*

* *where there are no building lines* # *Plot coverage for new buildings* *Max - Maximum* *Min. - Minimum* *Res. - Residential*

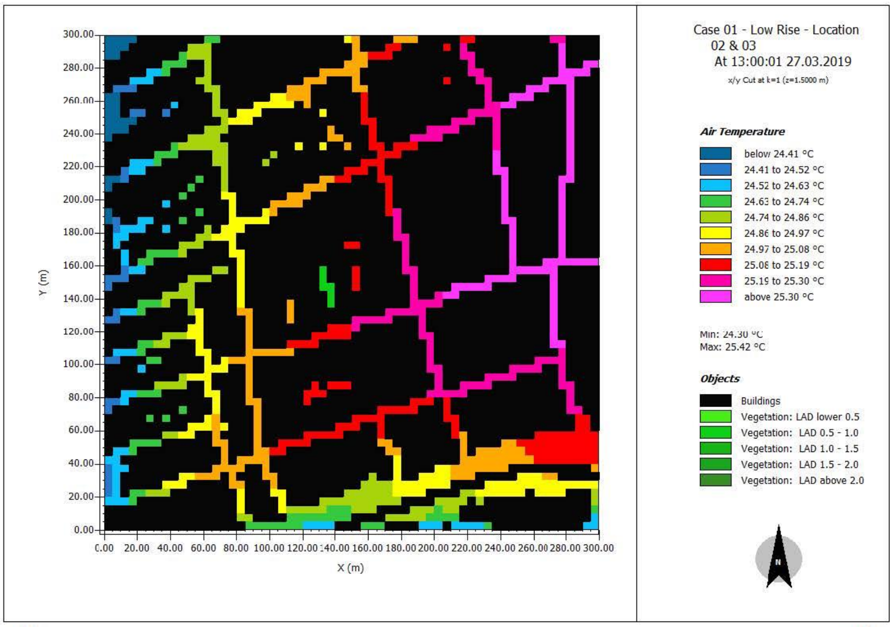
APPENDIX II: Simulated Air Temperature Maps for the Increasing Building Height Scenario.

<u>**Case 01 - Low Rise** at the time 0f 13:00:01 h</u>

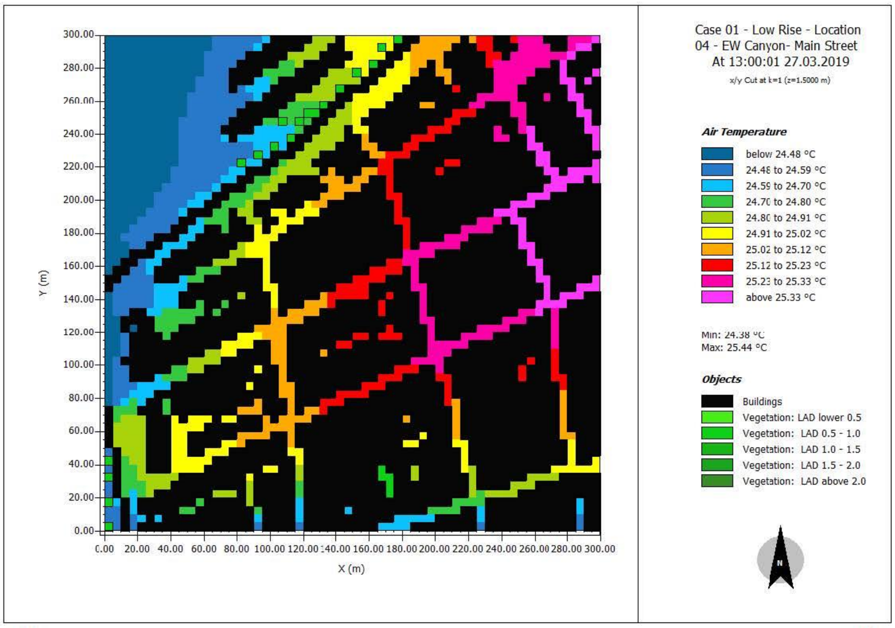
<u>Location 01</u>



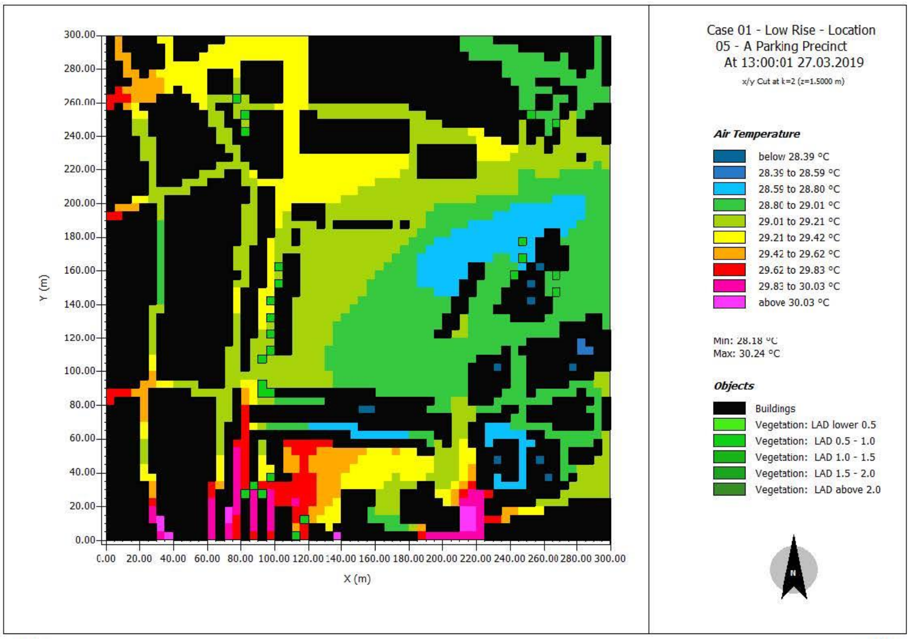
<u>Location 02 and Location 03</u>



Location 04

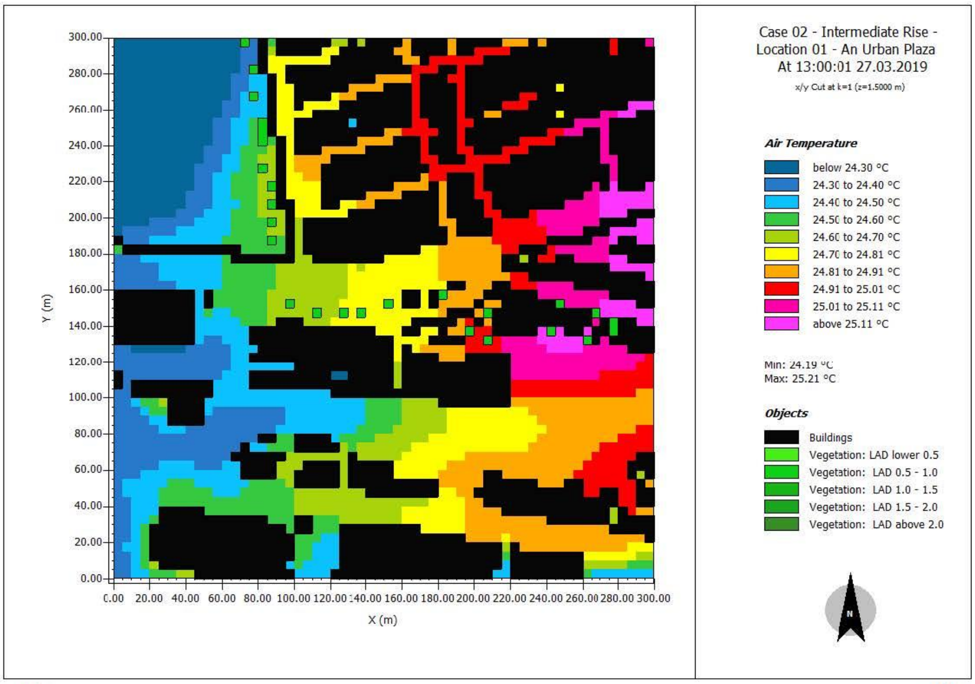


Location 05

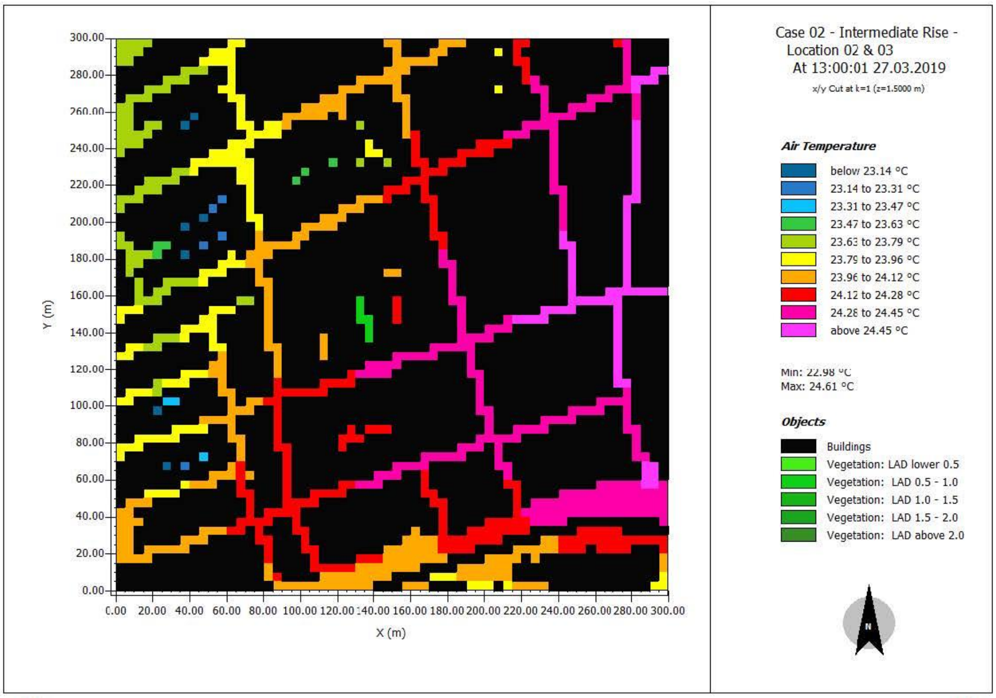


Case 02- Intermediate Rise at the time 0f 13:00:01 h

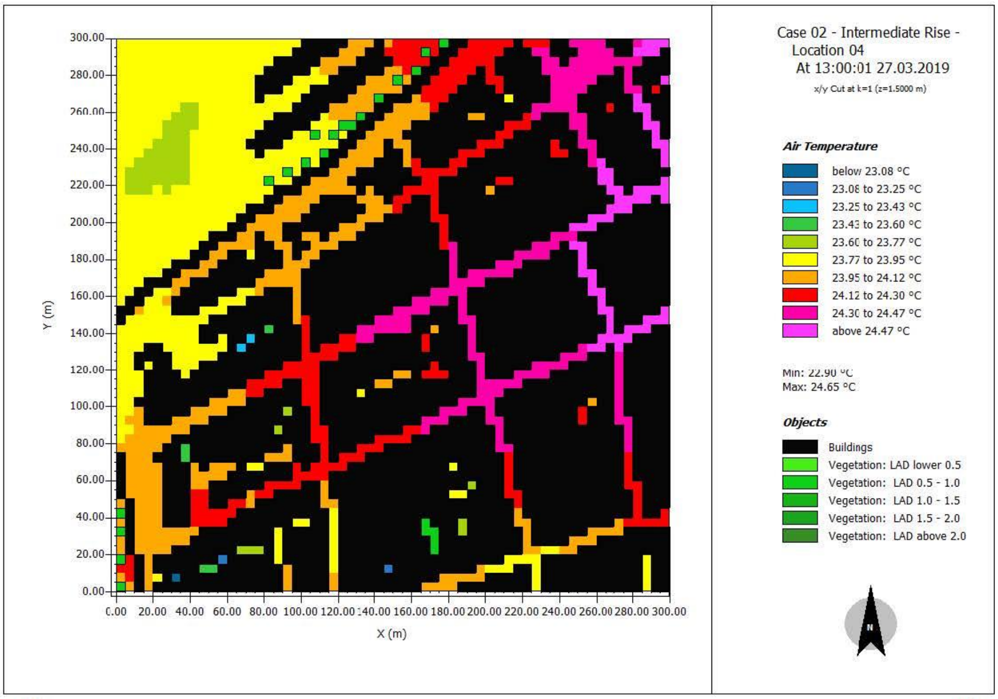
Location 01



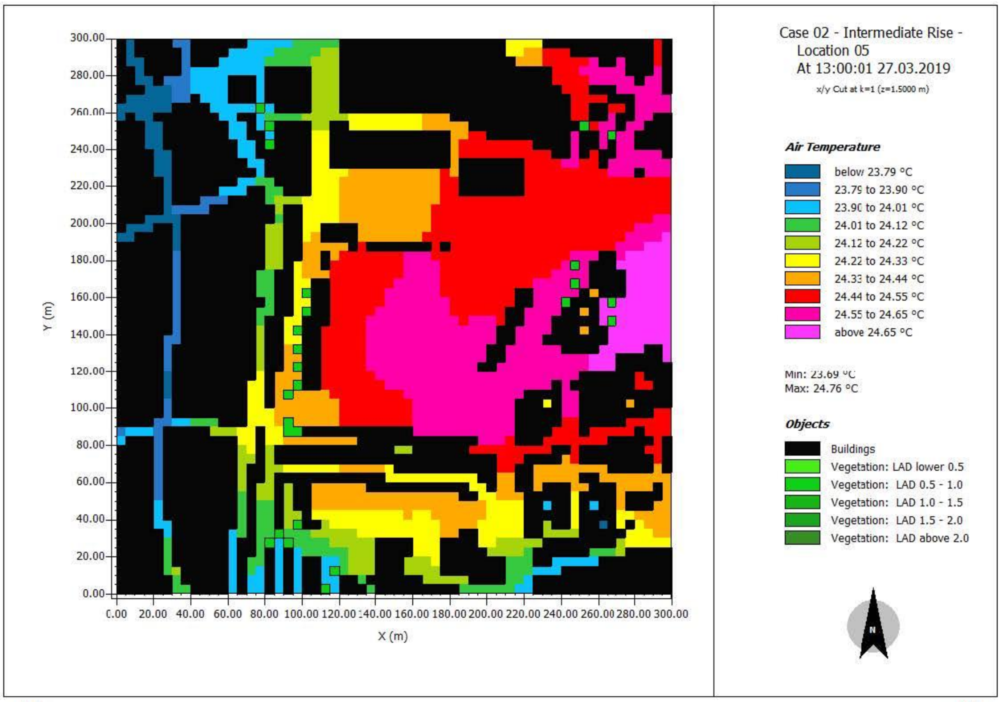
Location 02 and Location 03



Location 04

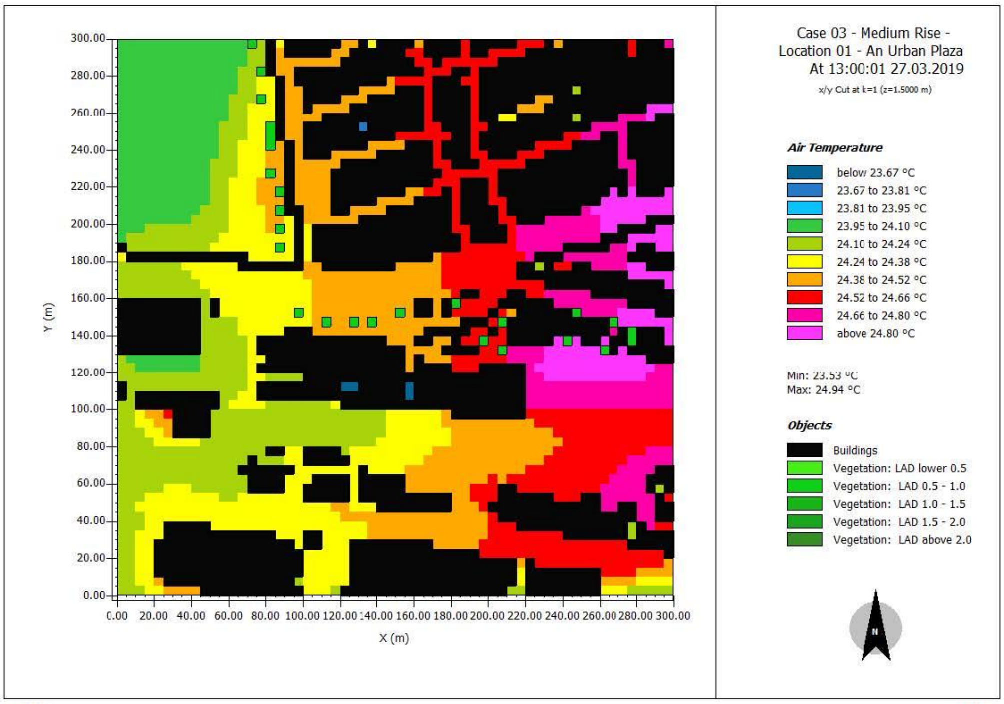


Location 05

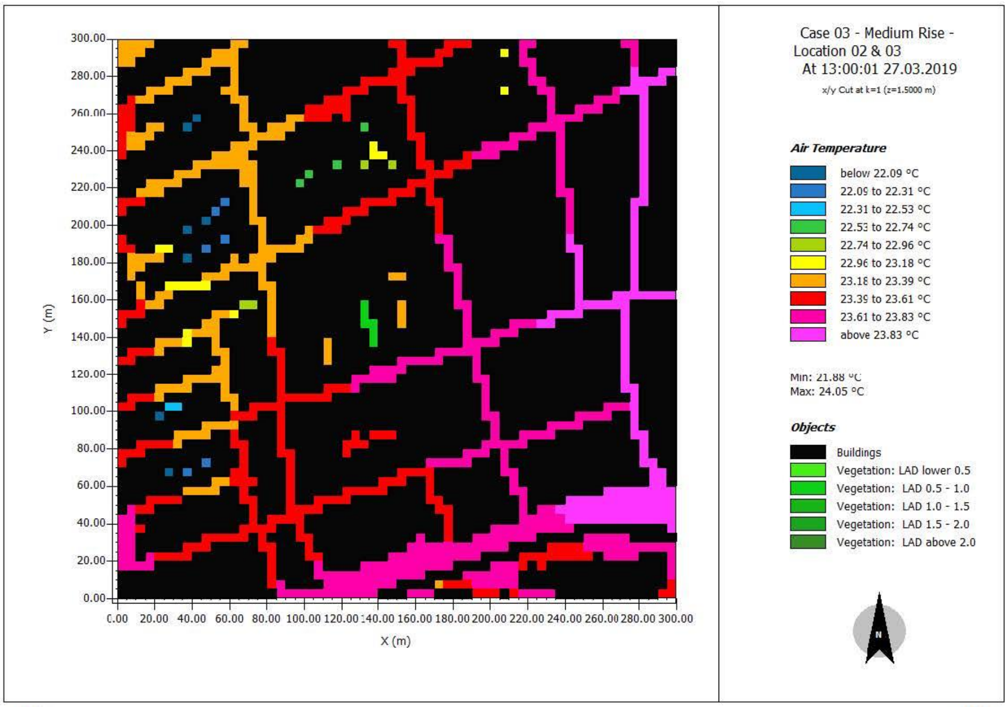


Case 03 - Medium Rise at the time 0f 13:00:01 h

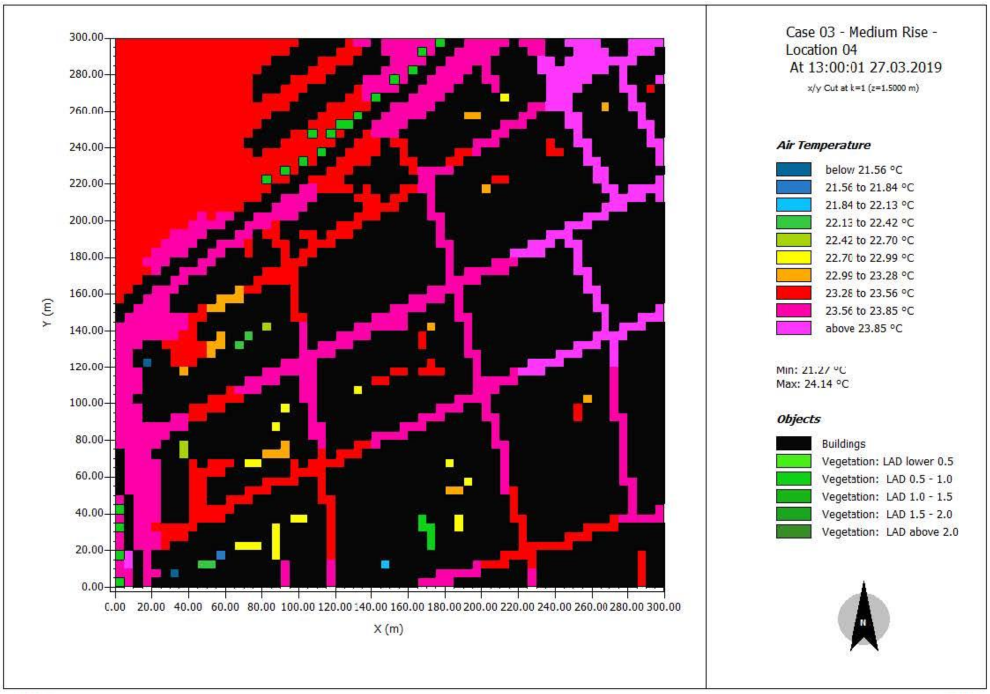
Location 01



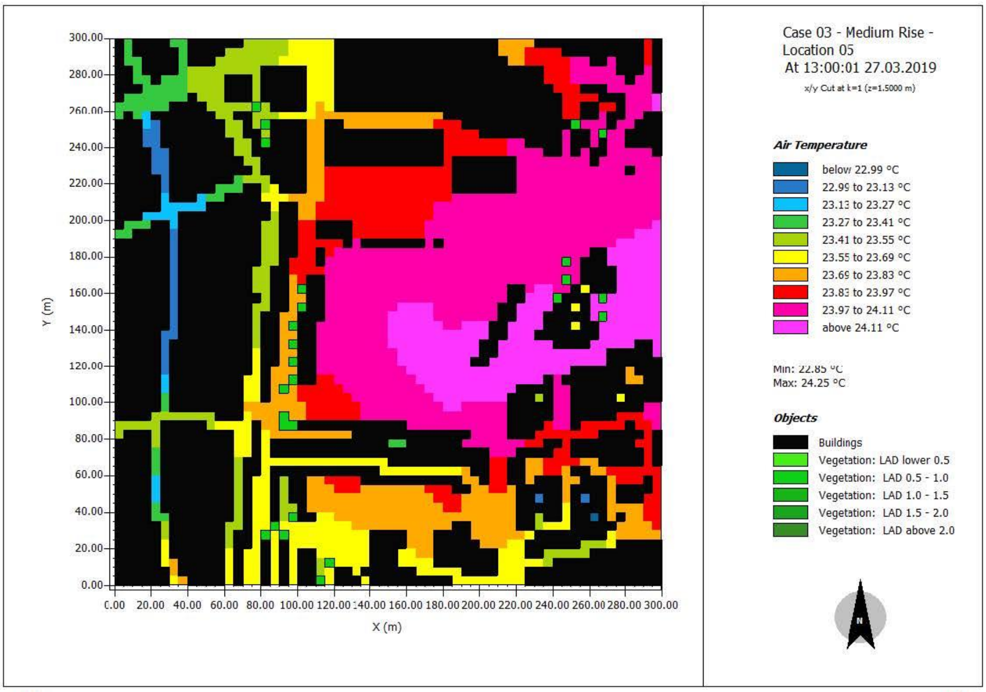
Location 02 and Location 03



Location 04

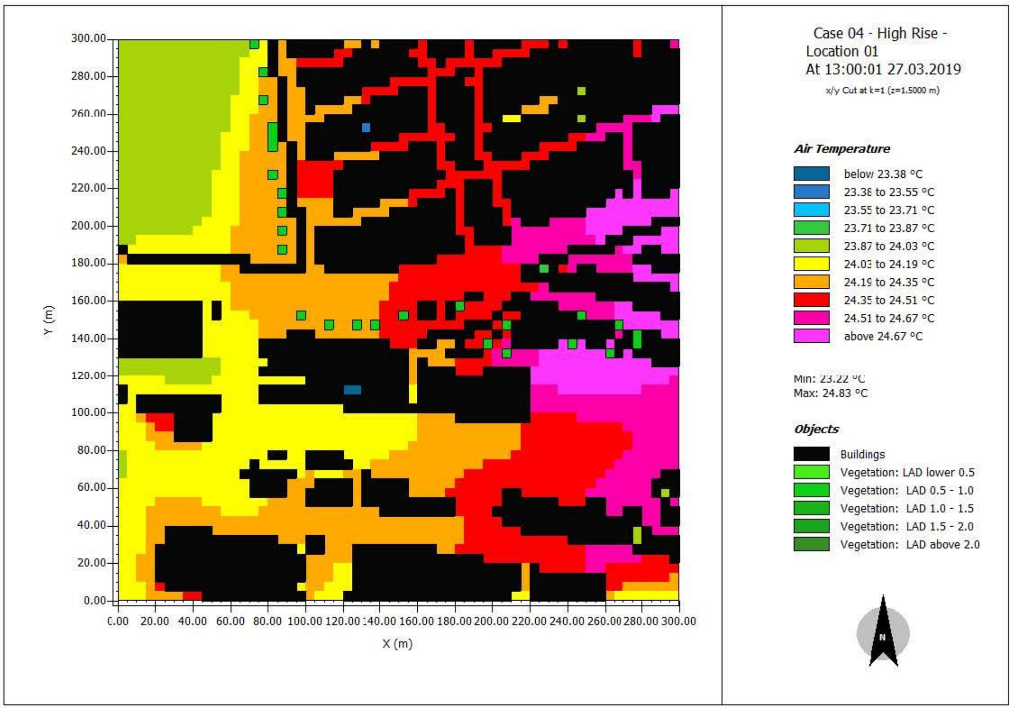


Location 05

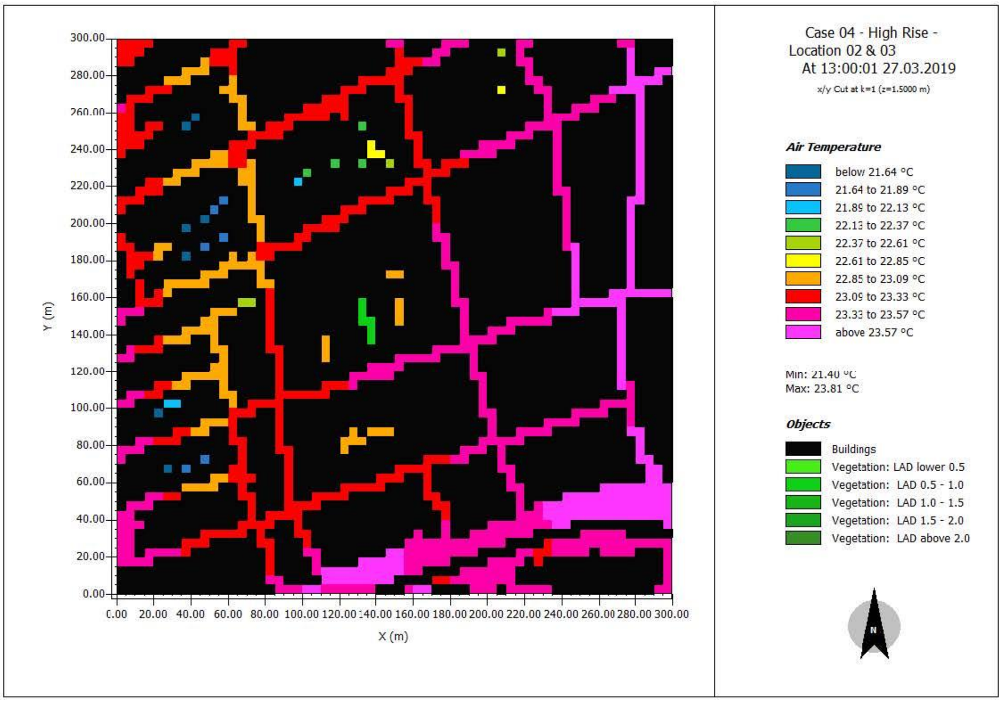


Case 04 - High Rise at the time 0f 13:00:01 h

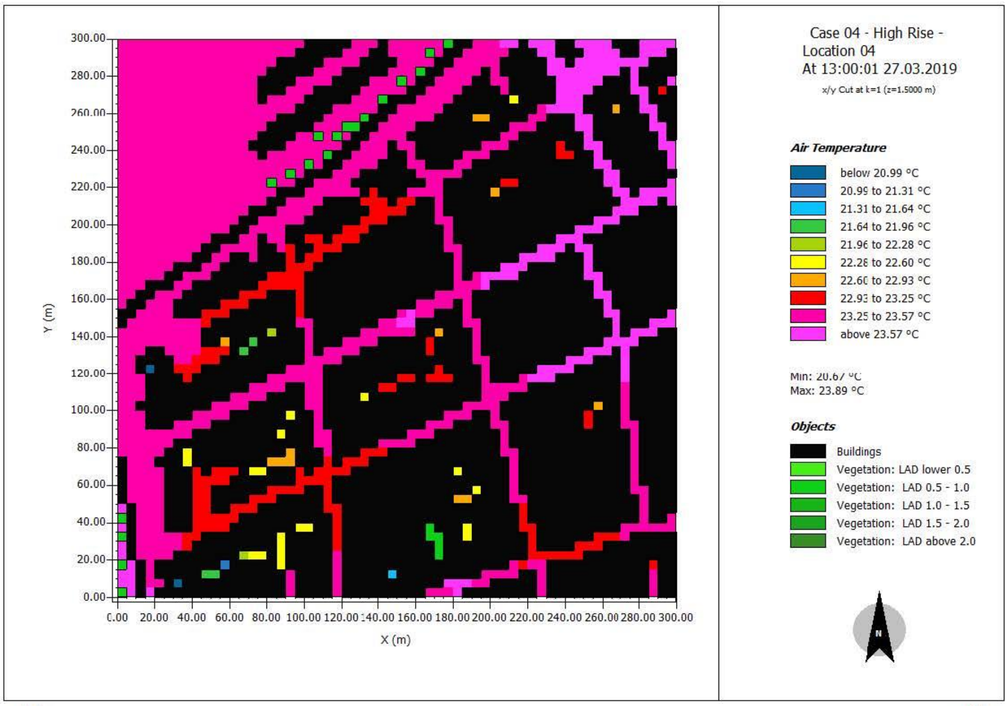
Location 01



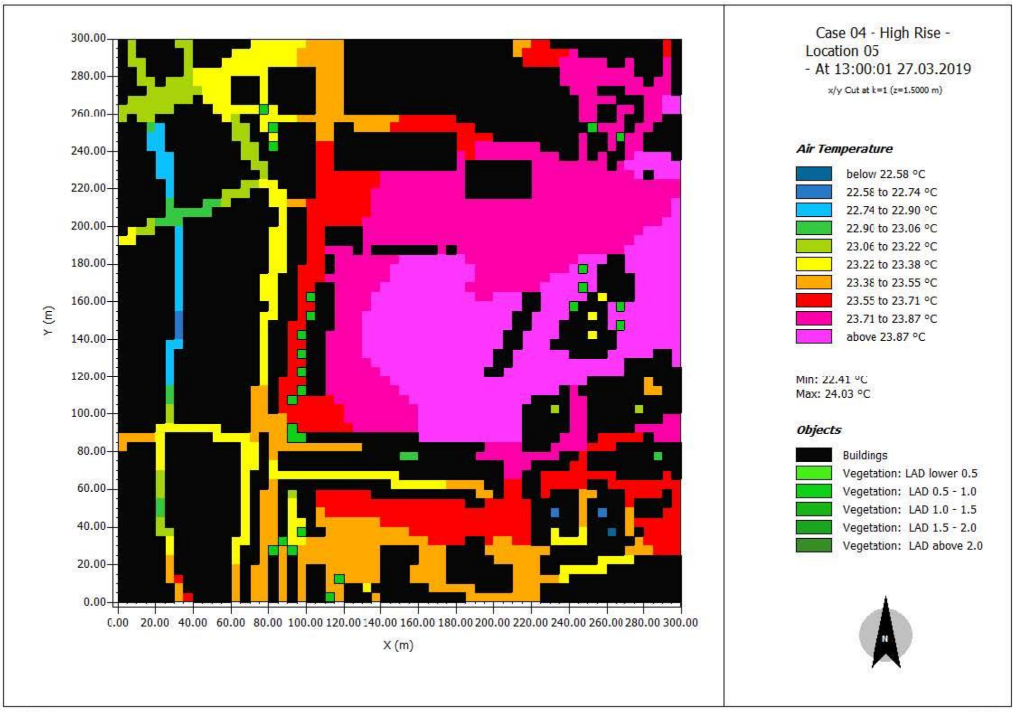
Location 02 and Location 03



Location 04



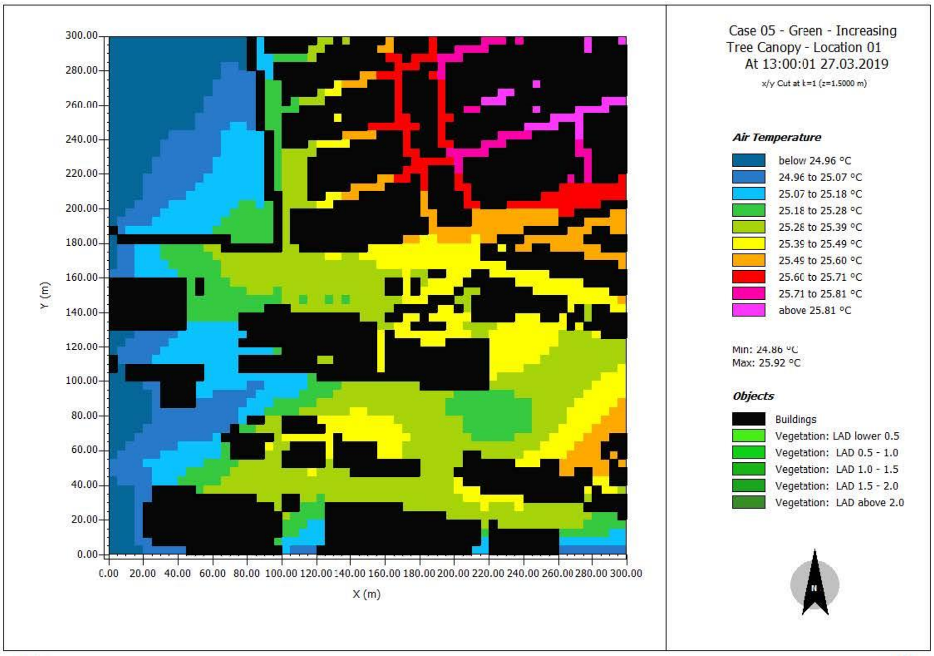
Location 05



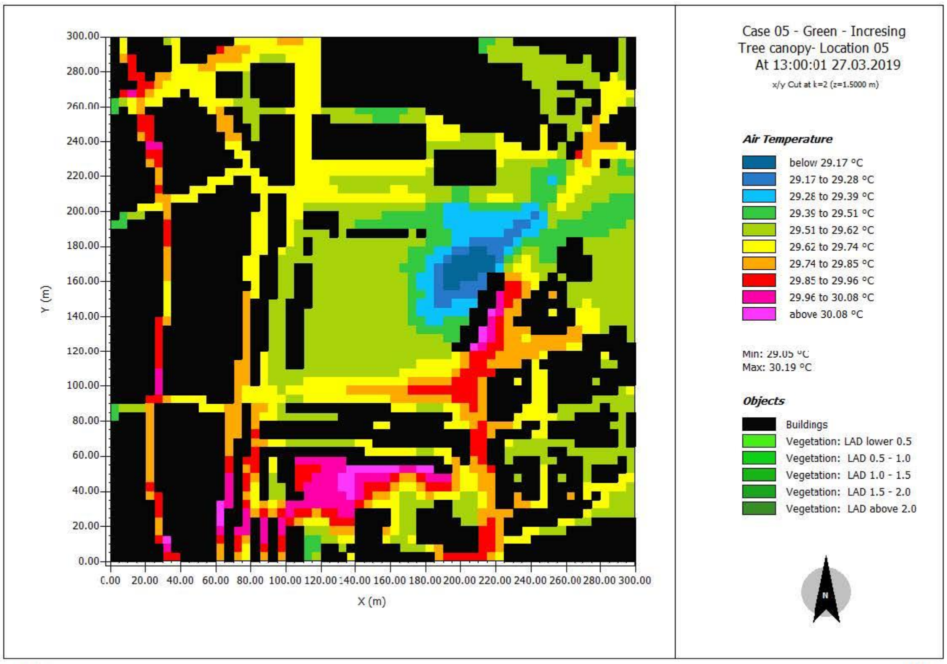
APPENDIX III : Simulated Air Temperature Maps for the Green Scenario

<u>Case 05 – Green – Increasing Tree Canopy</u> <u>at the time 0f 13:00:01 h</u>

<u>Location 01</u>

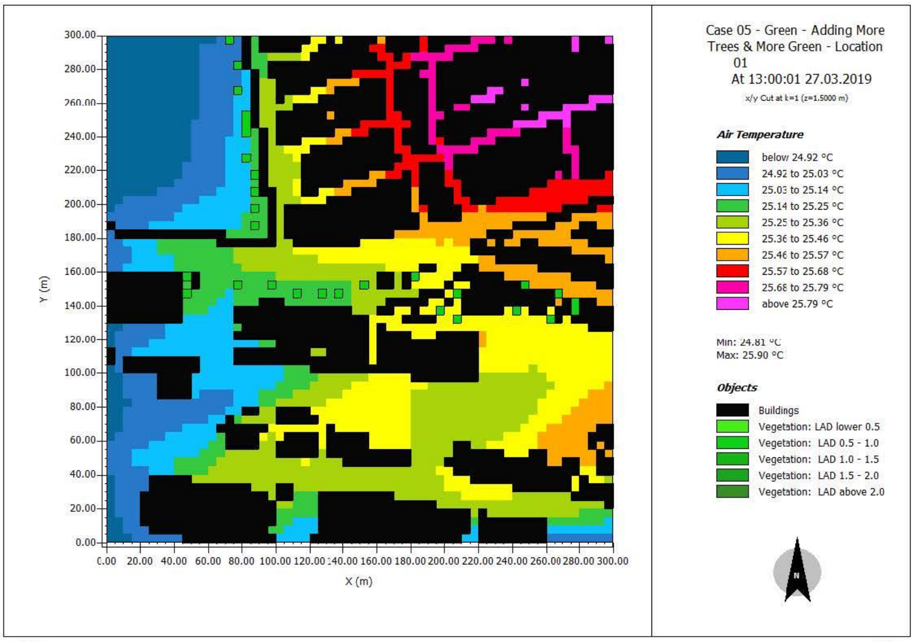


<u>Location 05</u>

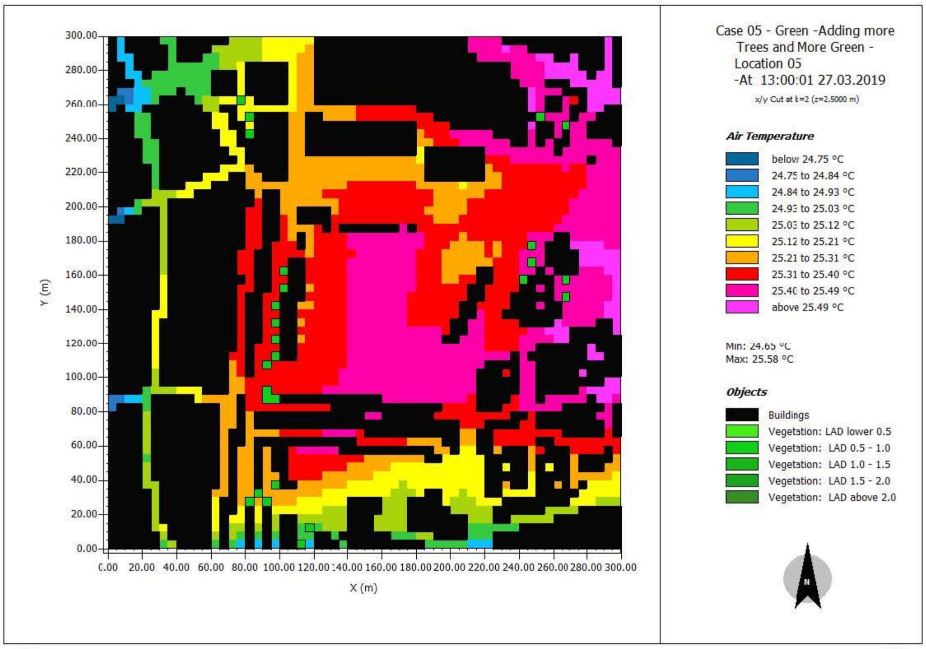


Case 05 – Green – Adding More Trees and More Green at the time 0f 13:00:01 h

Location 01

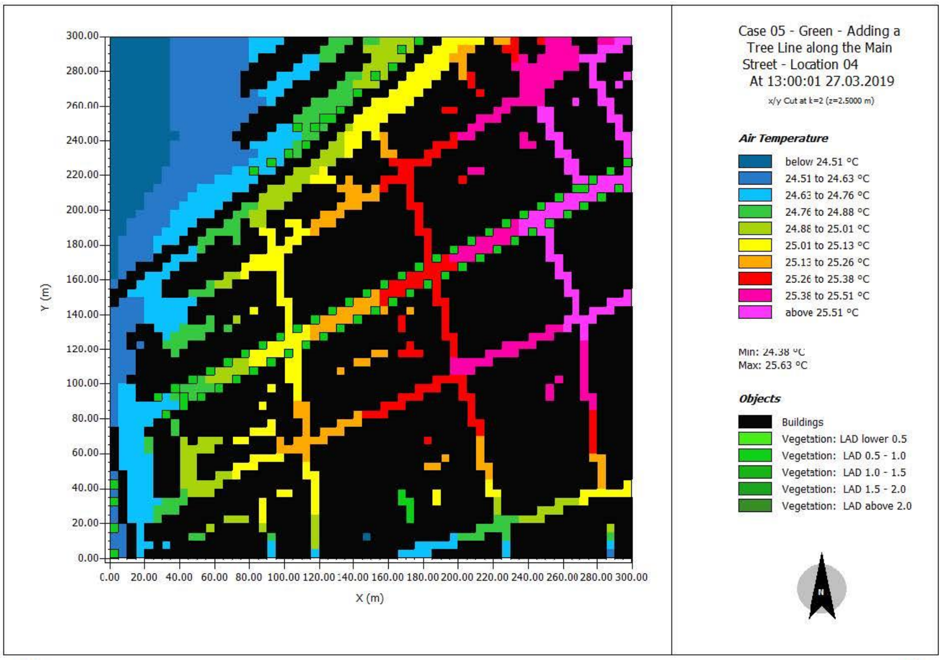


Location 05



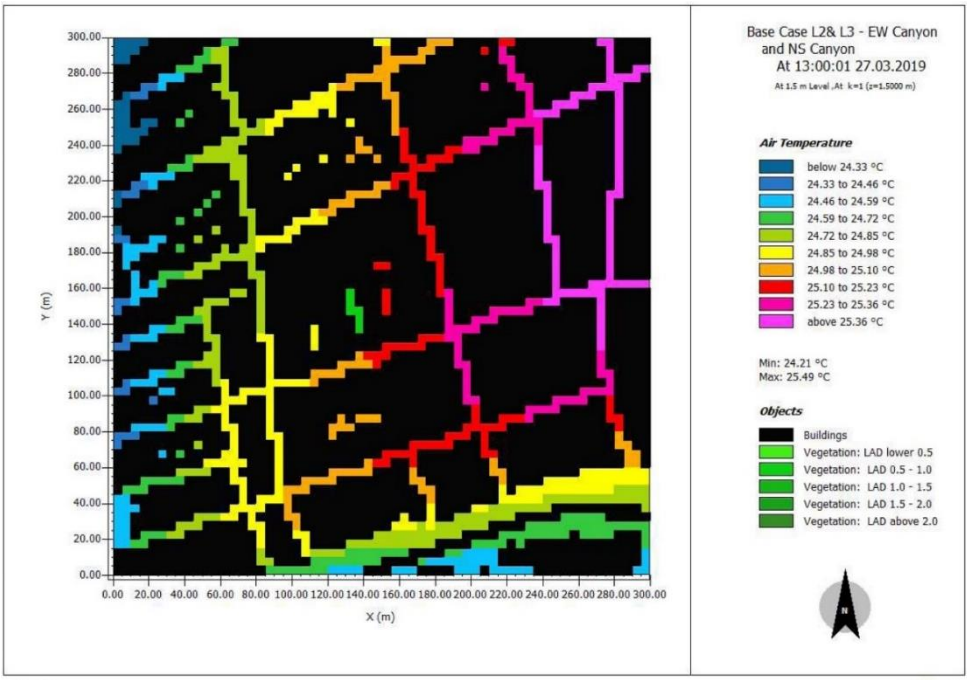
Case 05 – Green – Adding a Tree Line along the Main Street at the time 0f 13:00:01 h

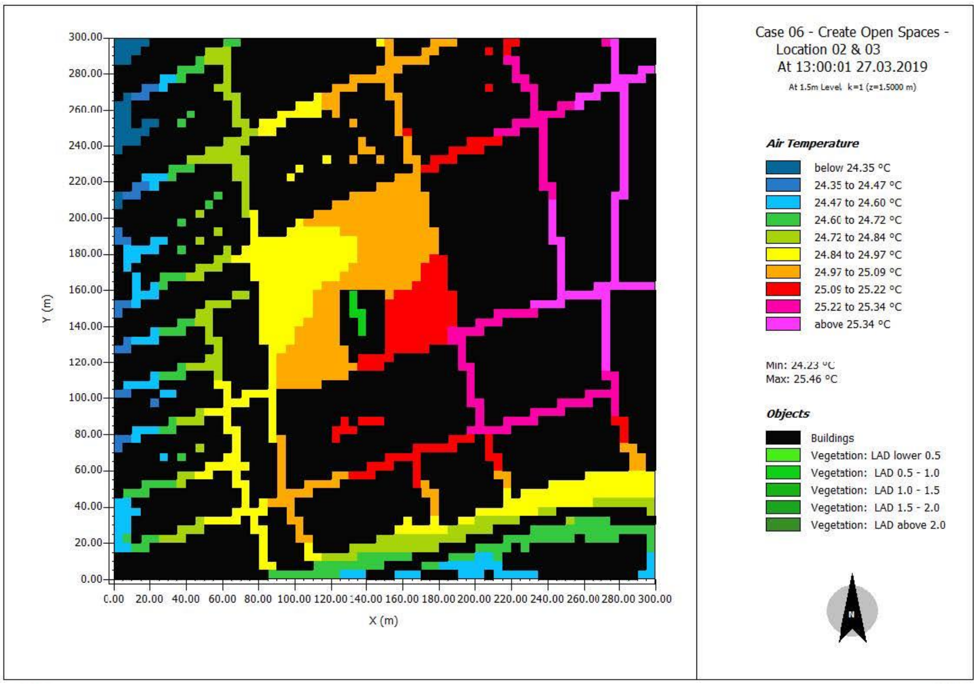
Location 01



APPENDIX IV : Simulated Air Temperature Maps for Create Open Spaces (Case 06) Scenario.

Simulated Air Temperature for Existing Situation and the Create an Open Space Scenario respectively where the Location of Existing Dutch Museum in Prince Street.

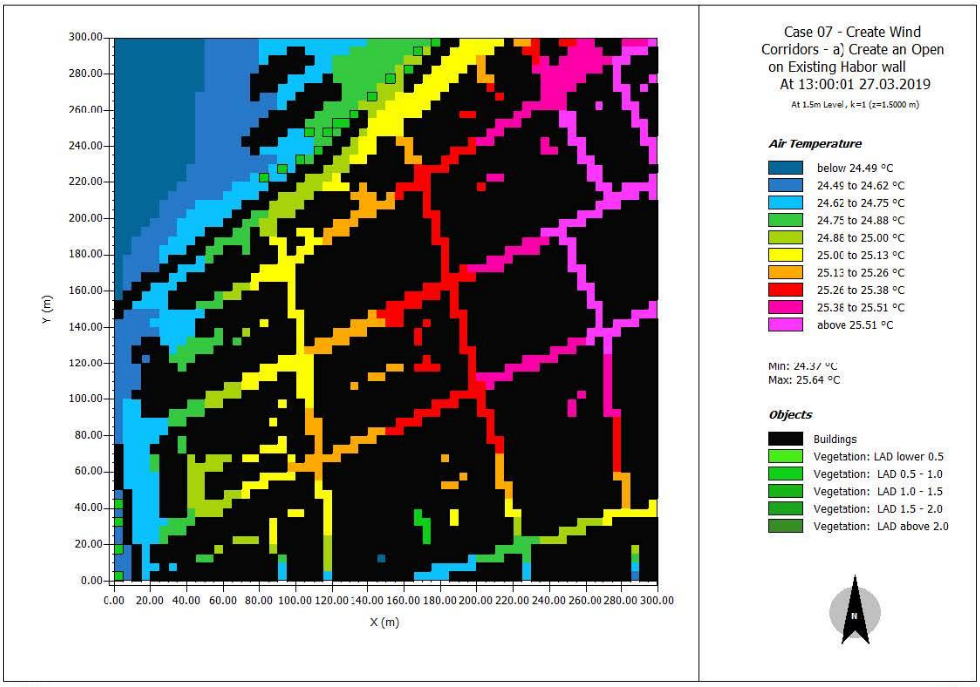




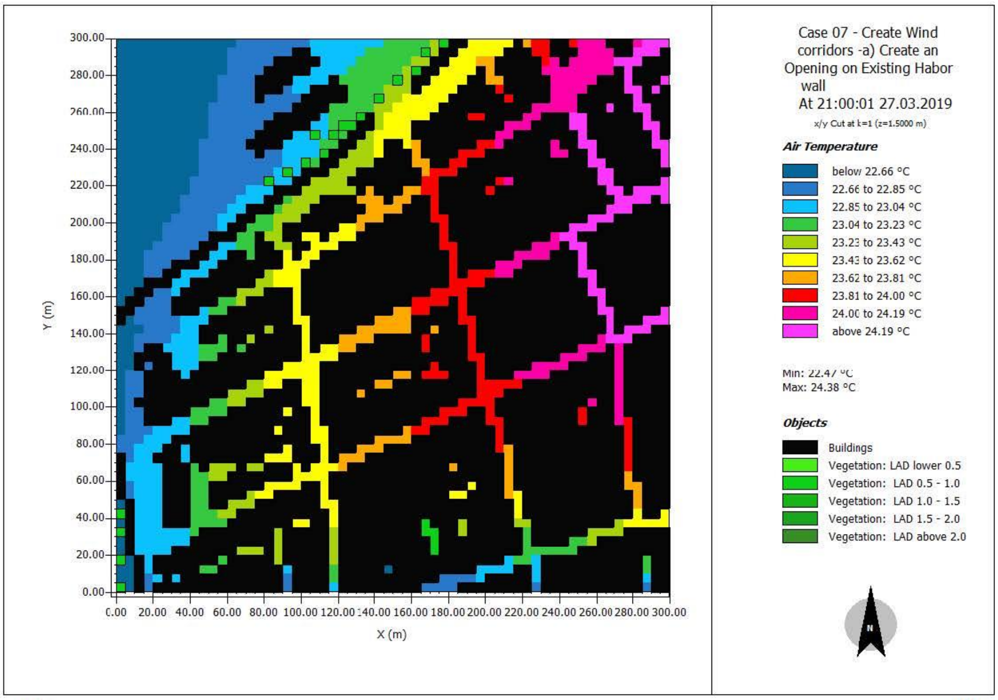
APPENDIX V: Simulated Air Temperature Maps for Creating Wind Corridors (Case 07) Scenario.

d.) Creating Openings at Existing Harbor wall.

- At Day time, 13:00:01h

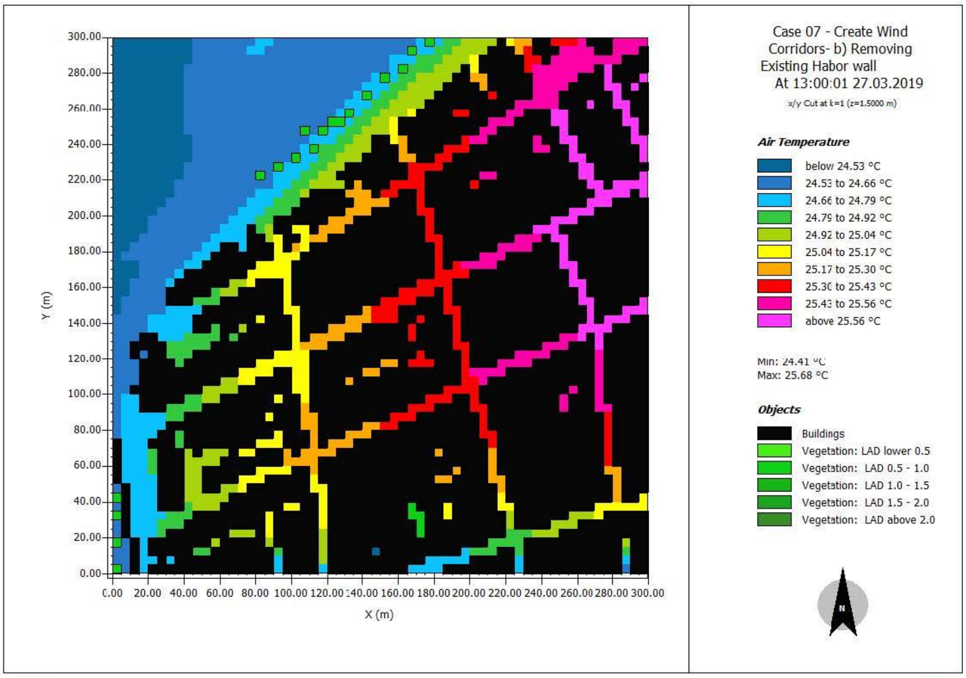


- At night Time, 21:00:01h

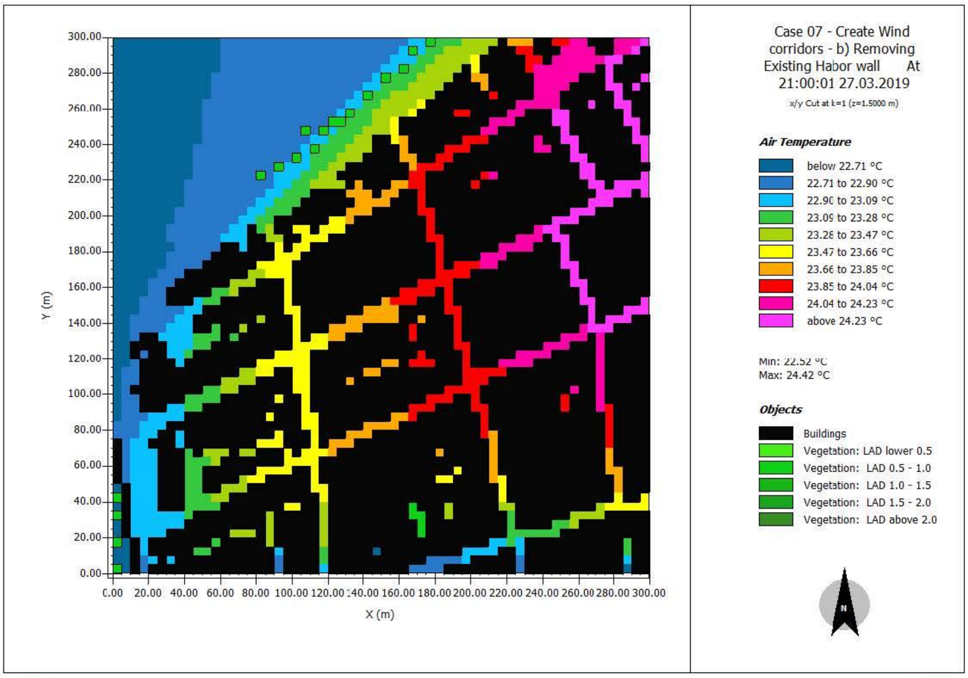


e.) Removing existing Harbor wall.

- At Day Time, 13:00:01h



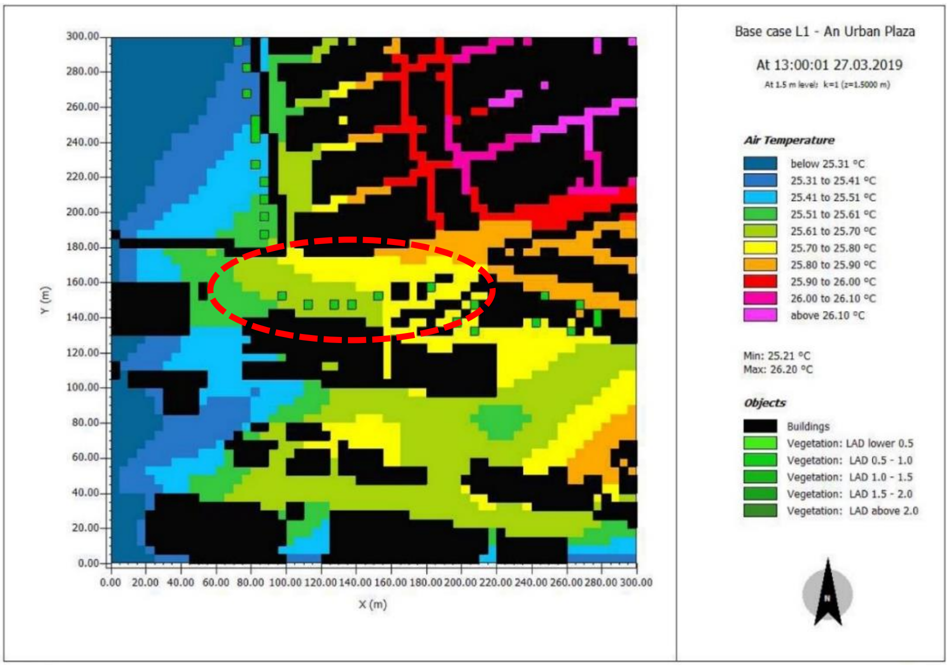
- At Night Time, 21:00:01h



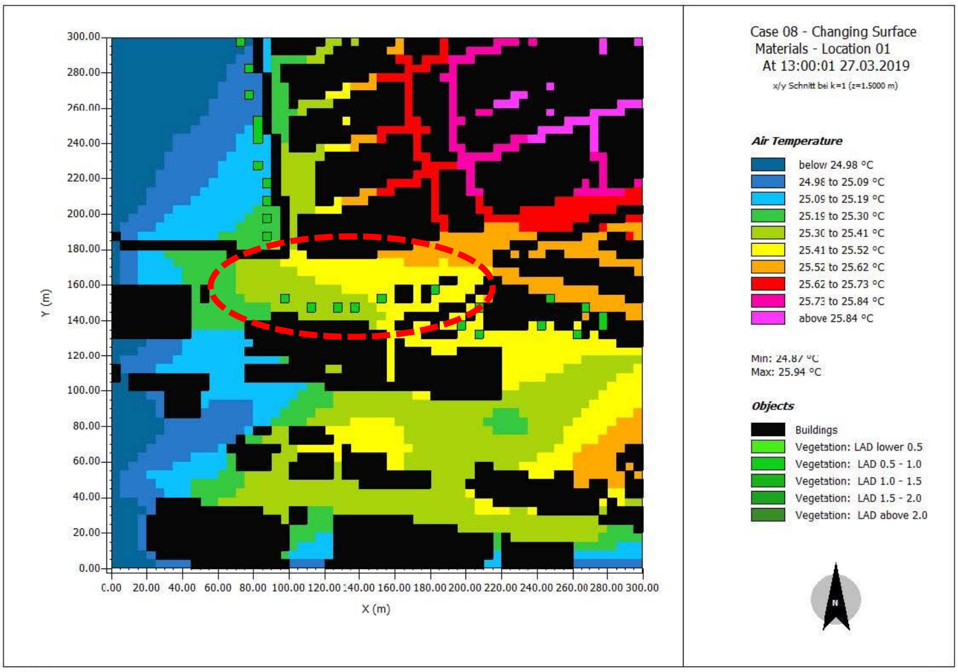
APPENDIX VI : Simulated Air Temperature Maps for Changing Surface Materials (Case 08) Scenario.

Simulated Air Temperature on Location 01 – An Urban Plaza for the Case 08 – Changing of Surface materials.

- **At Day Time, 13:00:01h**

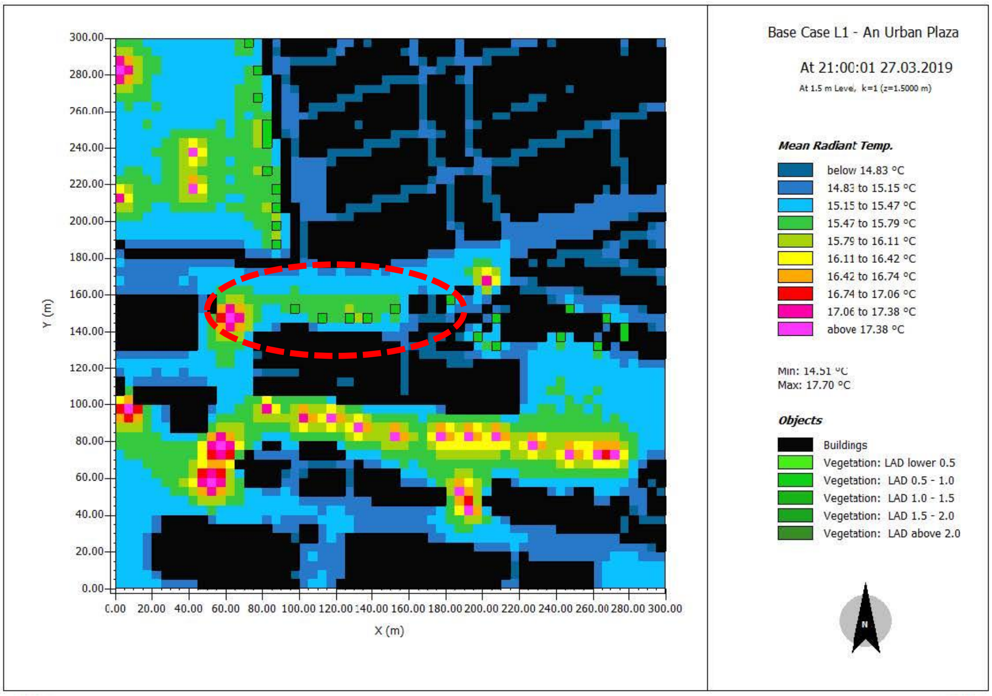


Base Case - Location 01 – An Urban Plaza

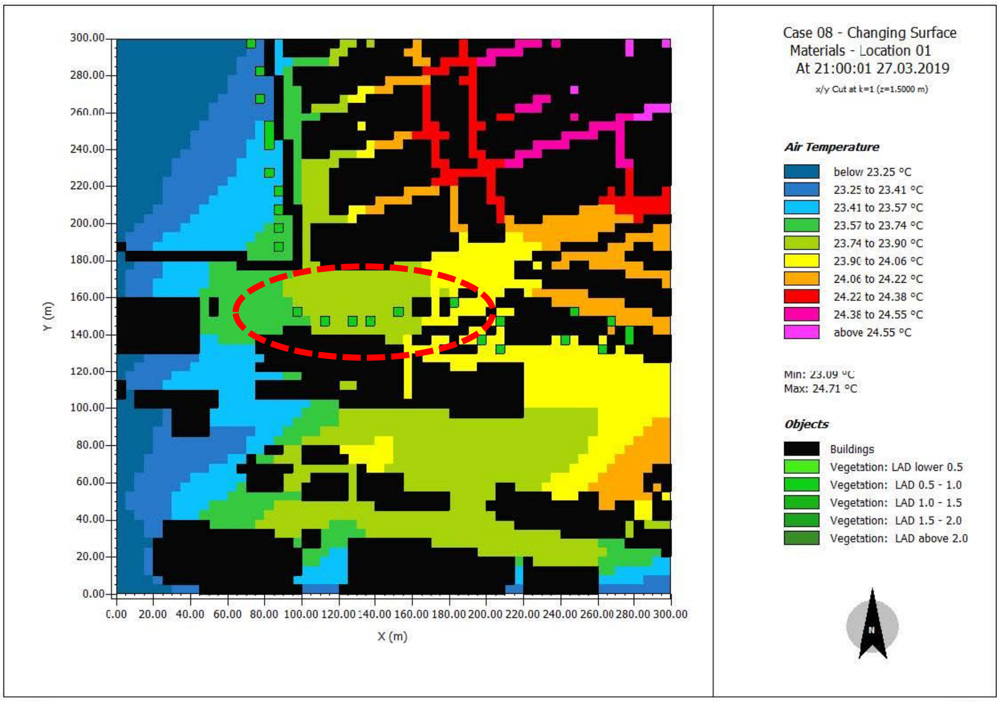


Case 08 – Changing Surface materials - Location 01 – An Urban Plaza

- **At Night Time, 21:00:01h**



Base Case - Location 01 – An Urban

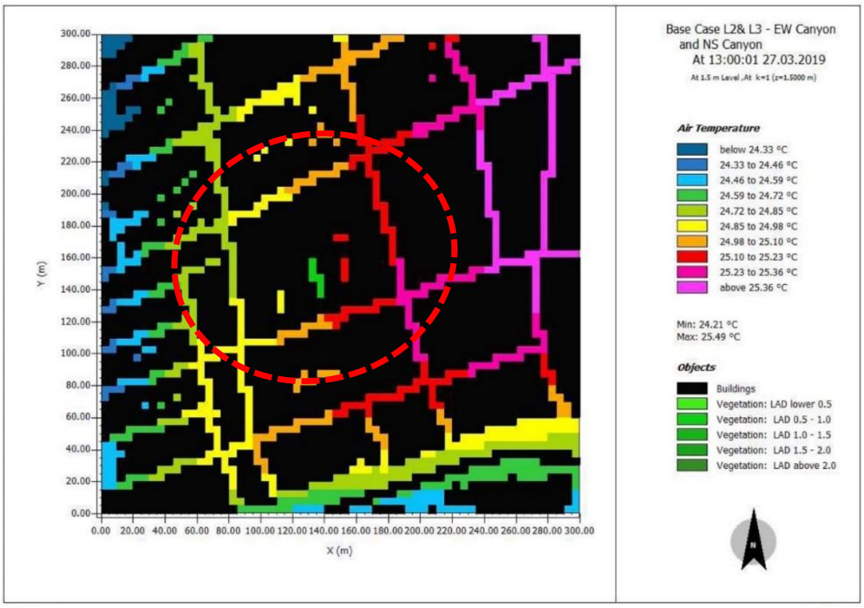


Case 08 – Changing Surface materials - Location 01 – An Urban Plaza

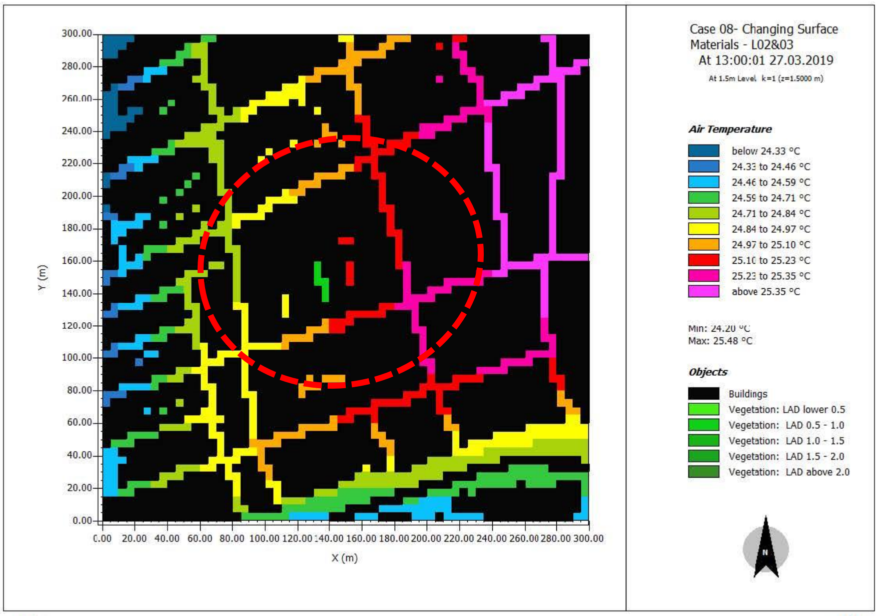
Simulated Air Temperature on Location 02 and 03– EW and NS Urban Canyons, Case 08 – Changing of Surface materials.

- **At Day Time , 13:00:01h**

Base Case - Location 01 – An Urban Plaza

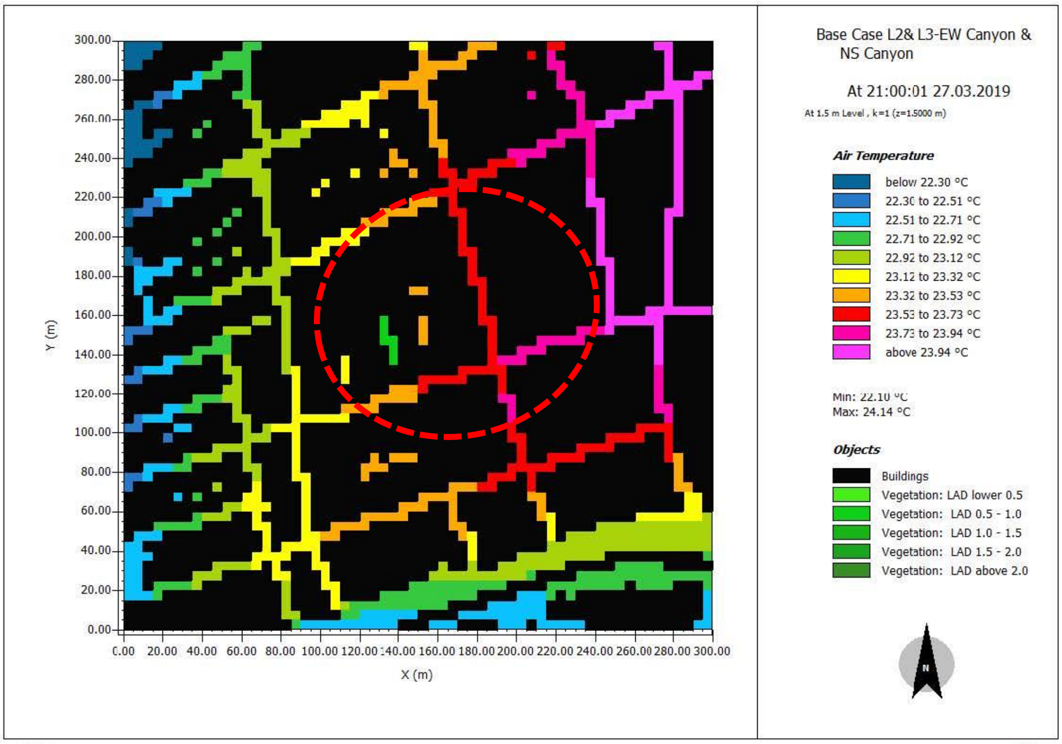


Base Case - Location 02 & 03 – EW Urban Canyon and NS Urban Canyon

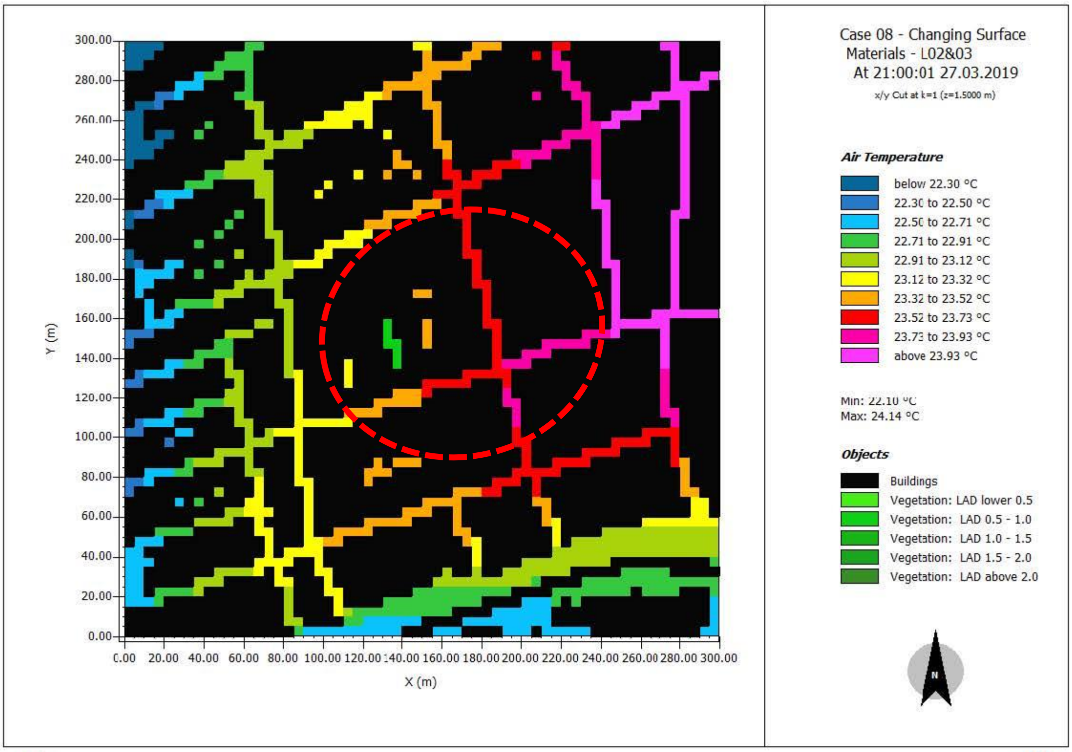


Case 08 – Changing Surface materials - Location 02 & 03 – EW Urban Canyon and NS Urban Canyon

- **At Night Time, 21:00:01h**



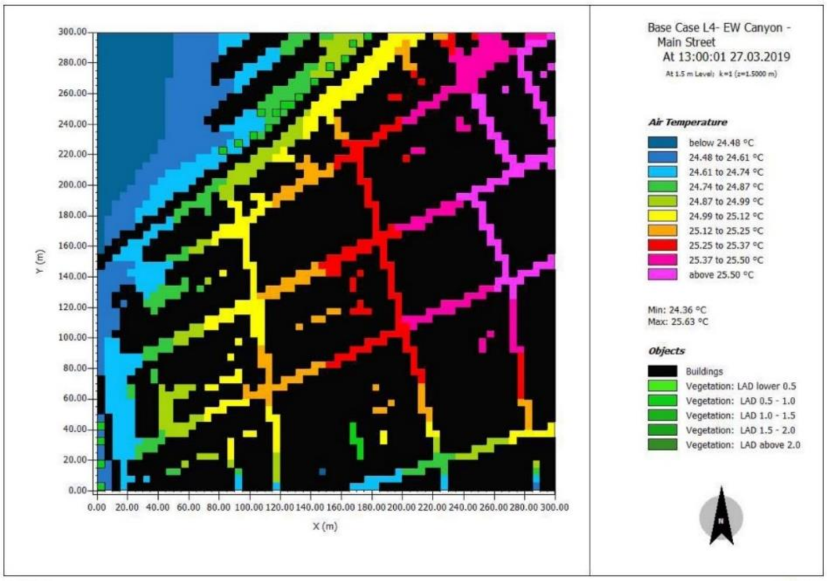
Base Case - Location 02 & 03 – EW Urban Canyon and NS Urban Canyon



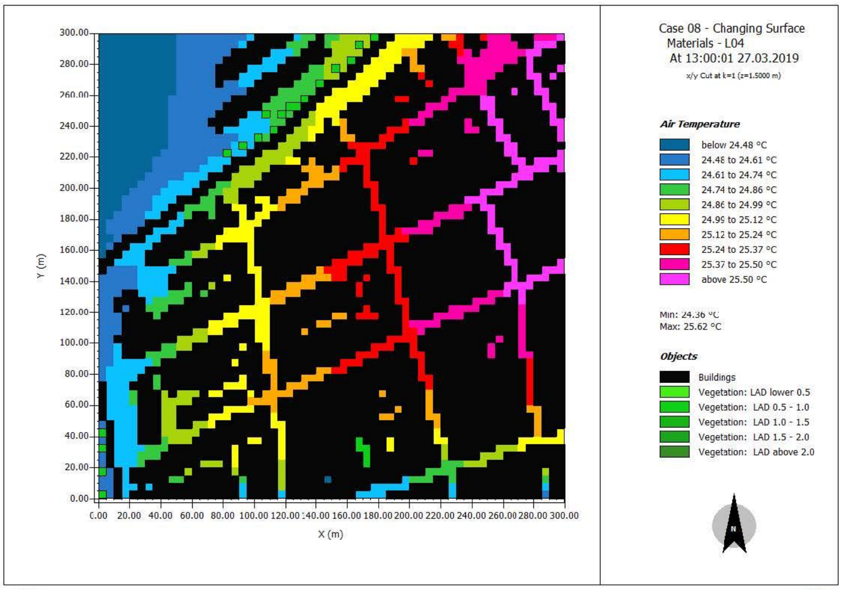
Case 08- Changing Surface Materials - Location 02 & 03 – EW Urban Canyon and NS Urban Canyon

Simulated Air Temperature on Location 04 – EW Urban Canyons- Main Street , Case 08 – Changing of Surface materials.

- **At Day Time, 13:00:01h**

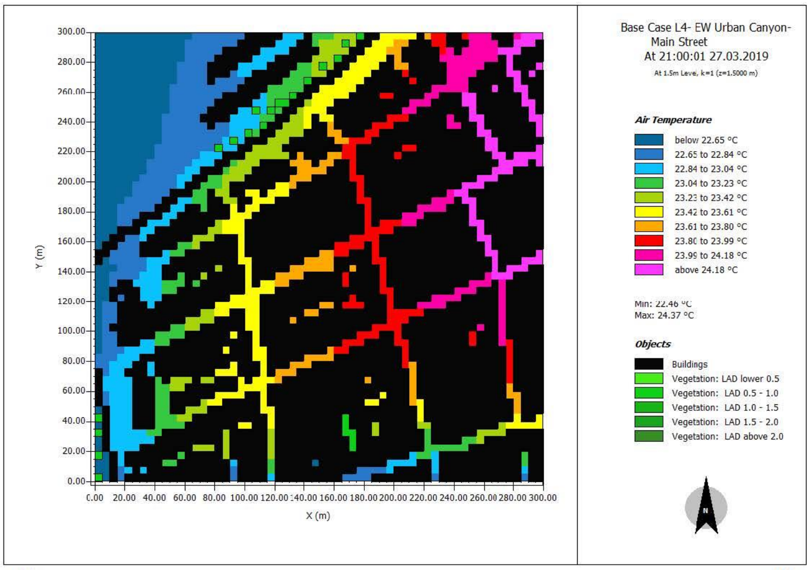


Base Case - Location 04– EW Urban Canyon – Main Street, time 13:00:01h

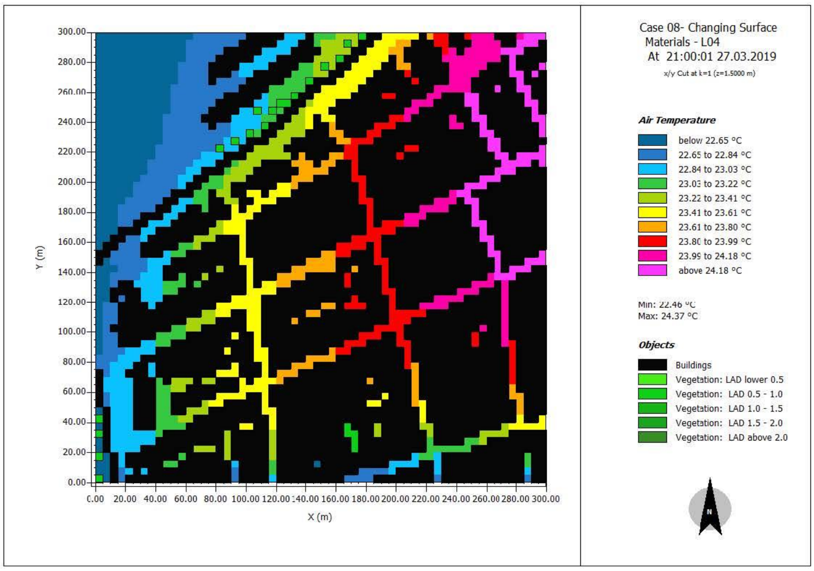


Case 08- Changing Surface Materials - Location 04– EW Urban Canyon – Main Street, time 13:00:01h

- **At Night Time, 21:00:01h**



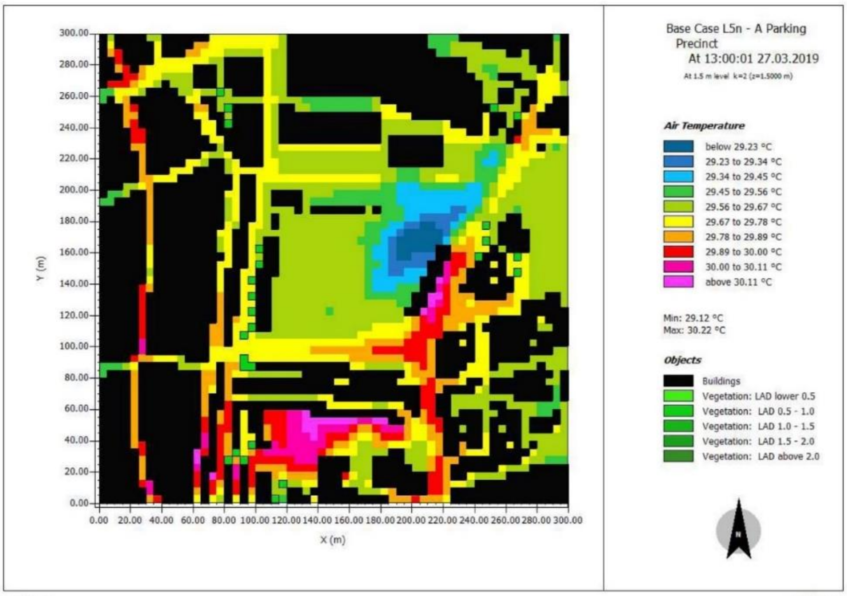
Base Case - Location 04– EW Urban Canyon – Main Street, time 21:00:01h



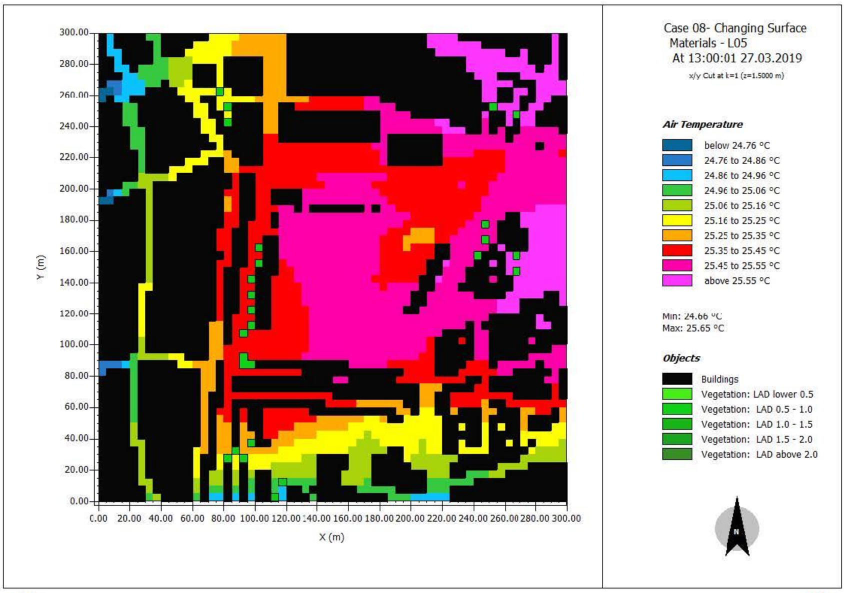
Case 08- Changing Surface Materials - Location 04– EW Urban Canyon – Main Street, time 21:00:01h

Simulated Air Temperature on Location 05 – A Parking Precinct, Case 08 – Changing of Surface materials.

- **At Day Time, 13:00:01h**

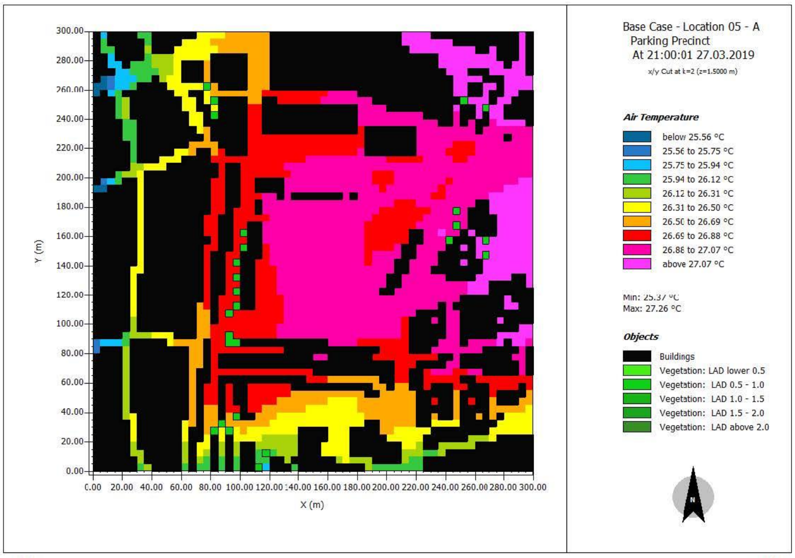


Base Case - Location 05– An Parking Precinct, time 13:00:01h

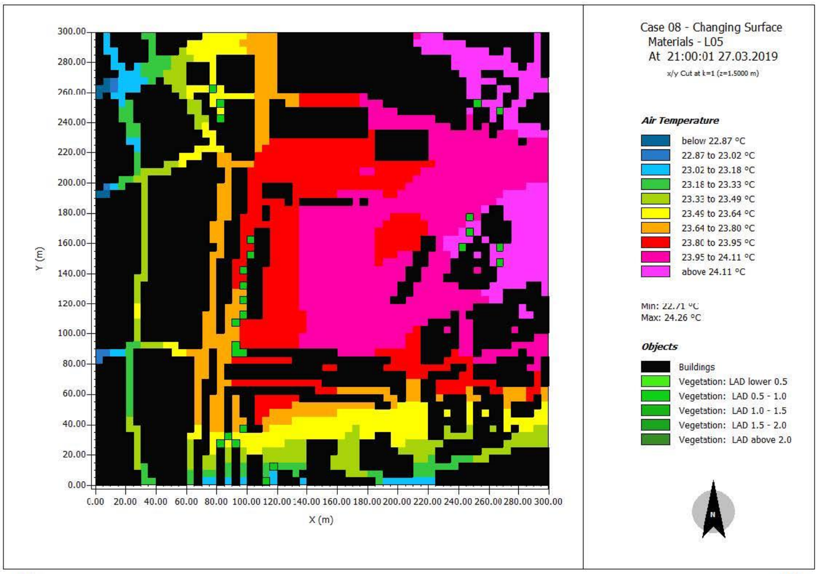


Case 08 – Changing Surface Materials - Location 05– An Parking Precinct, time 13:00:01h

- **At Night Time, 21:00:01h**



Base Case - Location 05– An Parking Precinct, time 21:00:01h

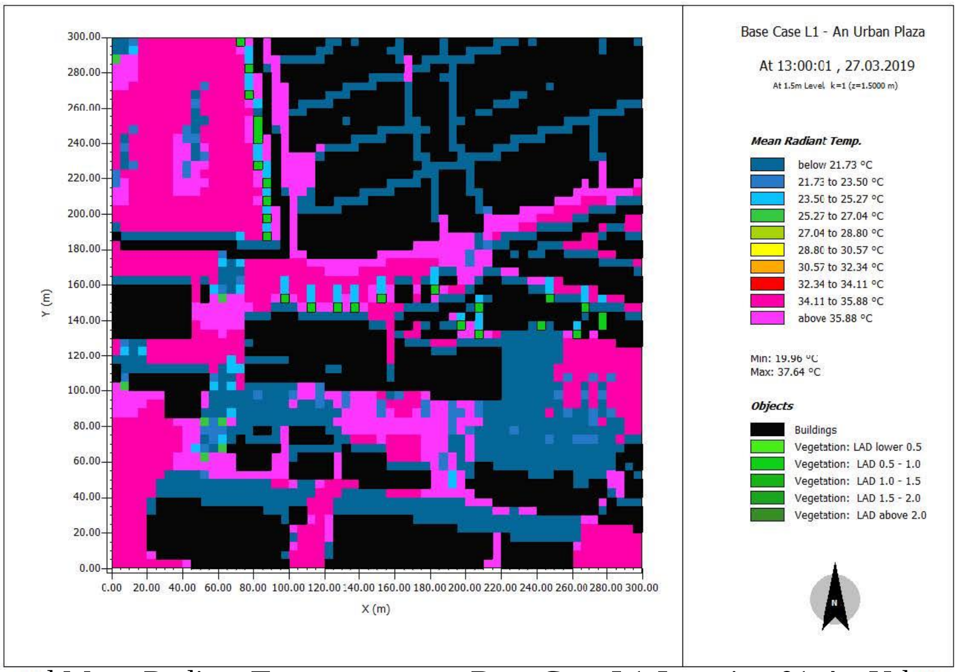


Case 08 – Changing Surface Materials - Location 05– An Parking Precinct, time 21:00:01h

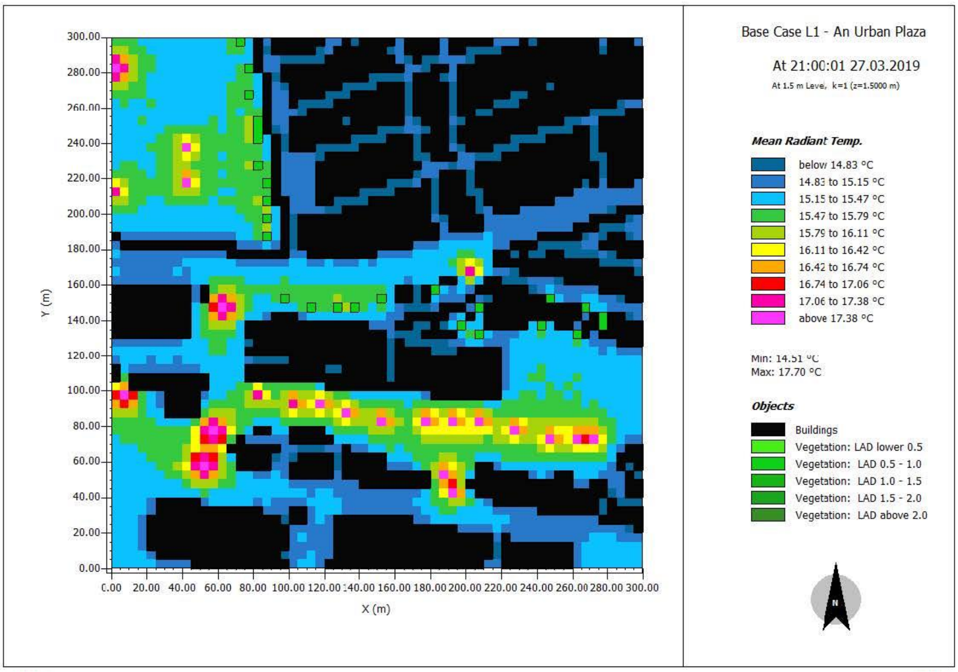
APPENDIX VII: Mean Radiant Temperature (MRT) Distribution Maps

- **Existing scenario**

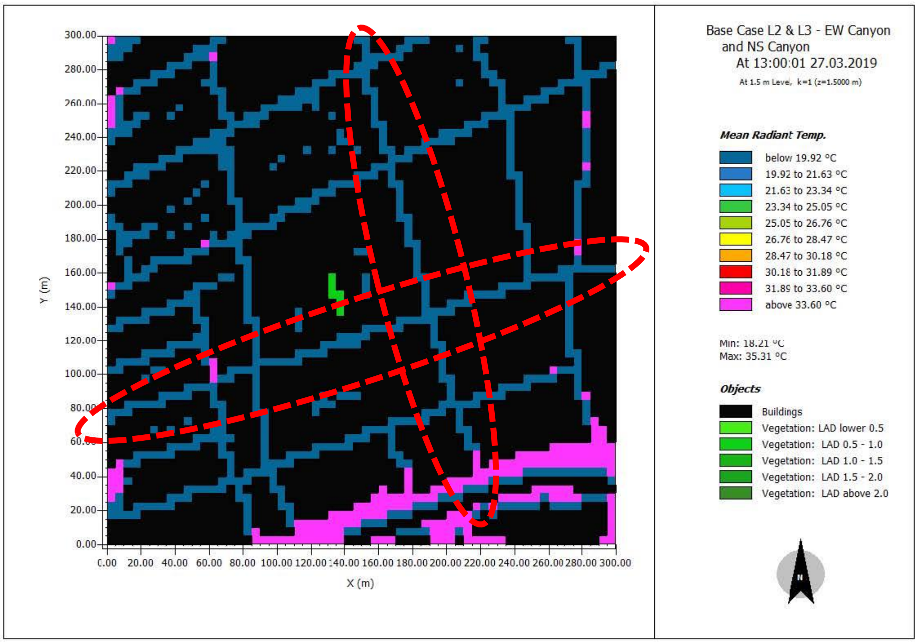
a.) Simulated Mean Radiant Temperature on, Base Case L1-Location 01-An Urban Plaza (i) at the Day Time 13:00:01h , (ii) at the Night Time 21:00:01h



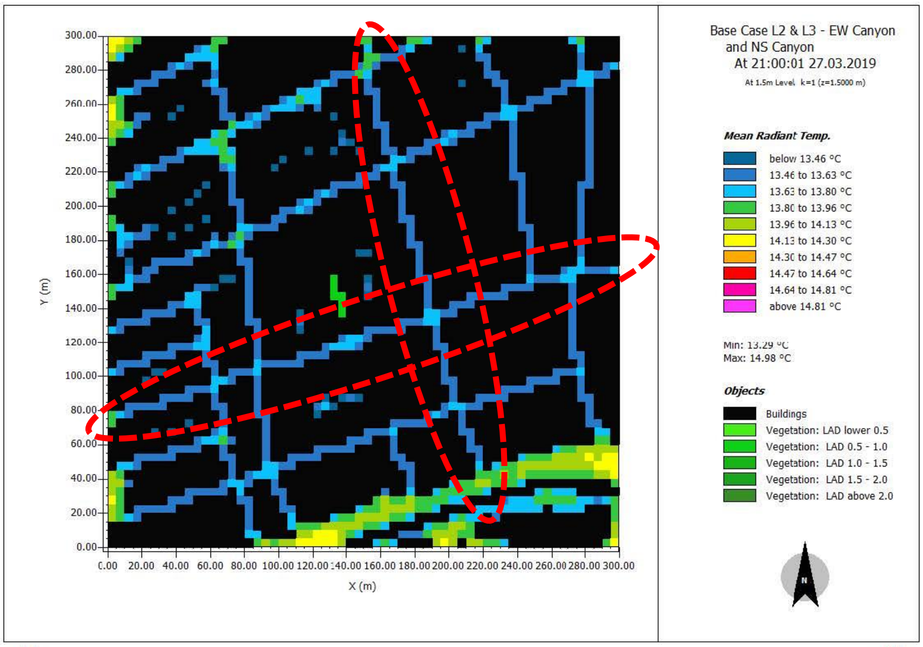
Simulated Mean Radiant Temperature on, Base Case L1-Location 01-An Urban Plaza (i) at the Day Time 13:00:01h



Simulated Mean Radiant Temperature on, Base Case L1-Location 01-An Urban Plaza (ii) at the Night Time 21:00:01h b.) Simulated Mean Radiant Temperature on Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h , (ii) at the Night Time 21:00:01h.

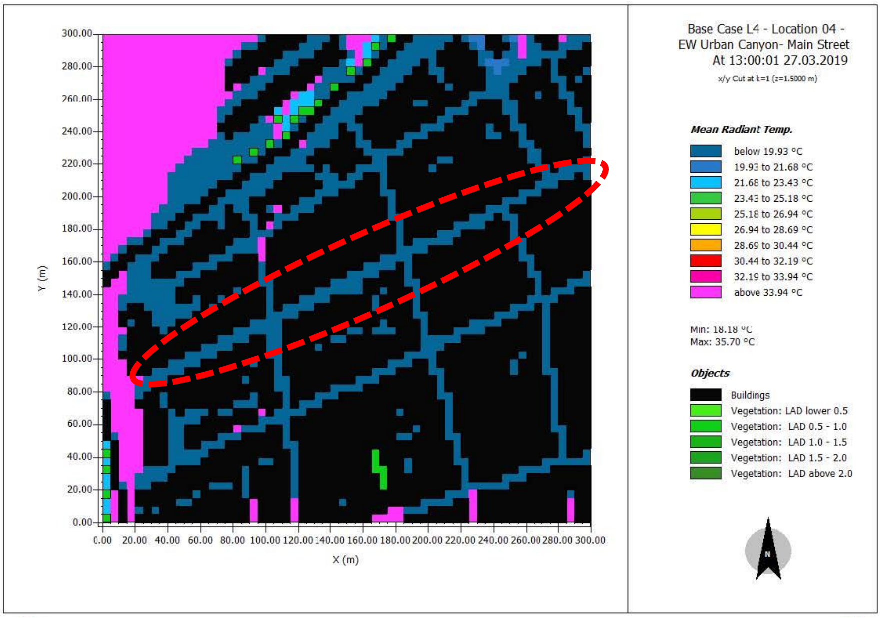


Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.

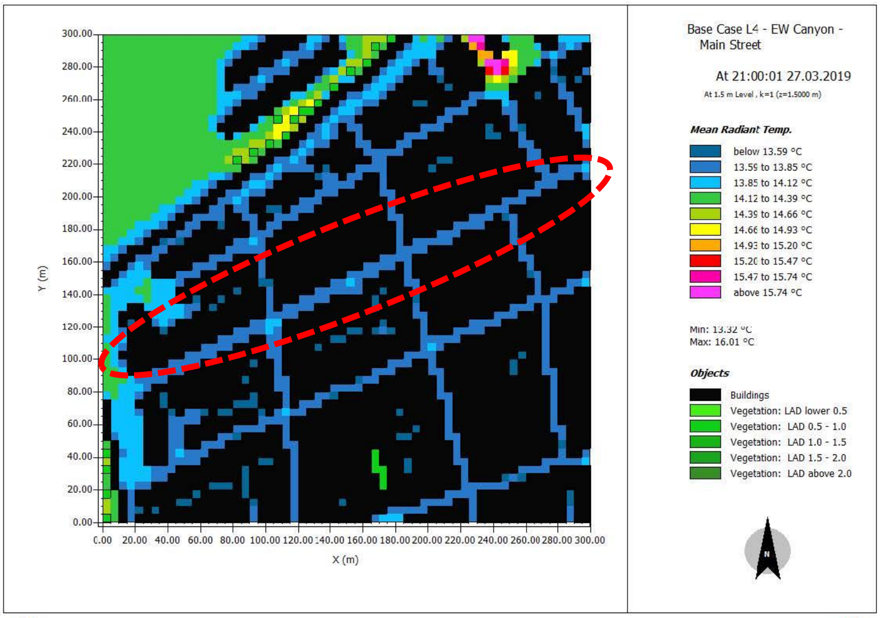


Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

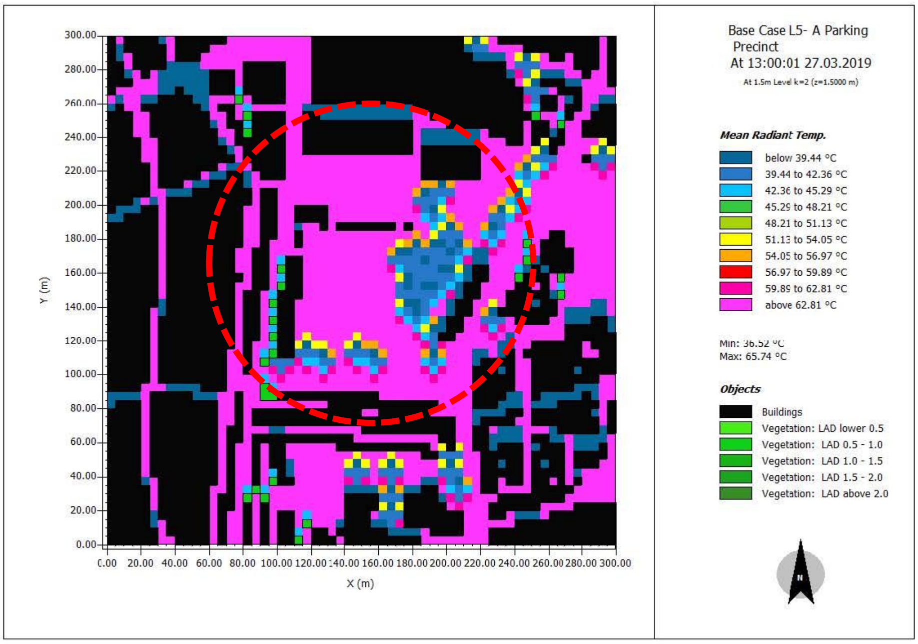
c.) Simulated Mean Radiant Temperature, on Base Case L4 – Location 04 – EW Canyon - Main Street, (i) at the Day Time 13:00:01h , (ii) at the Night Time 21:00:01h.



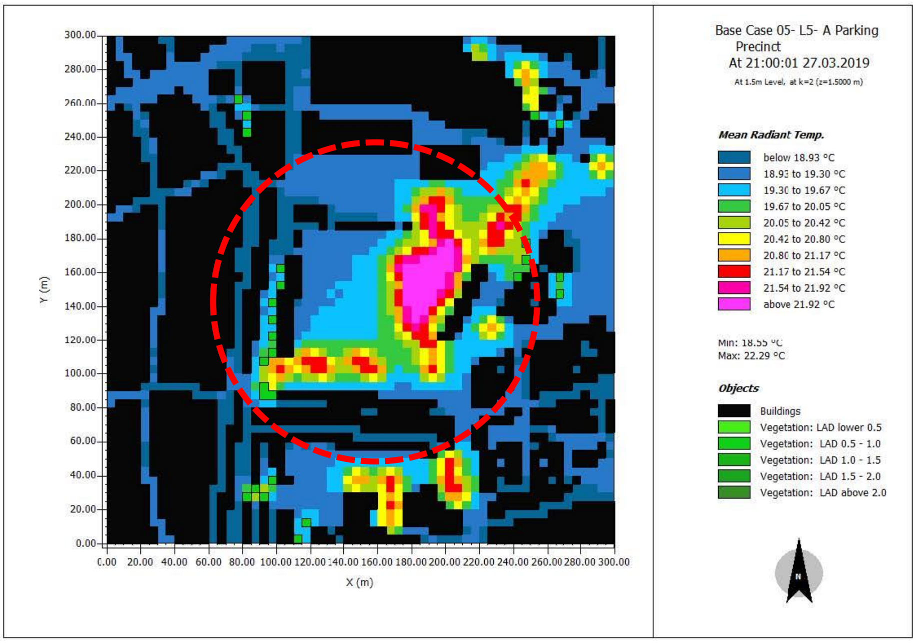
Base Case L4 – Location 04 – EW Canyon - Main Street, (i) at the Day Time 13:00:01h



Base Case L4 – Location 04 – EW Canyon - Main Street, (ii) at the Day Time 21:00:01h d.) Simulated Mean Radiant Temperature on, Base Case L5- Location 05 – A Parking Precinct, (i) at the Day Time 13:00:01h , (ii) at the Night Time 21:00:01h.



Base Case L5- Location 05 – A Parking Precinct, (i) at the Day Time 13:00:01h

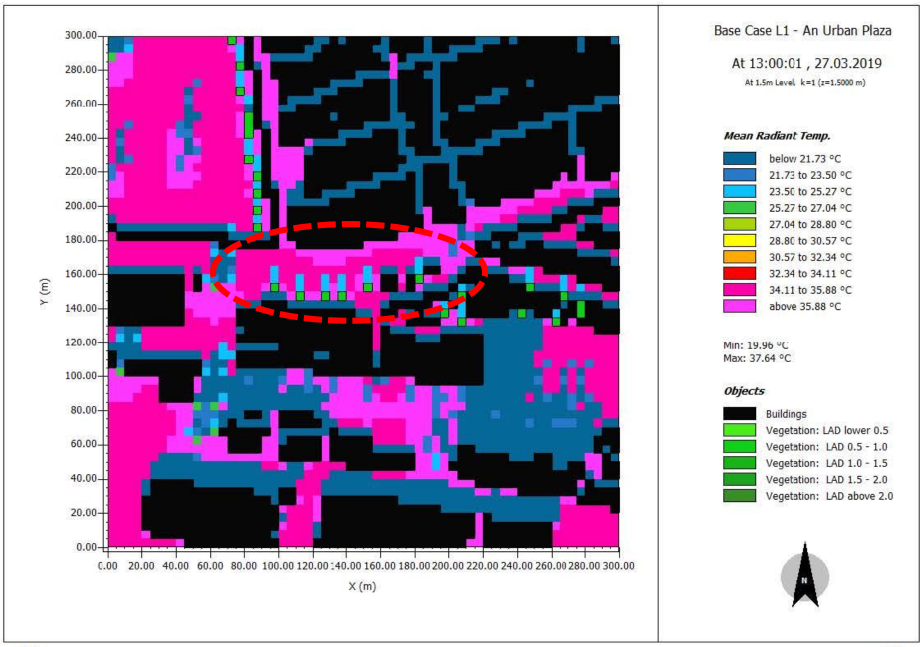


Base Case L5- Location 05 – A Parking Precinct, (ii) at the Night Time 21:00:01h

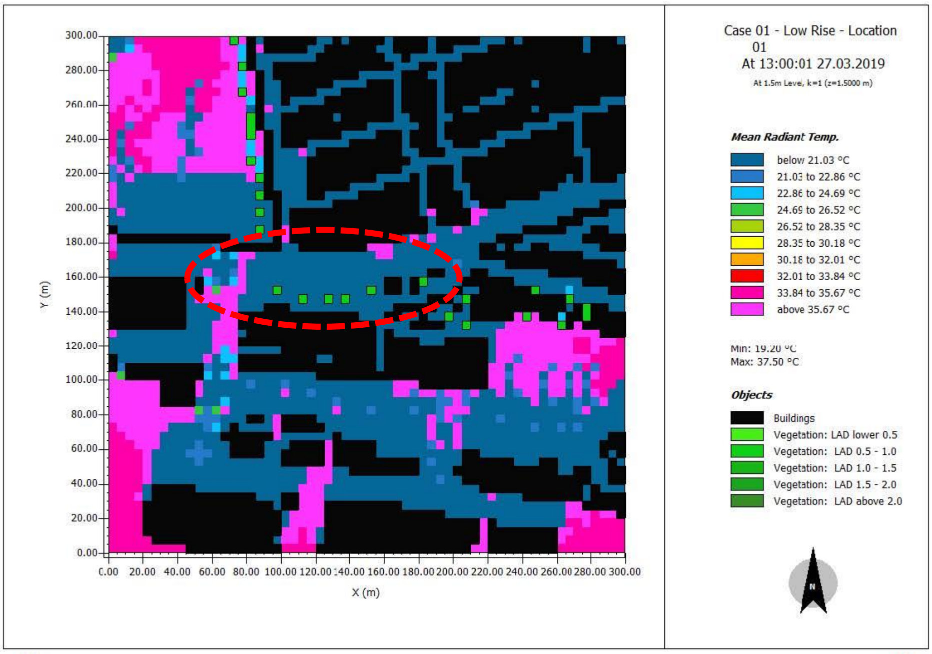
APPENDIX VIII : Mean Radiant Temperature (MRT) Distribution Maps

Case 01 – Low Rise (03 storied)

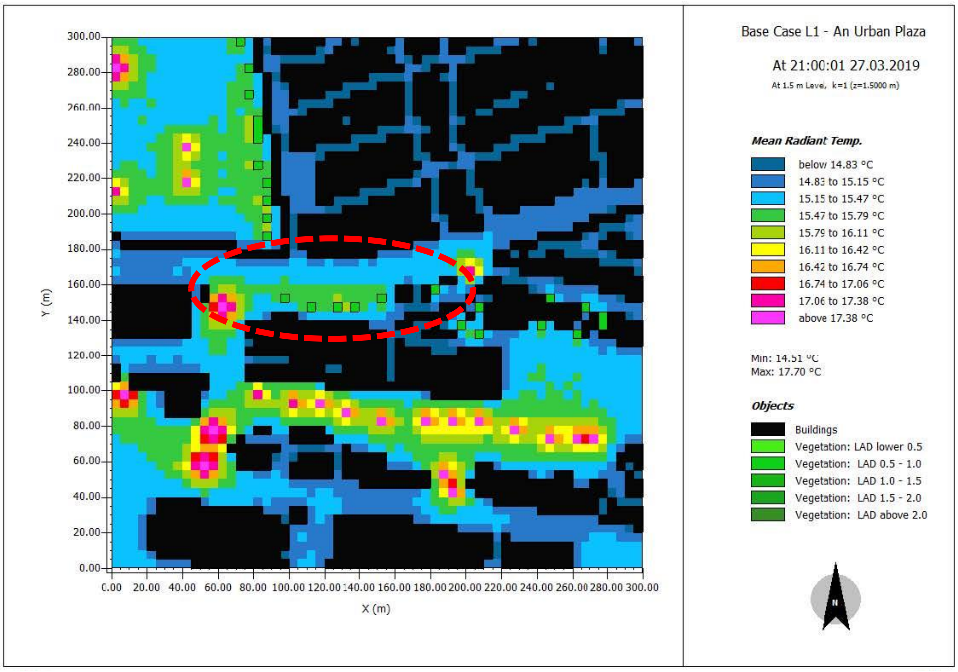
- **Location 01 – An Urban Plaza**



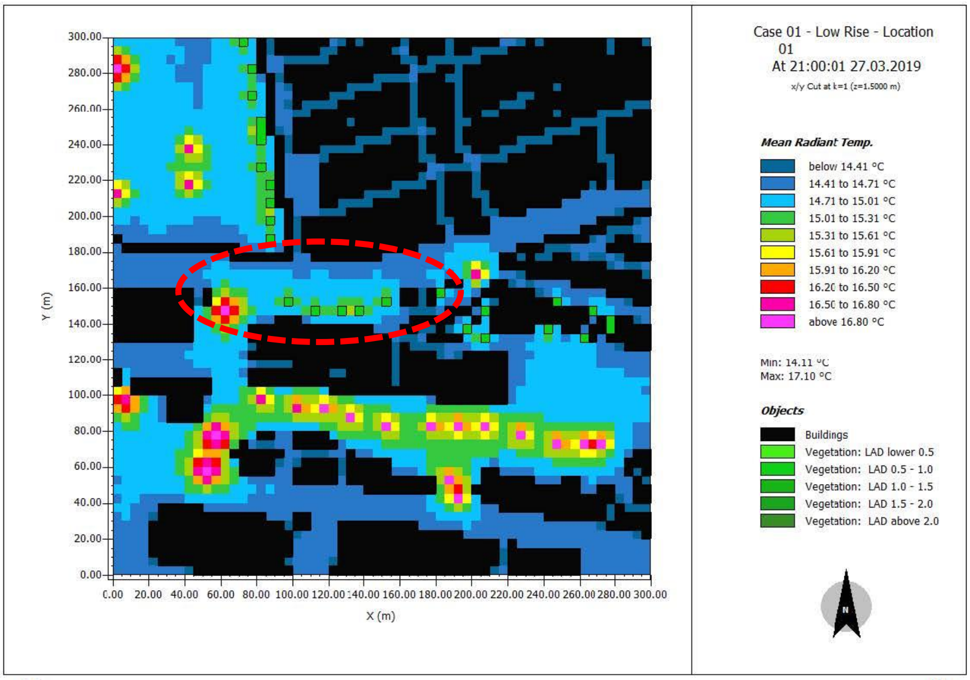
Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza at the Day Time 13:00:01h



Simulated Mean Radiant Temperature for, Case 01- Low Rise -Location 01-An Urban Plaza at the Night Time 13:00:01h

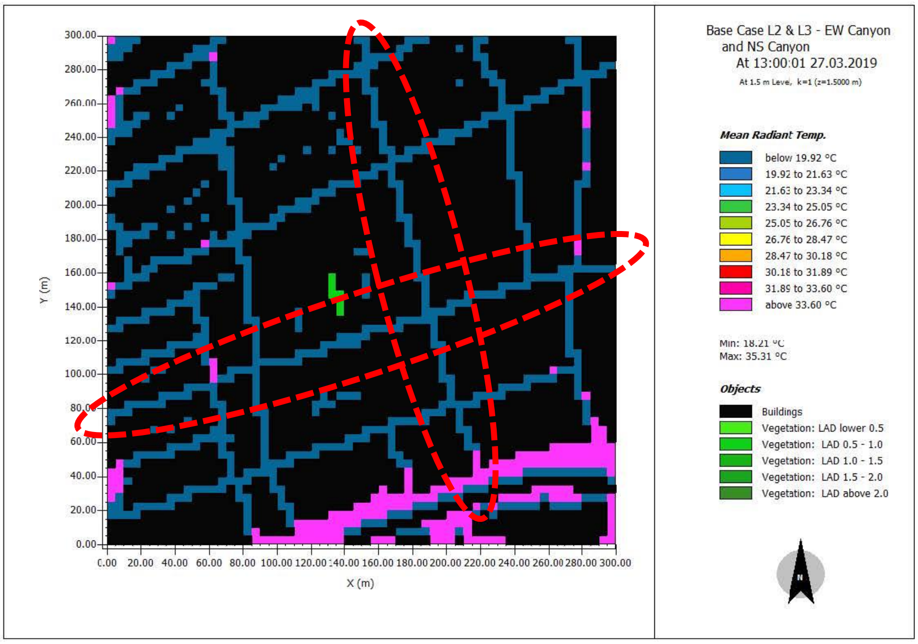


Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza at the Night Time 21:00:01h

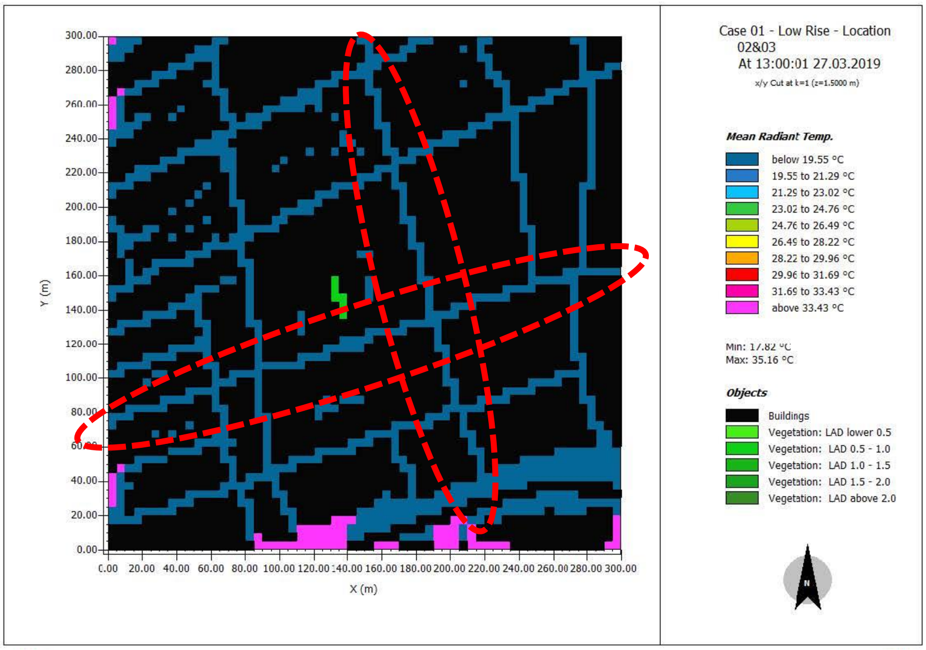


Simulated Mean Radiant Temperature for, Case 01- Low Rise -Location 01- An Urban Plaza at the Night Time 21:00:01h

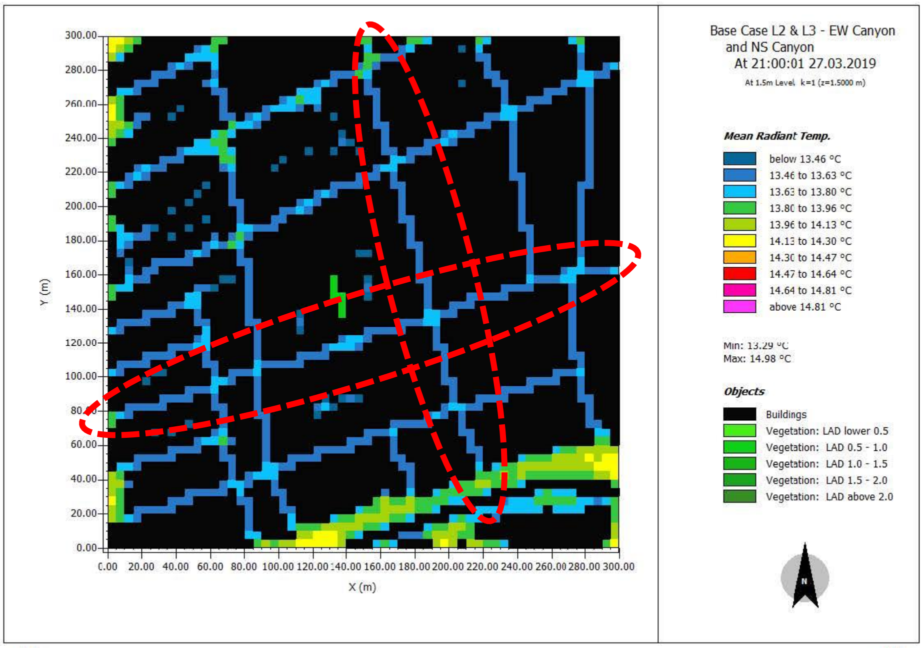
Location 02 and 03 – EW and NS Canyons (Prince Street and 02nd Cross Street)



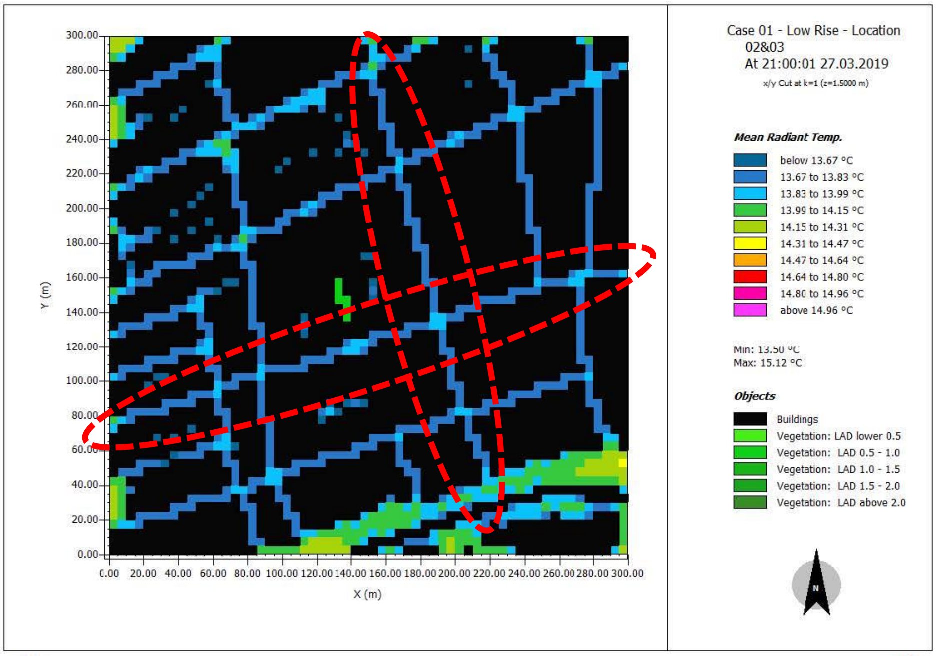
Simulated Mean Radiant Temperature for Base Case L2 and L3 – Location 02-EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 01- Low Rise – Location 02-EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street at the Day Time 13:00:01h.

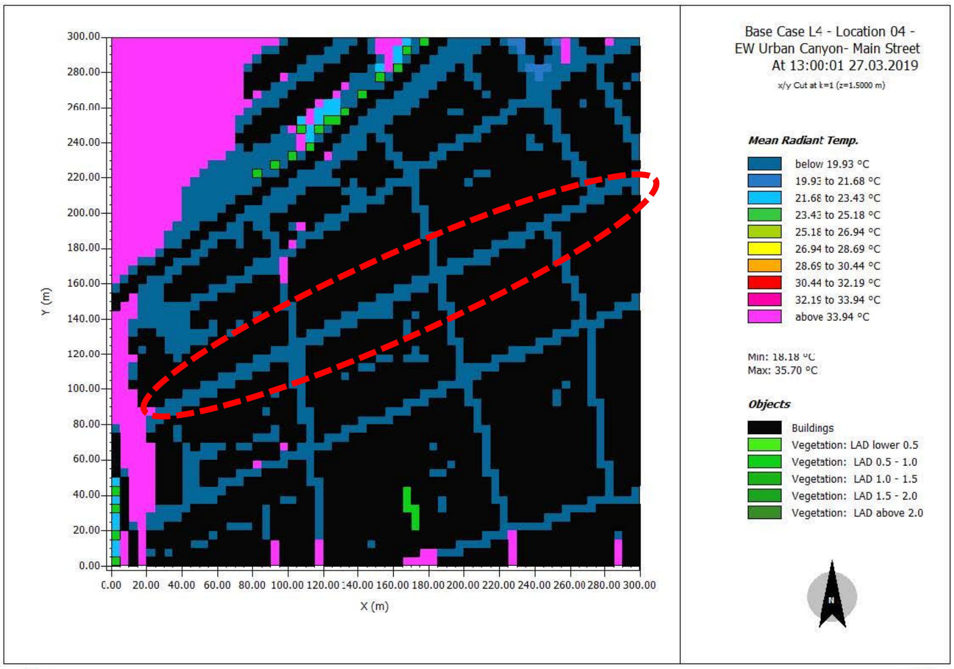


Simulated Mean Radiant Temperature for the Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street at the Night Time 21:00:01h.

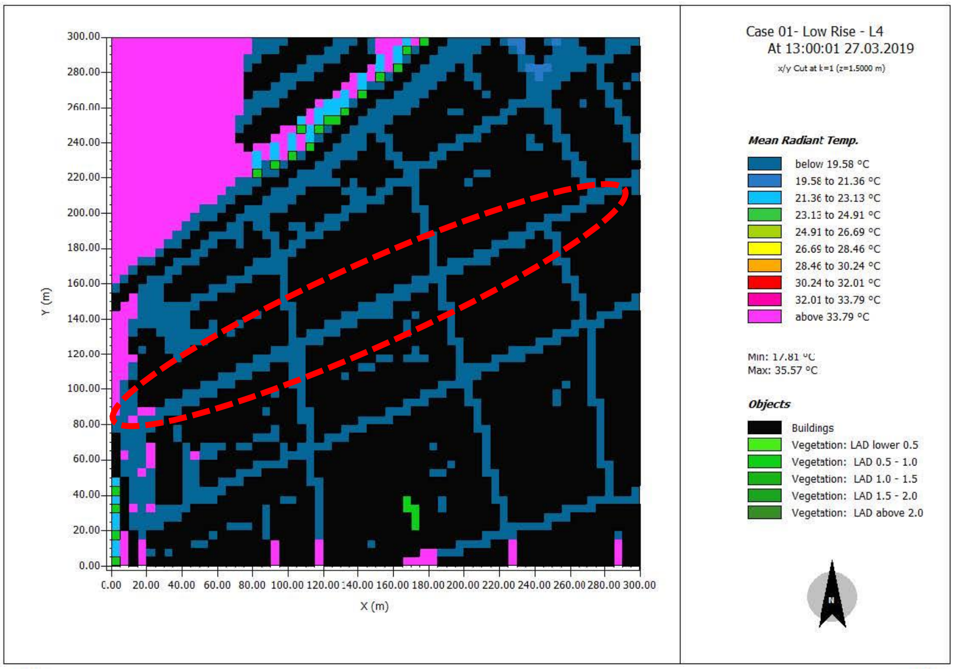


Simulated Mean Radiant Temperature for Case 01 – Low Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street at the Night Time 21:00:01h.

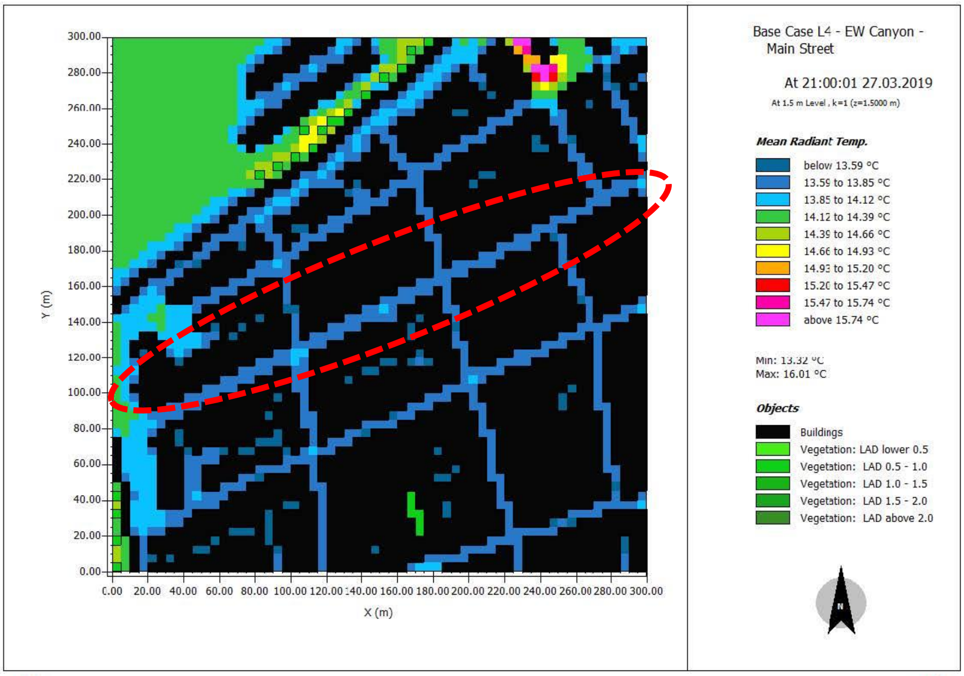
Location 04 – EW Canyon (Main Street)



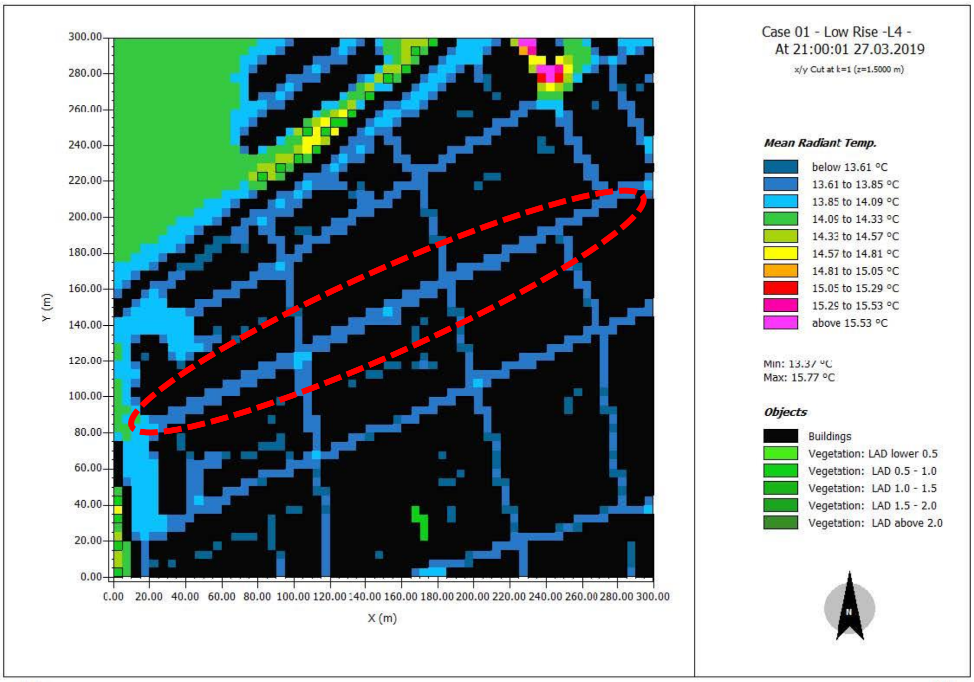
Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon – Main Street at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 01 – Low Rise – Location 04- EW Canyon –Main Street at the Day Time 13:00:01h.

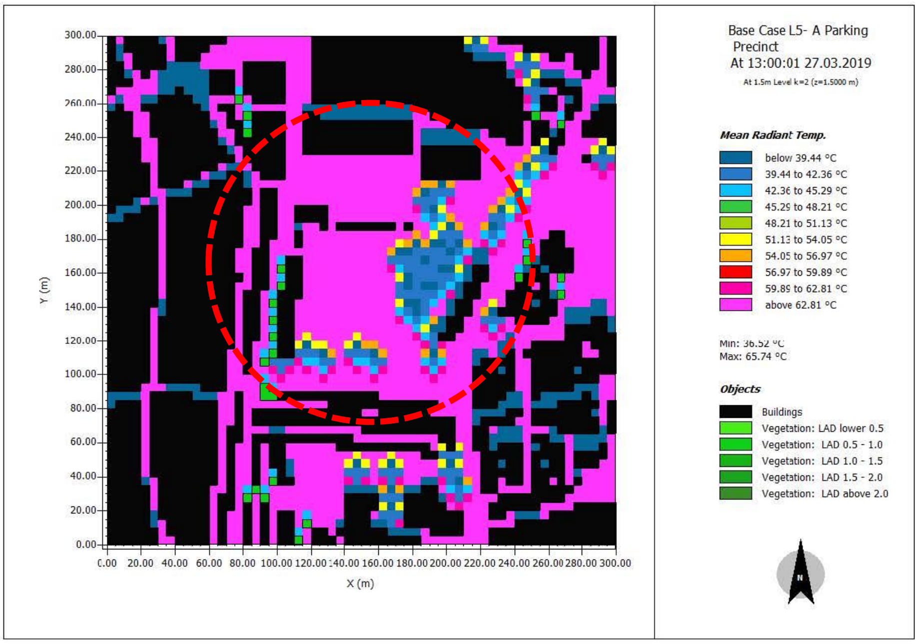


Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon – Main Street at the Night Time 21:00:01h.

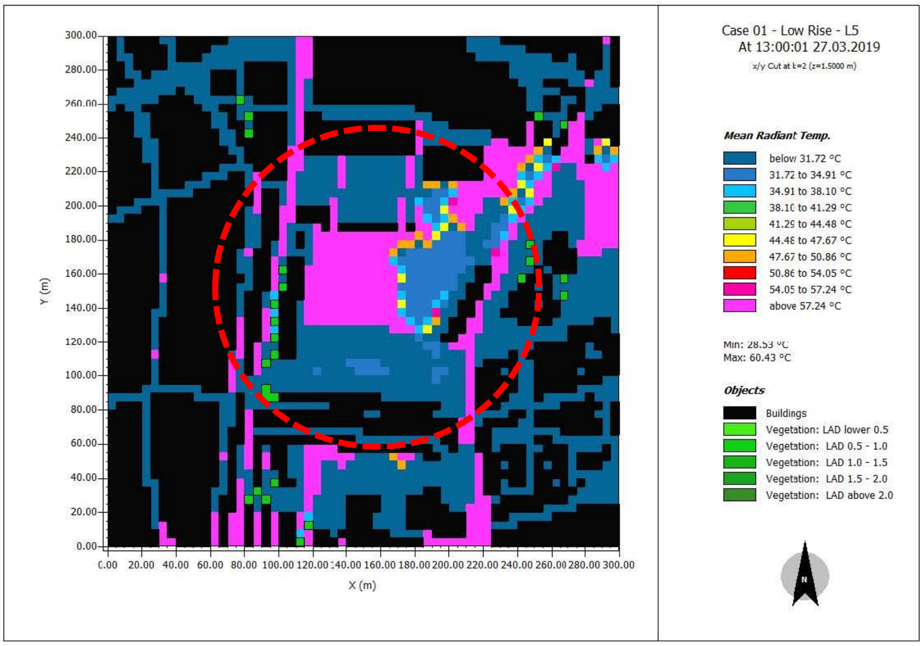


Simulated Mean Radiant Temperature for Case 01 – Low Rise – Location 04- EW Canyon –Main Street at the Night Time 21:00:01h.

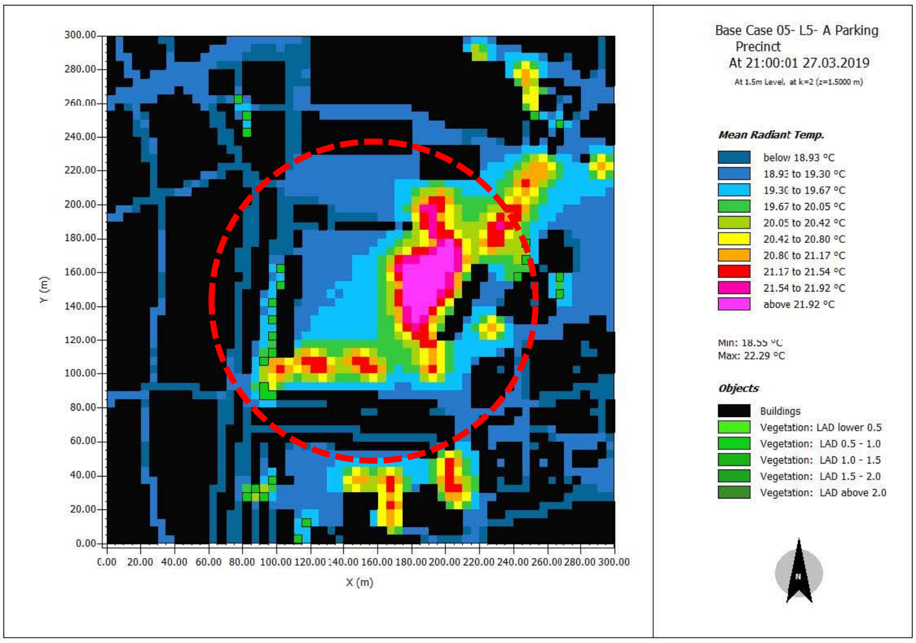
- **Location 05 – A Parking Precinct**



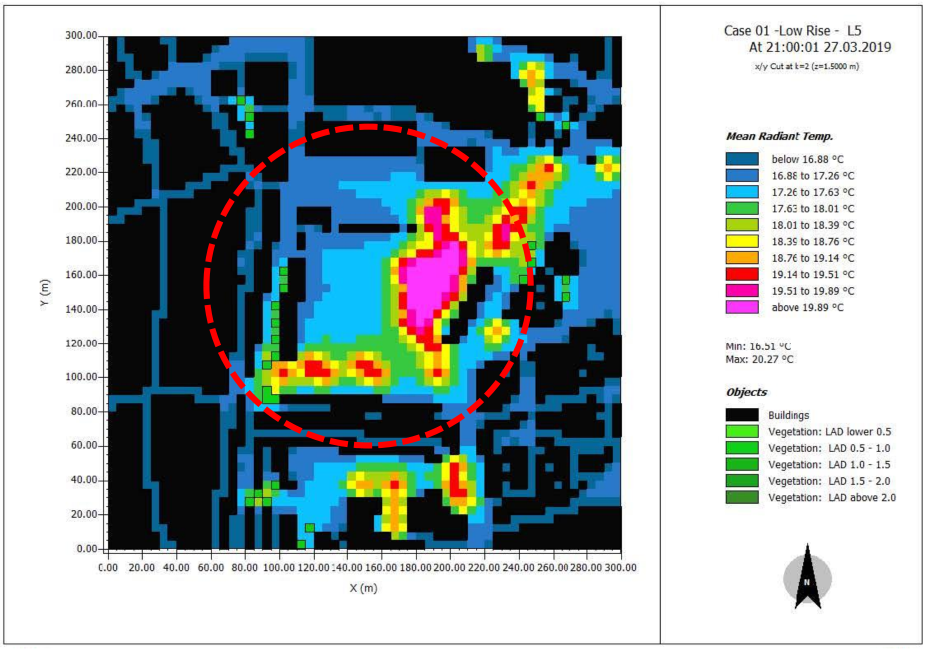
Simulated Mean Radiant Temperature for the Base Case L5 – Low Rise – Location 05- A Parking Precinct at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 01 – Low Rise – Location 05- A Parking Precinct at the Day Time 13:00:01h.



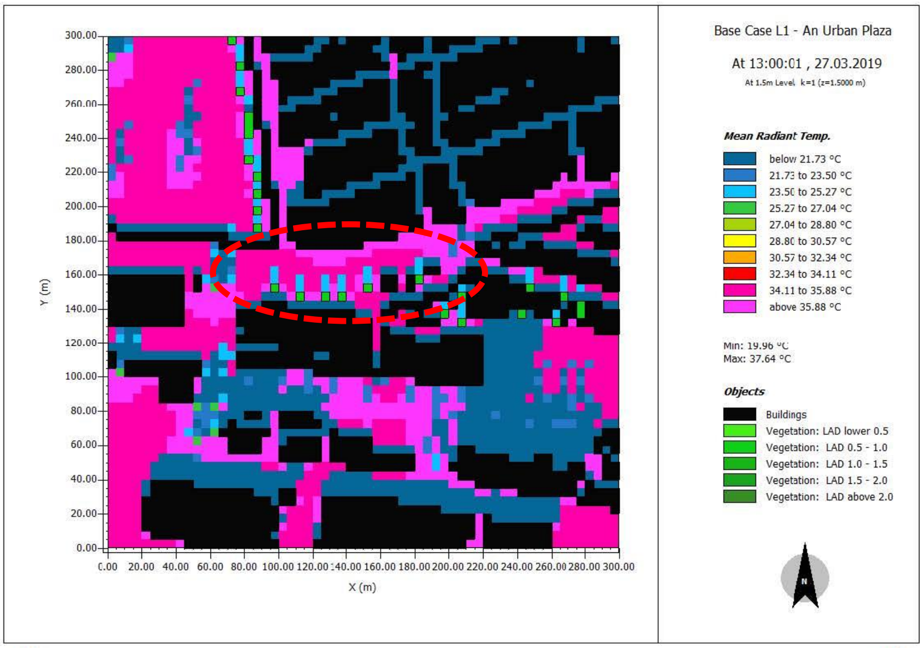
Simulated Mean Radiant Temperature for the Base Case L5 – Low Rise – Location 05- A Parking Precinct at the Night Time 21:00:01h.



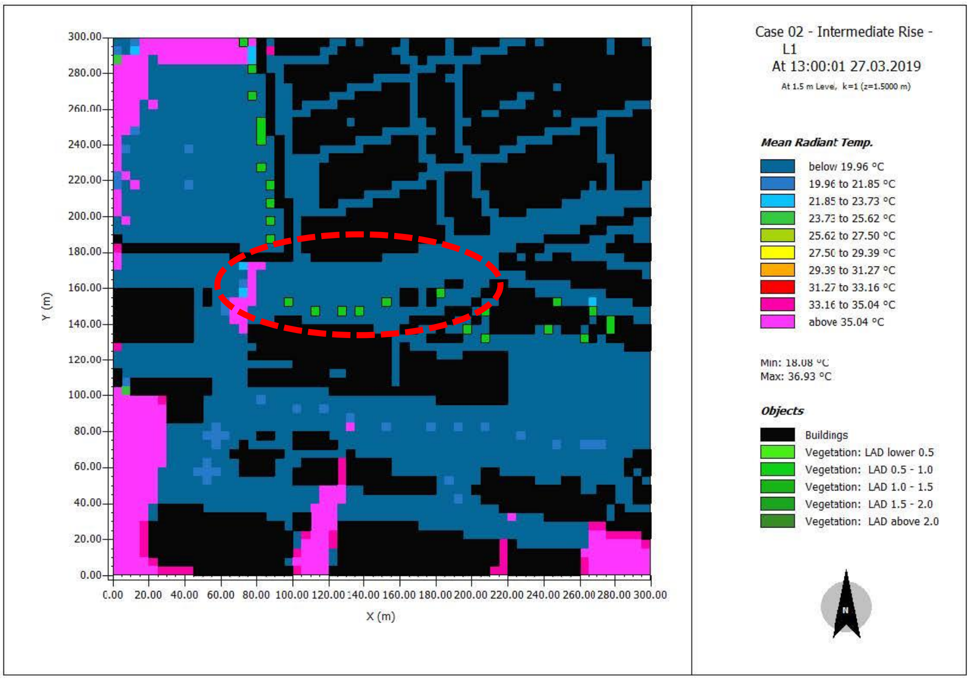
Simulated Mean Radiant Temperature for Case 01 – Low Rise – Location 05- A Parking Precinct at the Night Time 21:00:01h.

Analysis of Case 02- Intermediate Rise (08 storied) scenario.

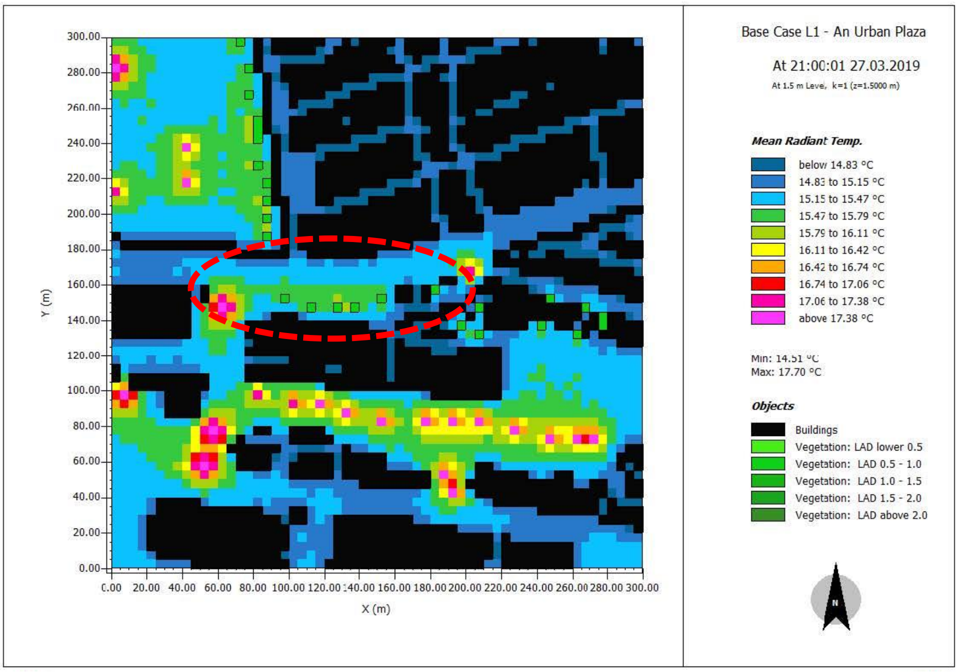
Location 01 – An Urban Plaza



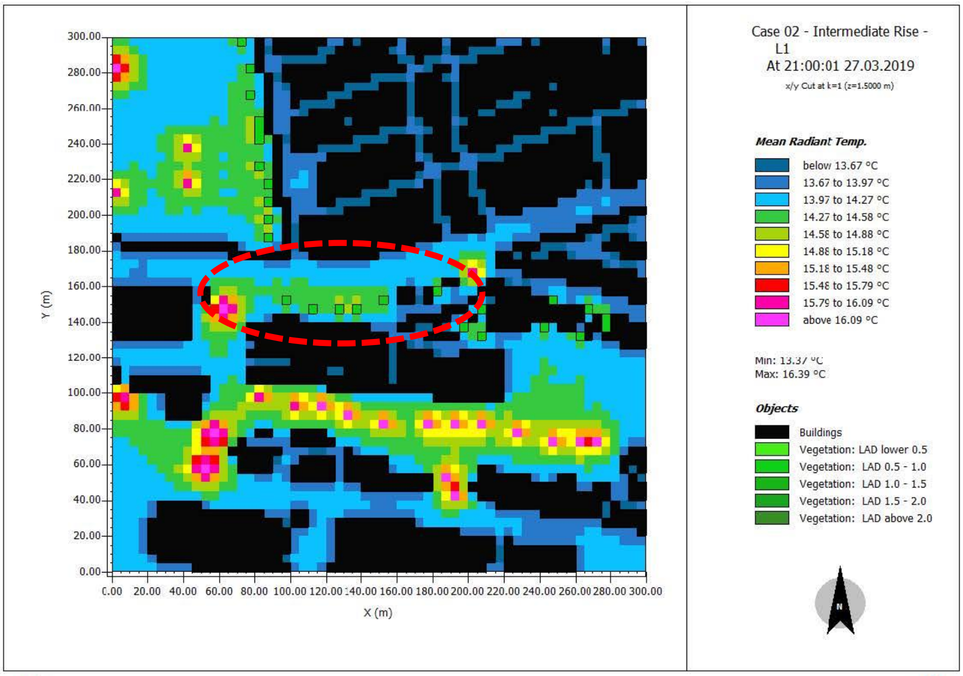
Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Day Time 13:00:01h



Simulated Mean Radiant Temperature for, Case 02- Intermediate Rise -Location 01-An Urban Plaza (i) at the Day Time 13:00:01h

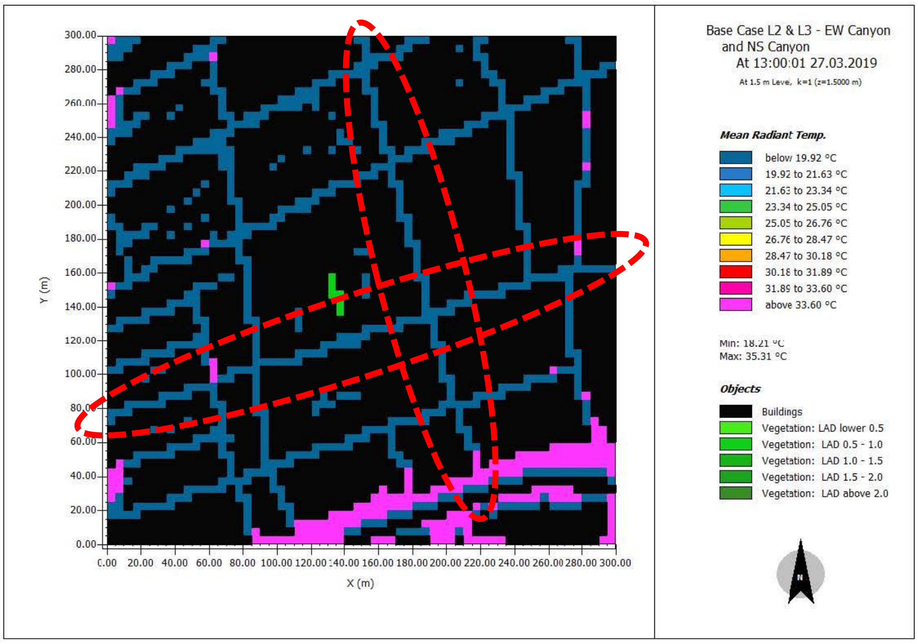


Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Night Time 21:00:01h

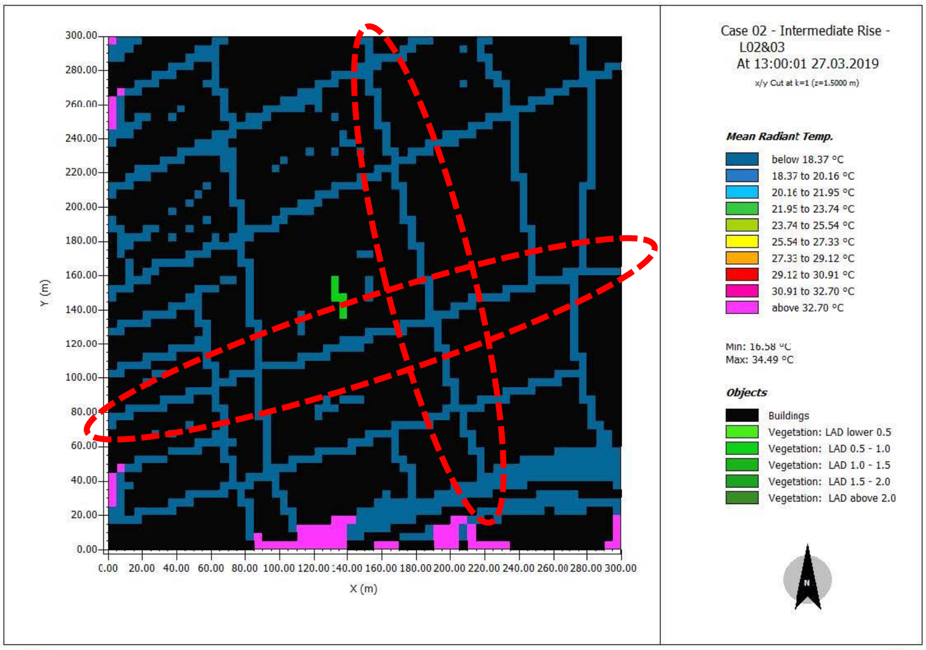


Simulated Mean Radiant Temperature for, Case 02- Intermediate Rise -Location 01-An Urban Plaza (i) at the Night Time 21:00:01h

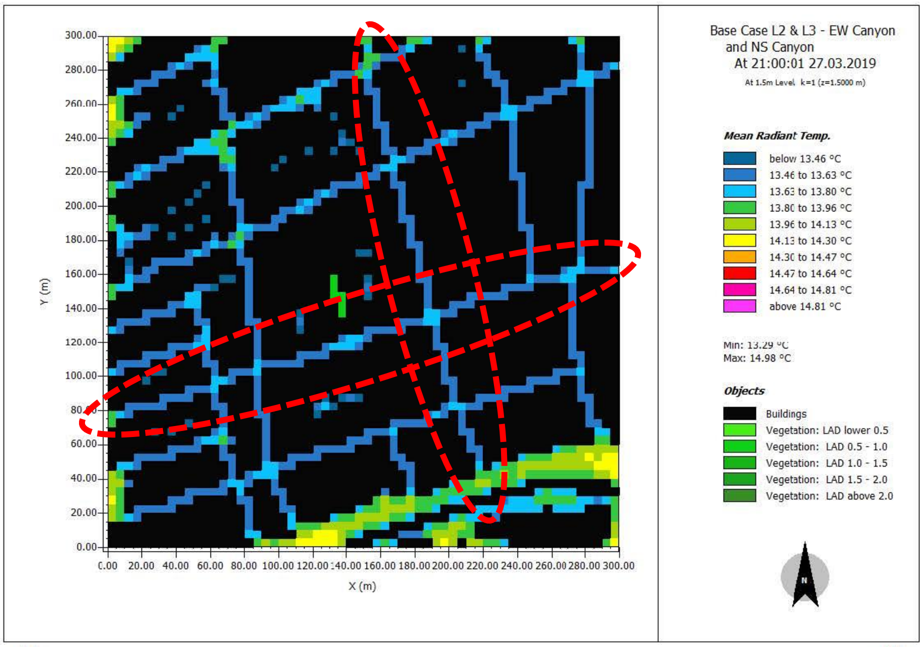
Location 02 and 03 – EW and NS Canyons (Prince Street and 02nd Cross Street)



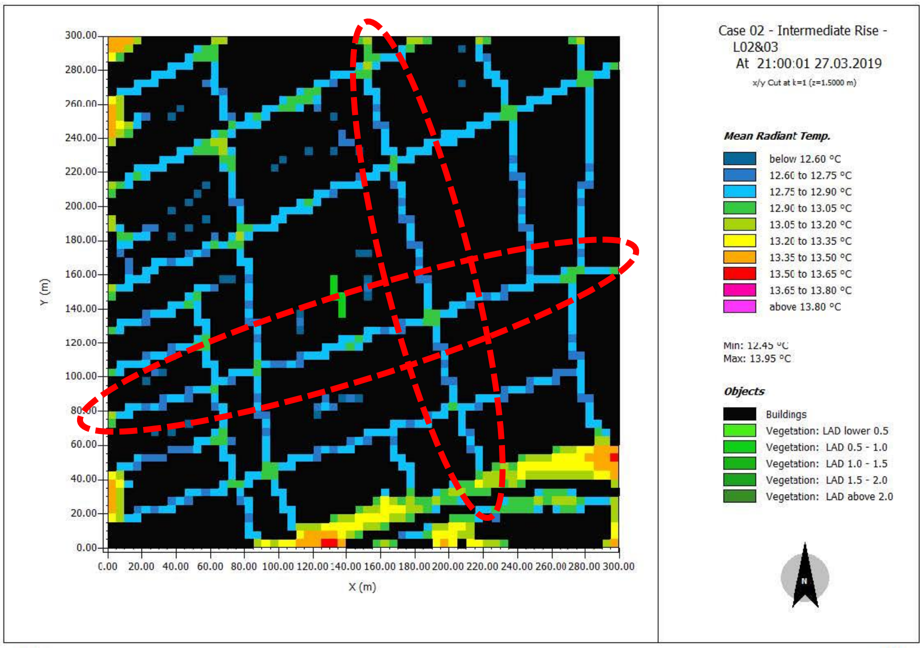
Simulated Mean Radiant Temperature for Base Case L2 and L3 – Location 02-EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 02- Intermediate Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.

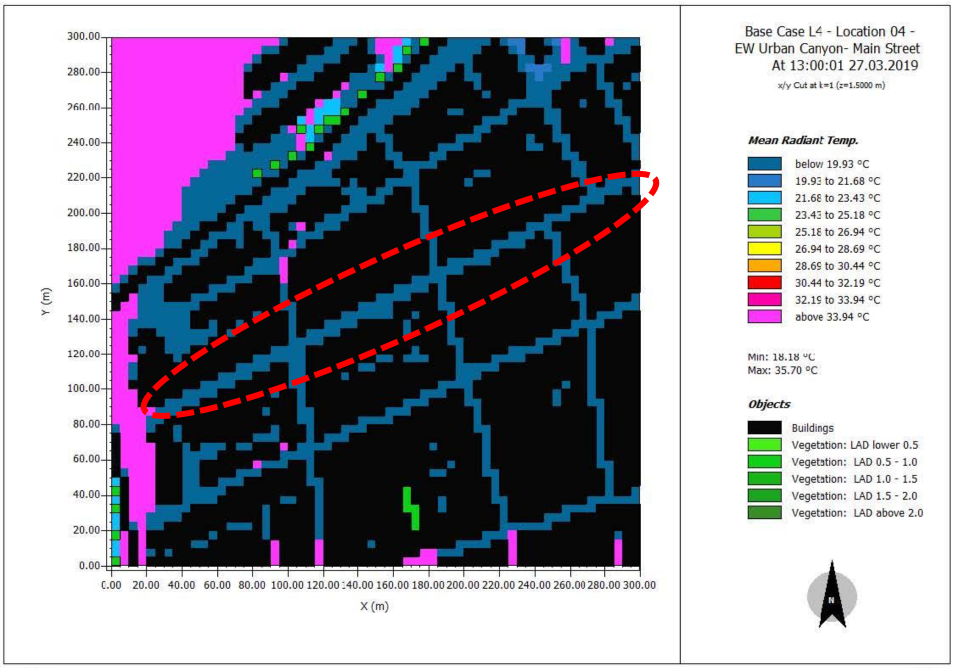


Simulated Mean Radiant Temperature for the Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

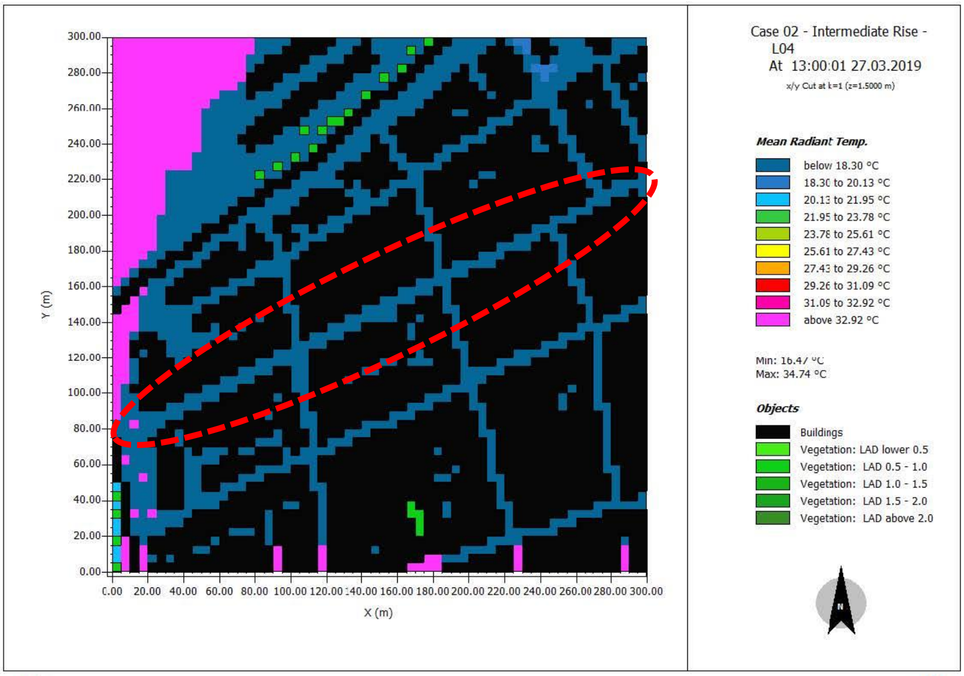


Simulated Mean Radiant Temperature for Case 02 – Intermediate Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

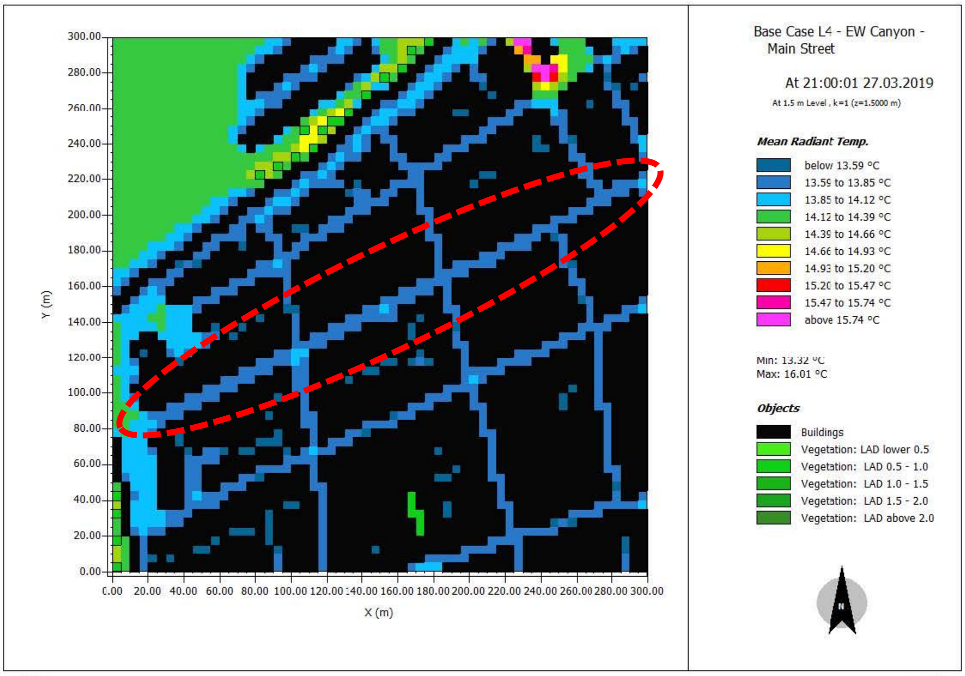
Location 04 – EW Canyon (Main Street)



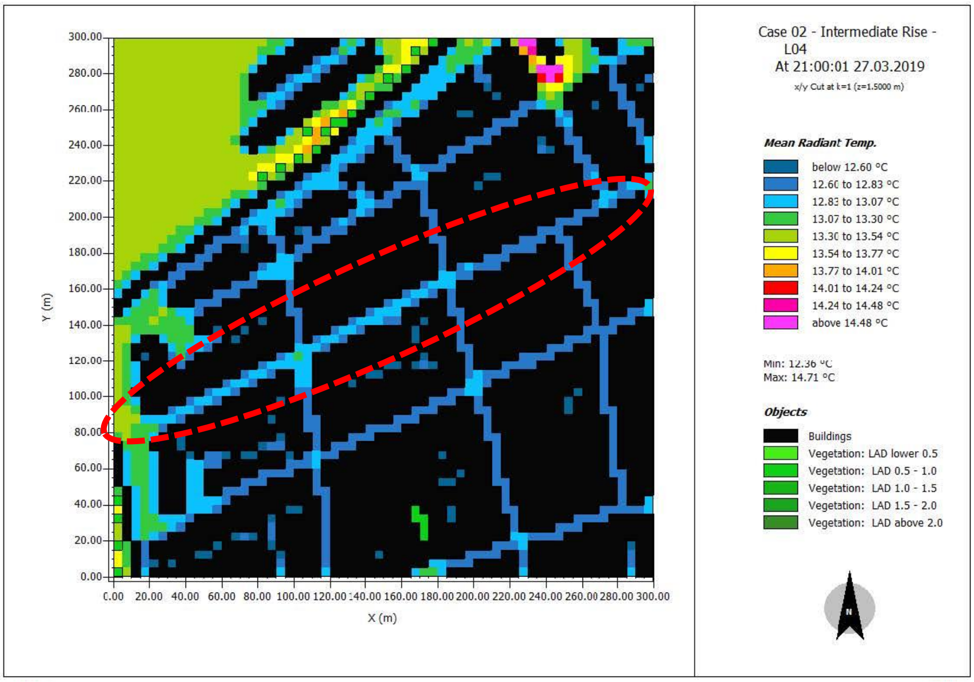
Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 02 – Intermediate Rise – Location 04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.

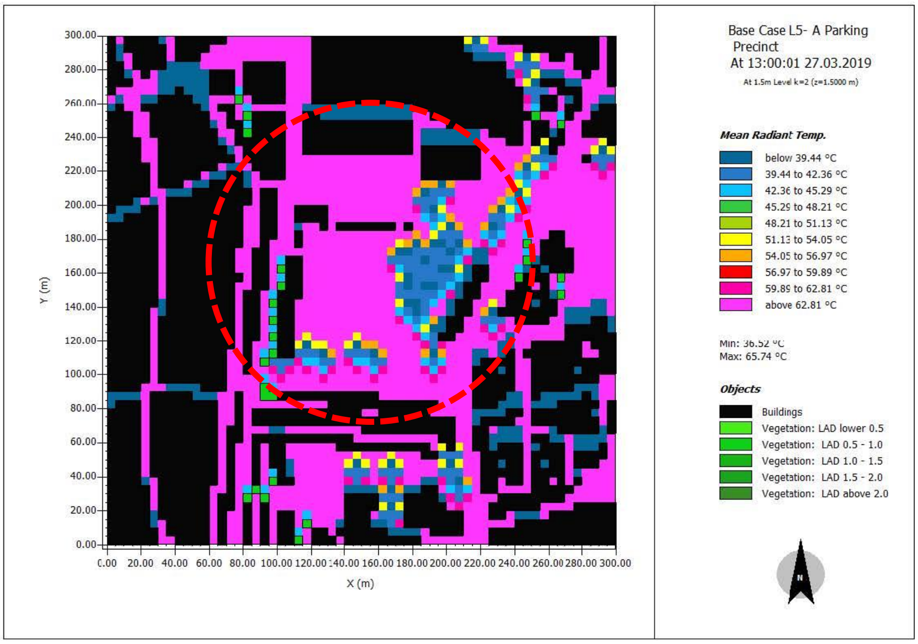


Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

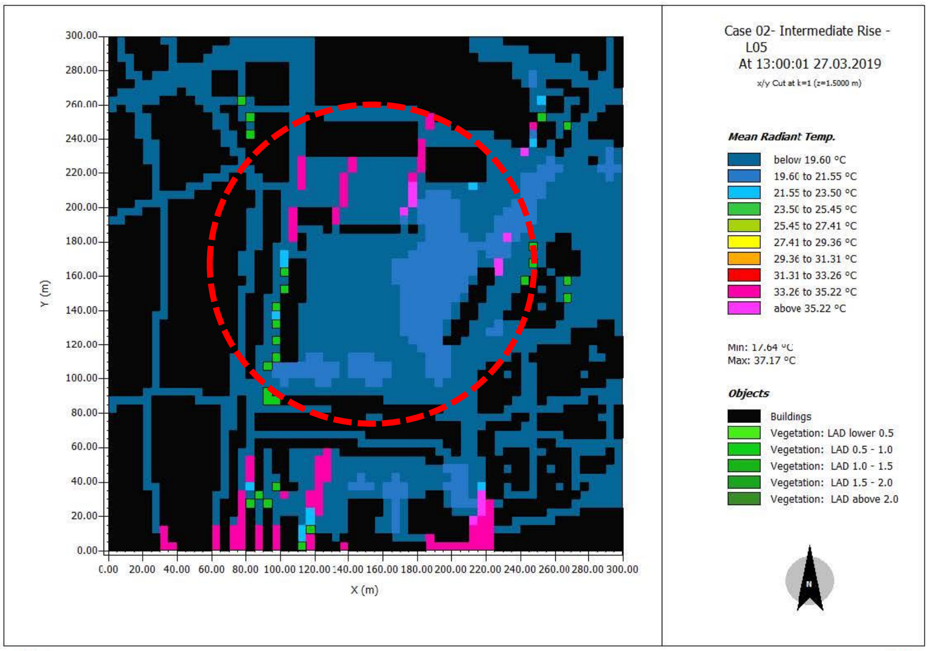


Simulated Mean Radiant Temperature for Case 02 – Intermediate Rise – Location 04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

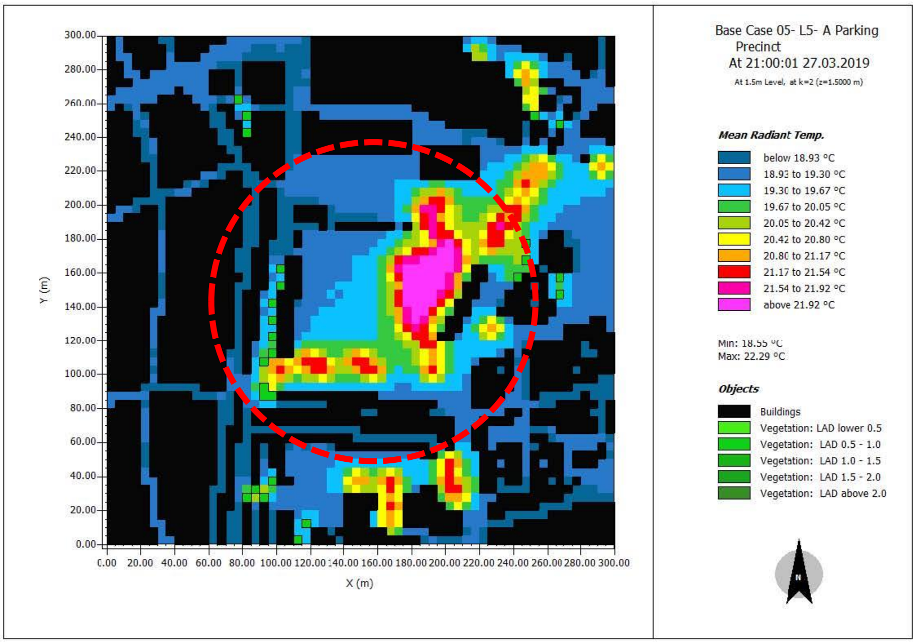
Location 05 – A Parking Precinct



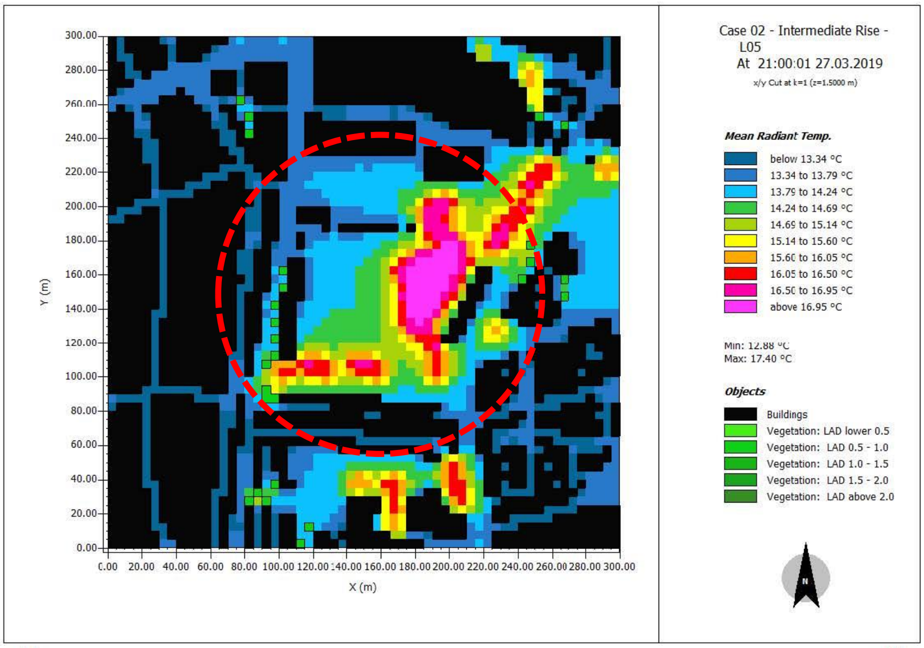
Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 02 – Intermediate Rise – Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



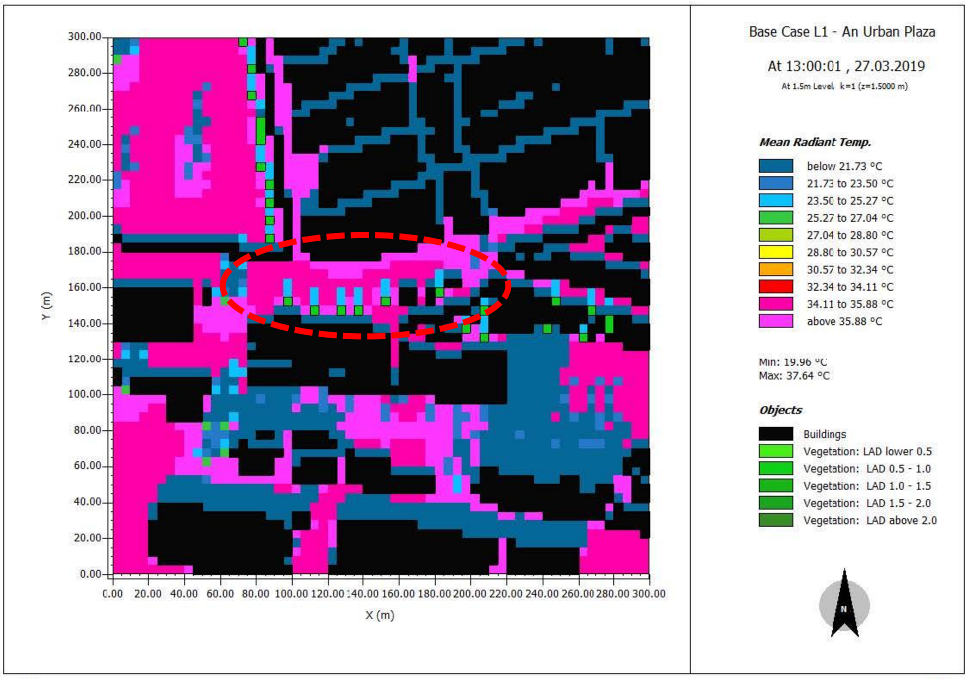
Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.



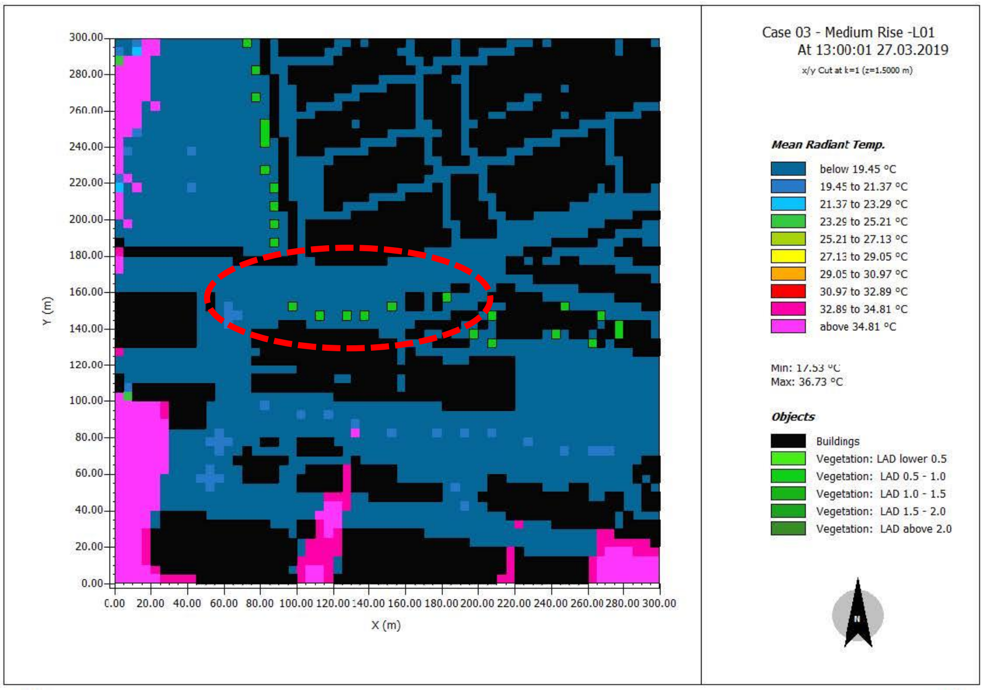
Simulated Mean Radiant Temperature for Case 02 – Intermediate Rise – Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.

Analysis of Case 03- Medium Rise (12 storied) scenario

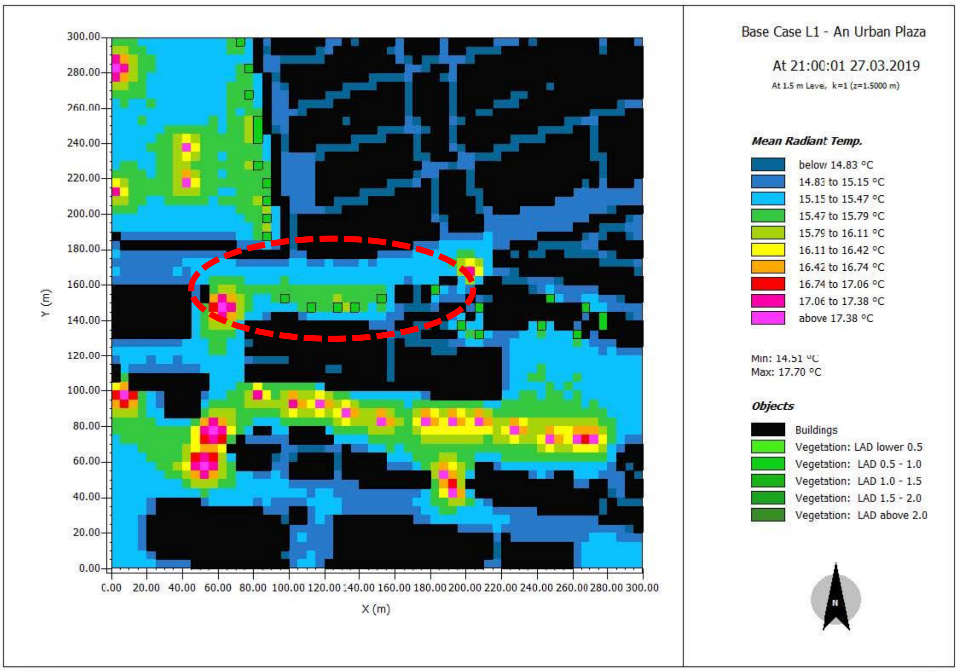
Location 01 – An Urban Plaza



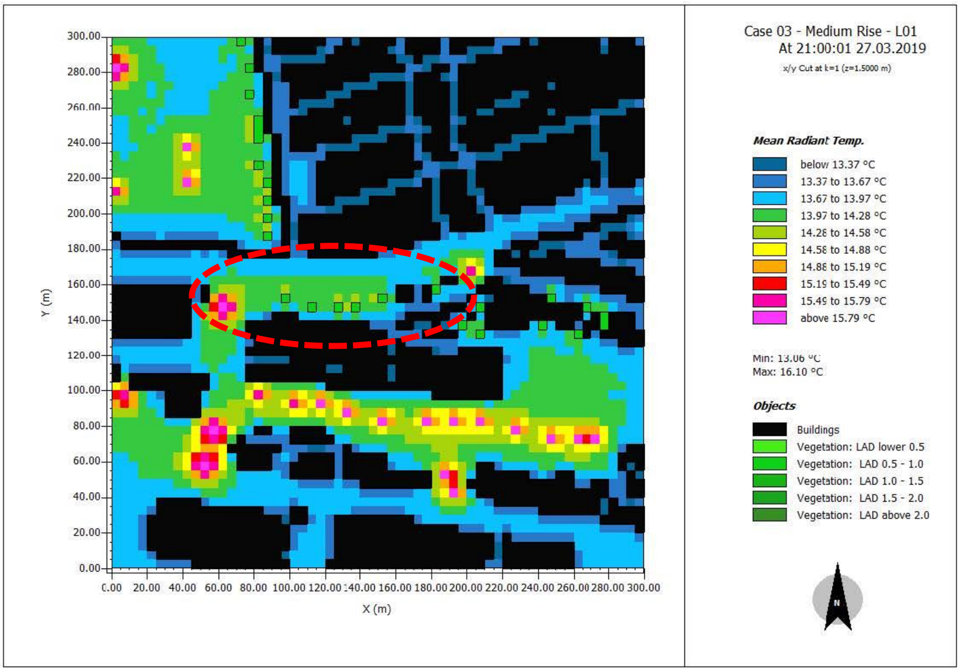
Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Day Time 13:00:01h



Simulated Mean Radiant Temperature for, Case 03- Medium Rise -Location 01-An Urban Plaza (i) at the Day Time 13:00:01h

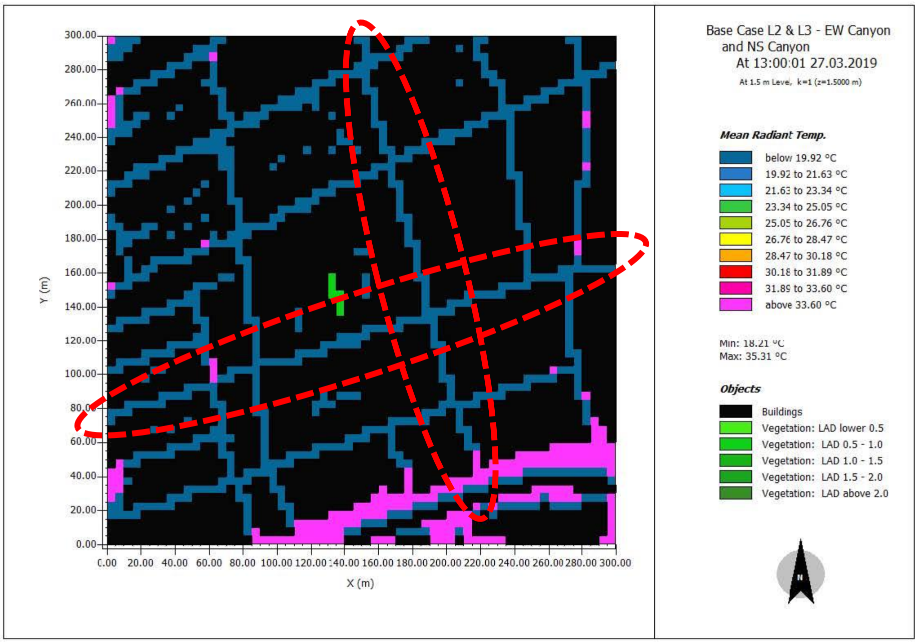


Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Night Time 21:00:01h

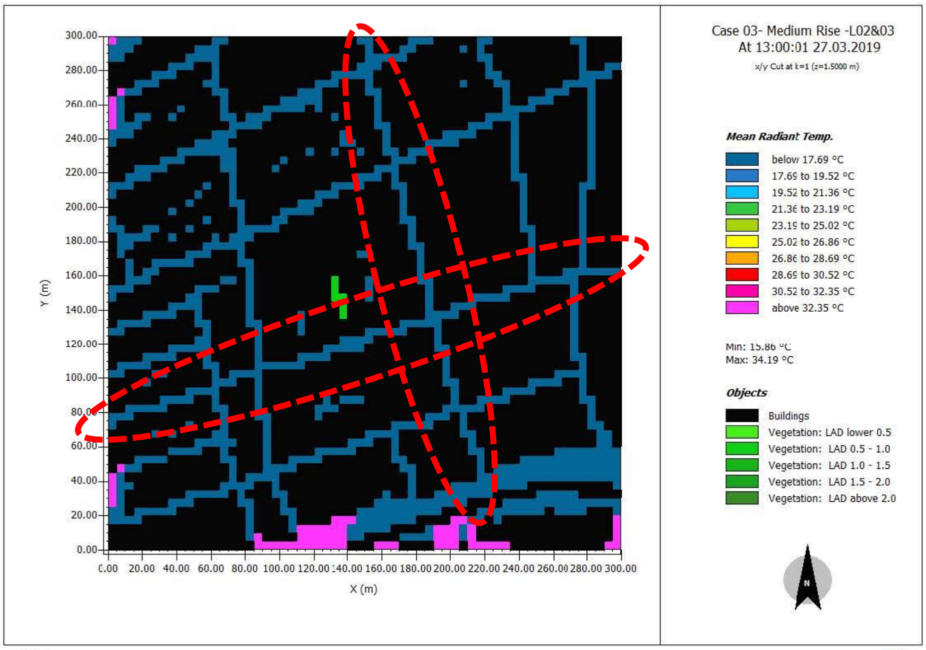


Simulated Mean Radiant Temperature for, Case 03- Medium Rise -Location 01-An Urban Plaza (i) at the Night Time 21:00:01h

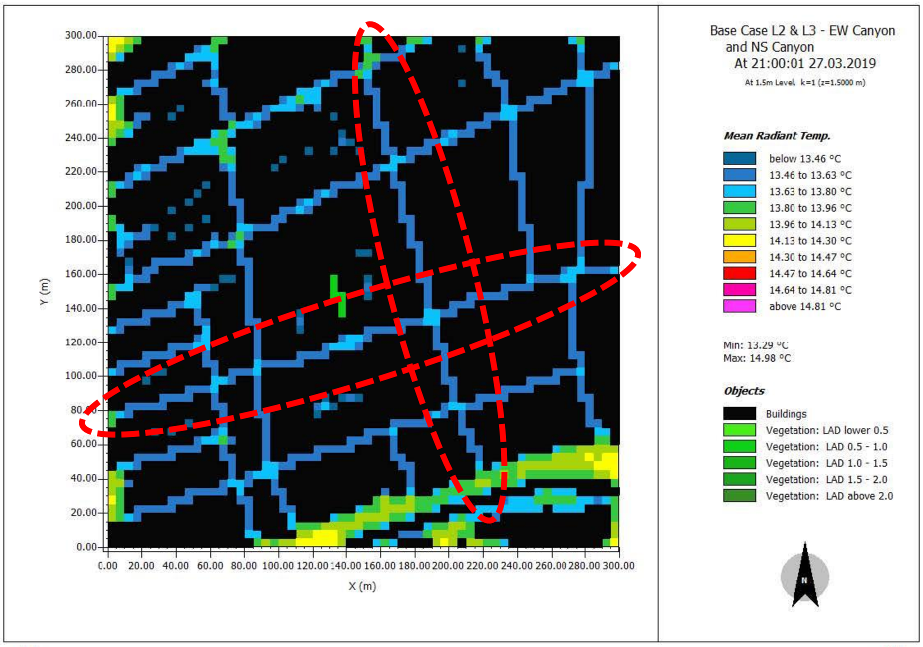
Location 02 and 03 – EW and NS Canyons (Prince Street and 02nd Cross Street)



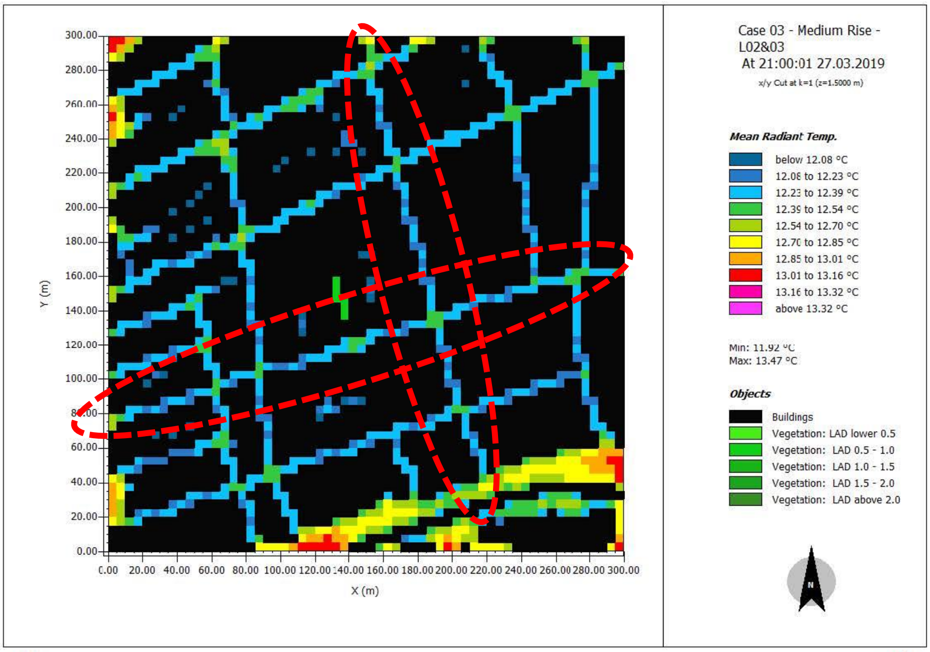
Simulated Mean Radiant Temperature for Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 03- Medium Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.

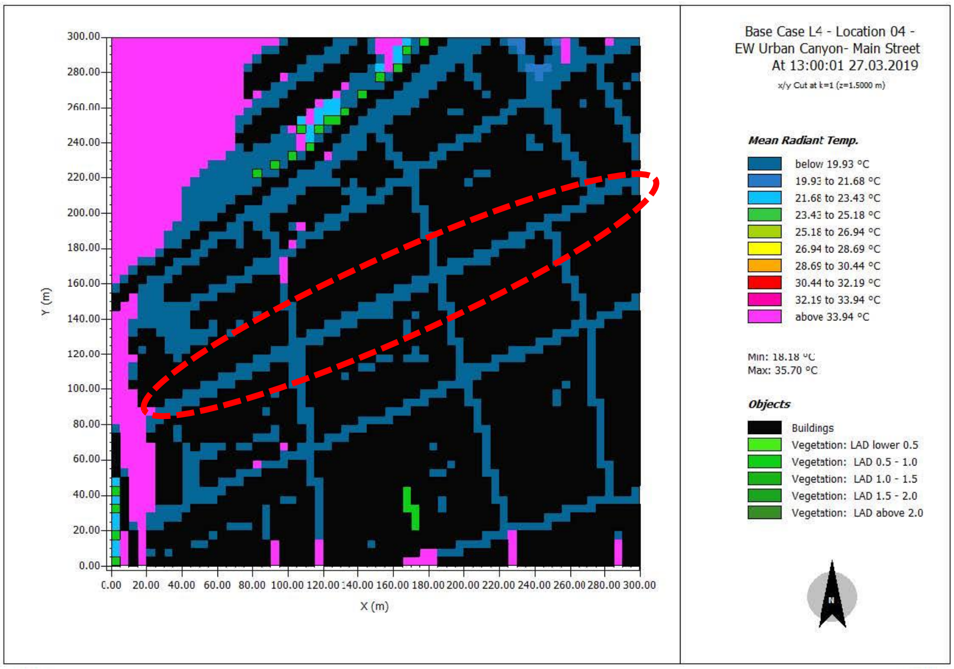


Simulated Mean Radiant Temperature for the Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

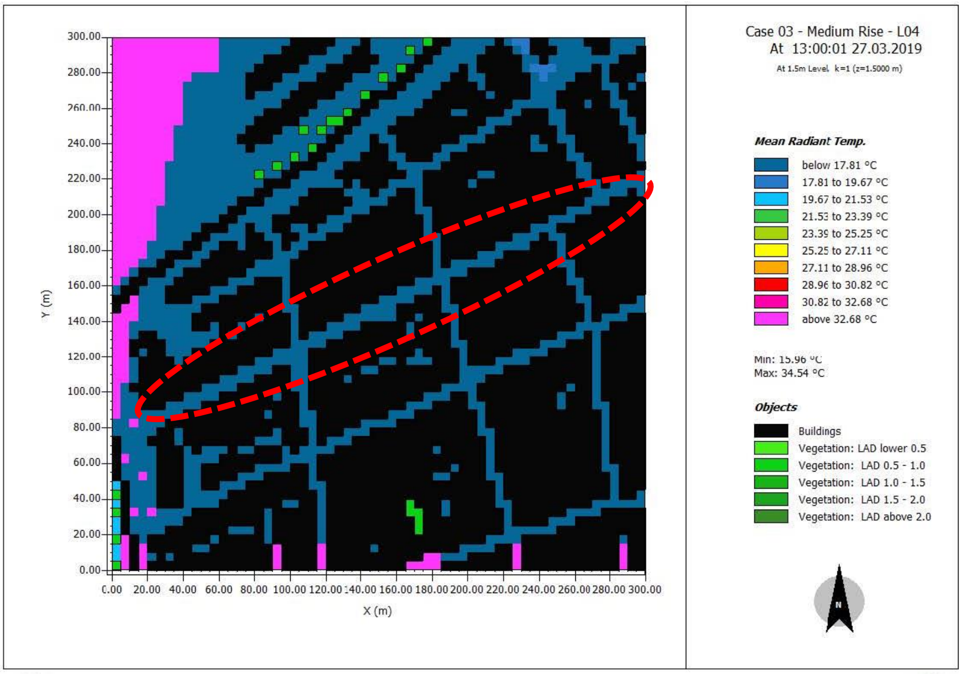


Simulated Mean Radiant Temperature for Case 03 – Medium Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

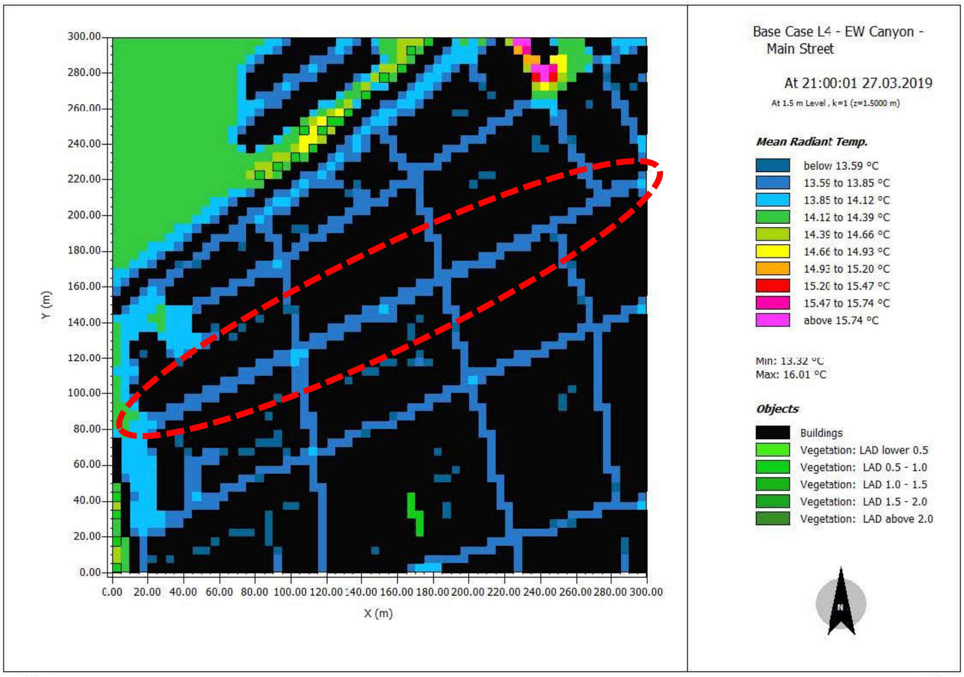
Location 04 – EW Canyon (Main Street)



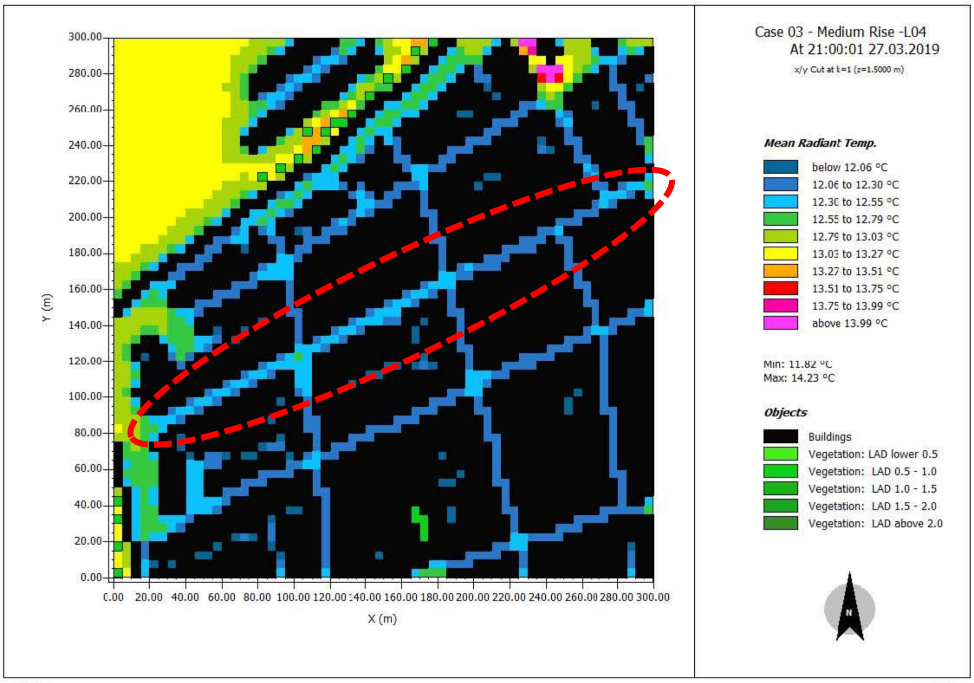
Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 03 – Medium Rise – Location 04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.

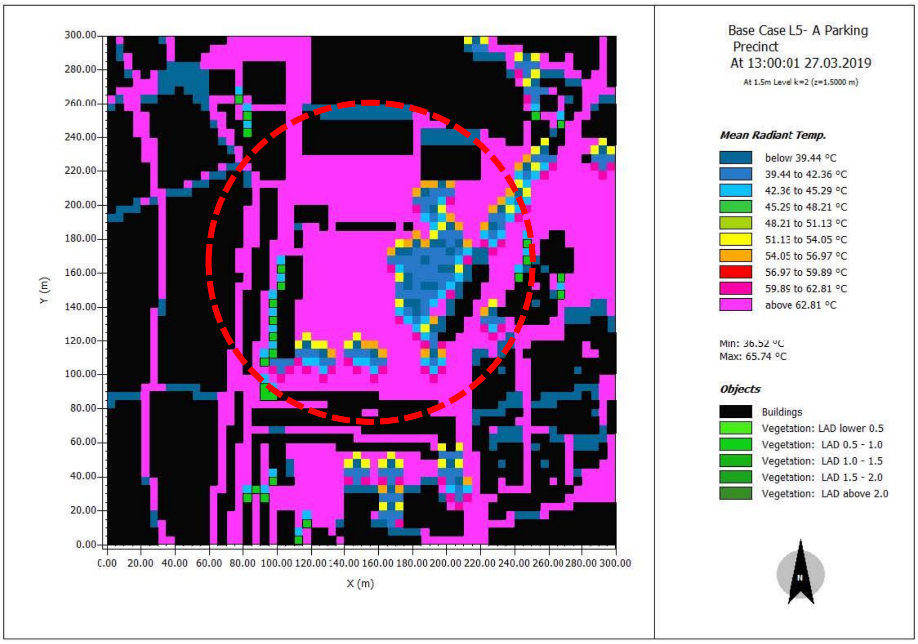


Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

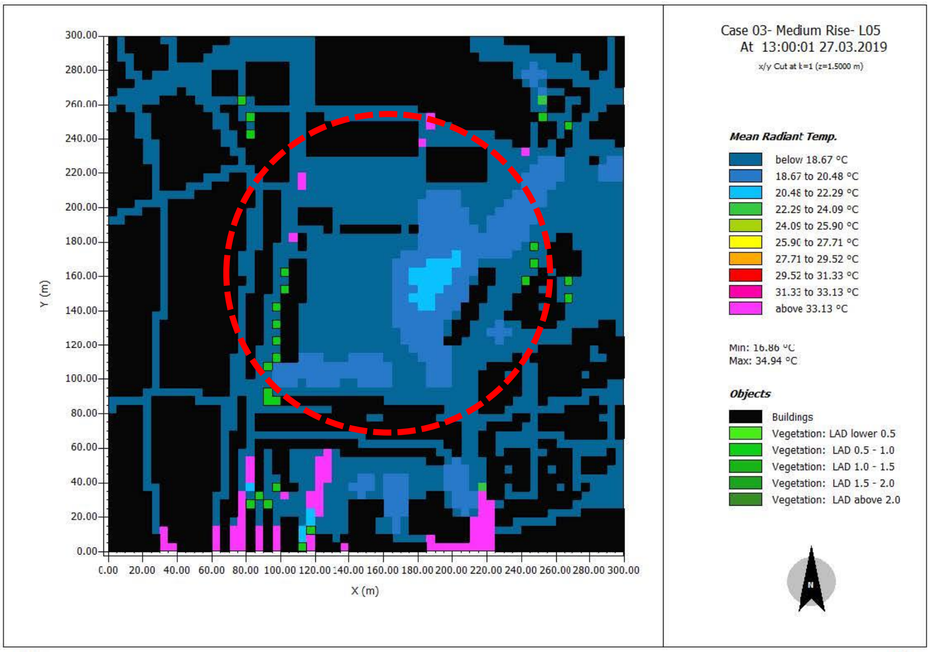


Simulated Mean Radiant Temperature for Case 03 – Medium Rise – Location 04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

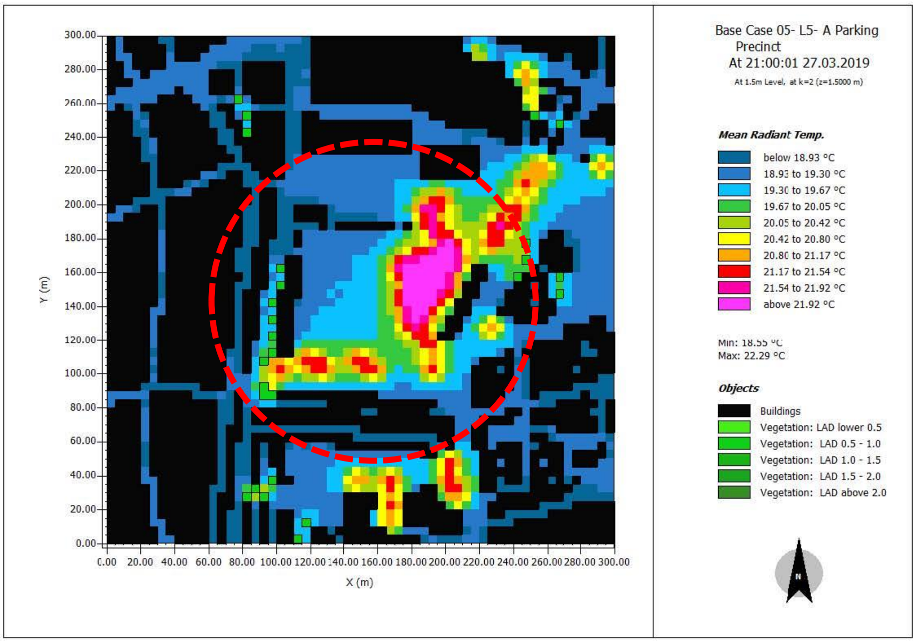
Location 05 – A Parking Precinct



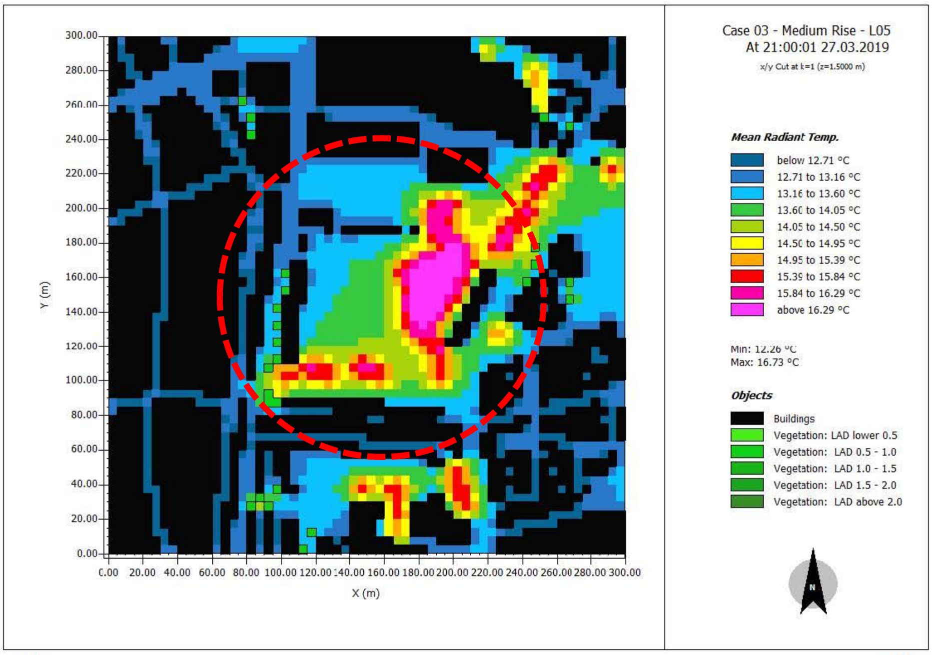
Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 03 – Medium Rise – Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



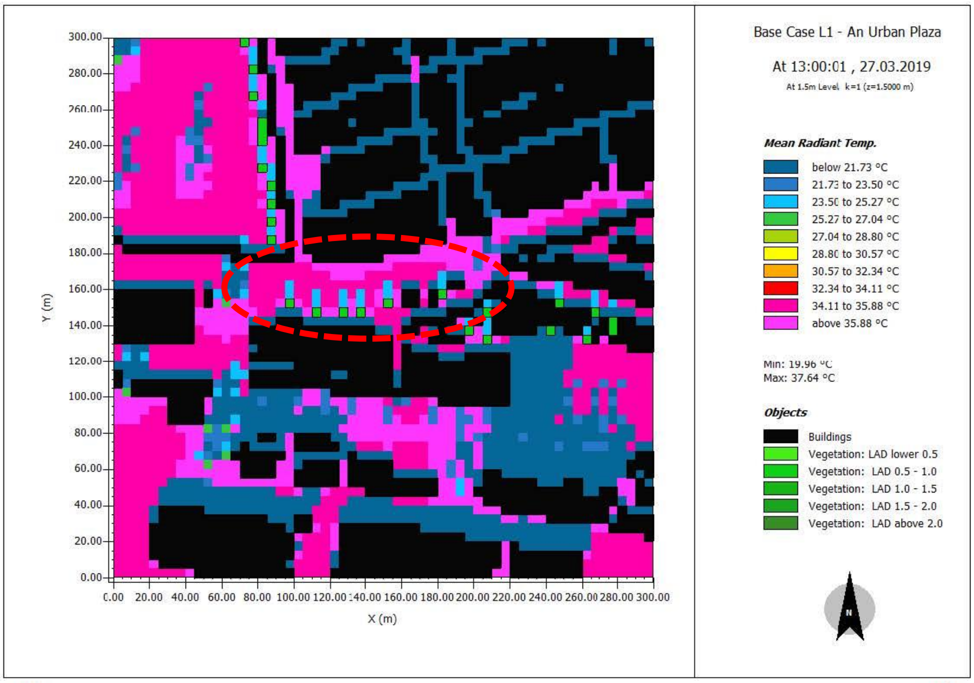
Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.



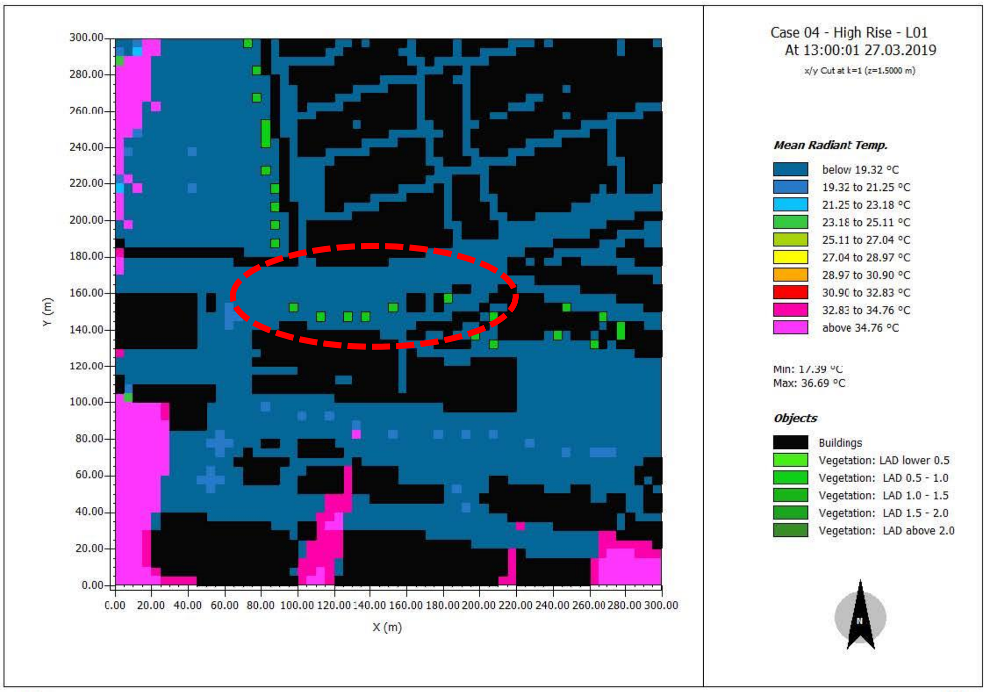
Simulated Mean Radiant Temperature for Case 03 – Medium Rise – Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.

Analysis of Case 04- High Rise (14 storied) scenario

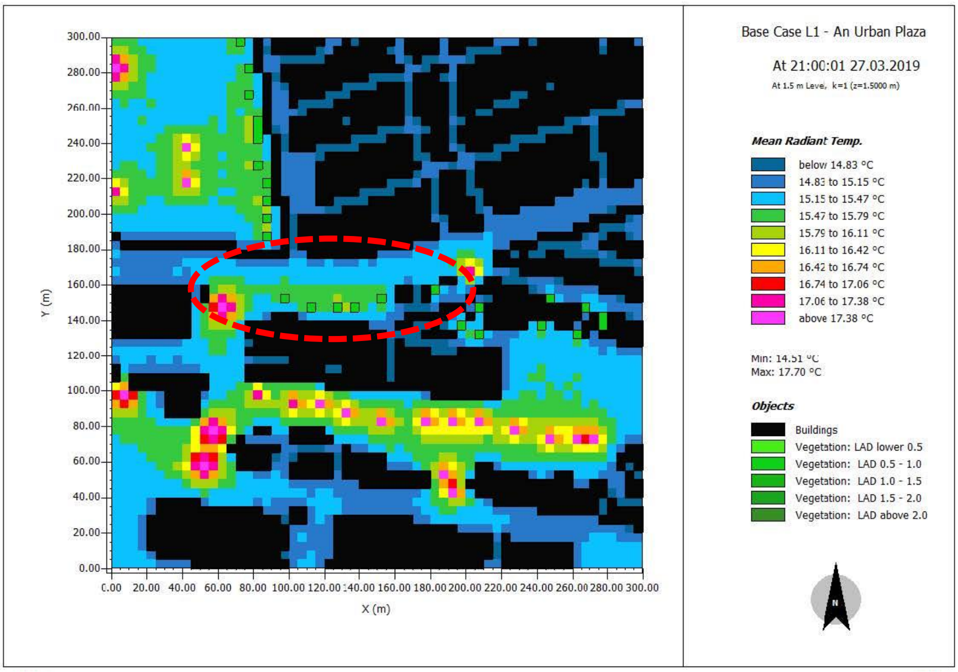
Location 01 – An Urban Plaza



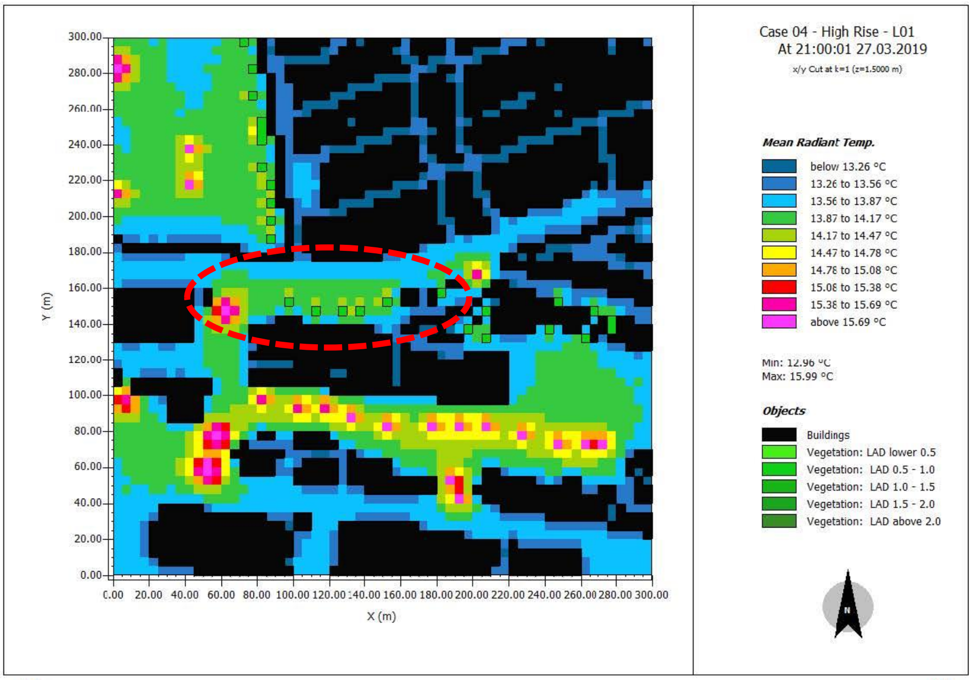
Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Day Time 13:00:01h



Simulated Mean Radiant Temperature for, Case 04- High Rise -Location 01-An Urban Plaza (i) at the Day Time 13:00:01h

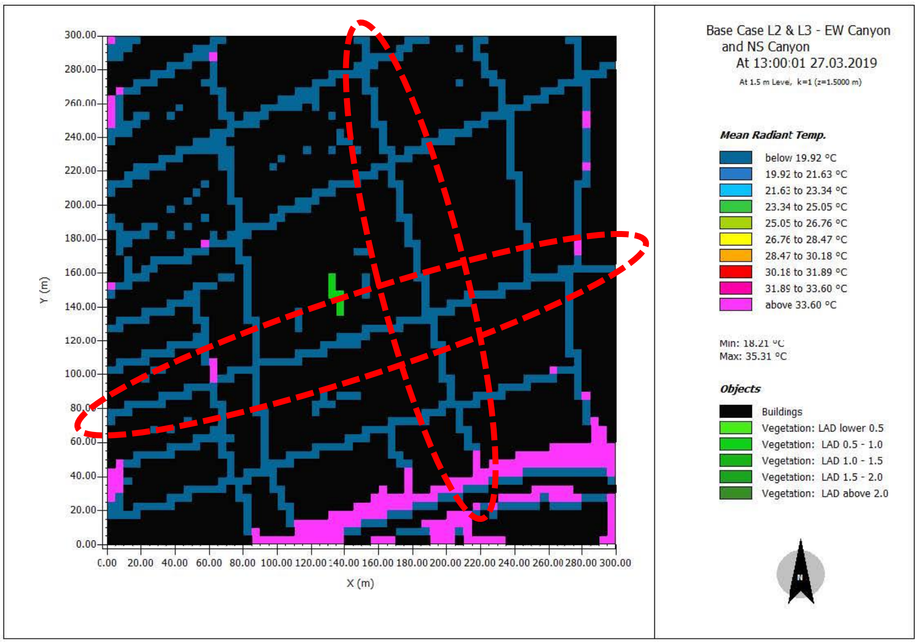


Simulated Mean Radiant Temperature for, Base Case L1-Location 01-An Urban Plaza (i) at the Night Time 21:00:01h

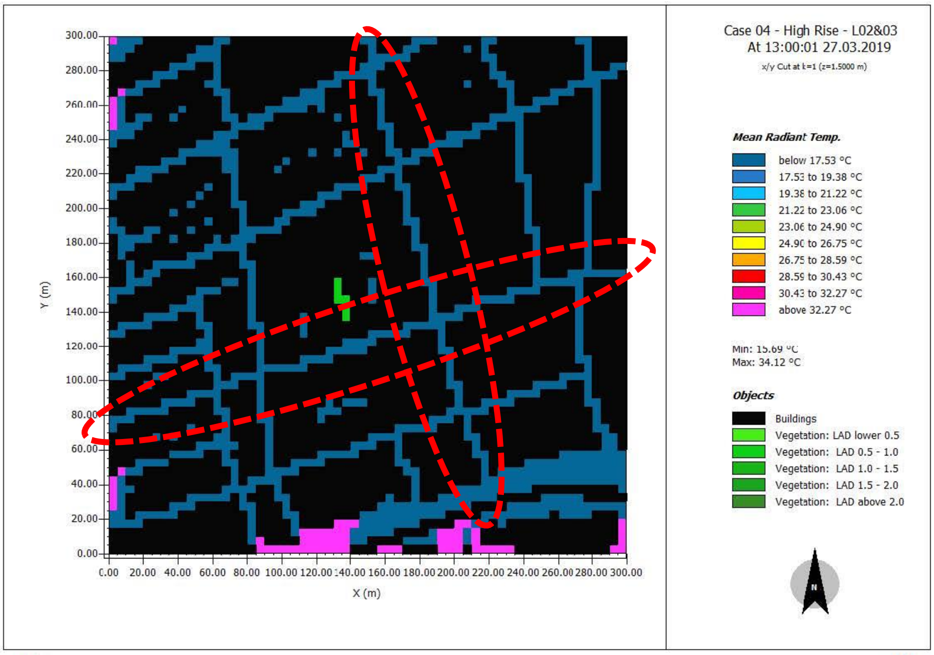


Simulated Mean Radiant Temperature for, Case 04- High Rise -Location 01- An Urban Plaza (i) at the Night Time 21:00:01h

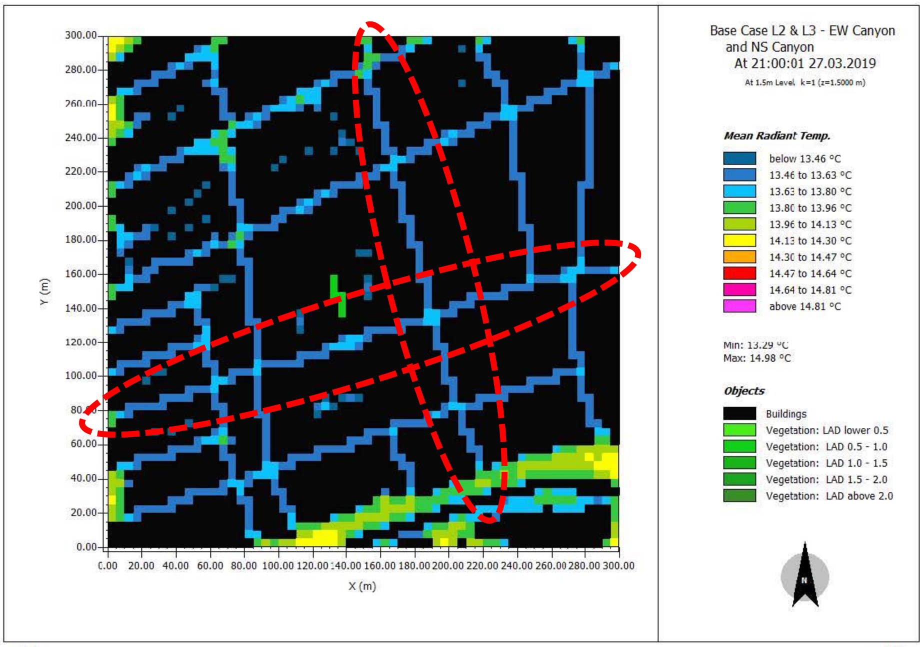
Location 02 and 03 – EW and NS Canyons (Prince Street and 02nd Cross Street)



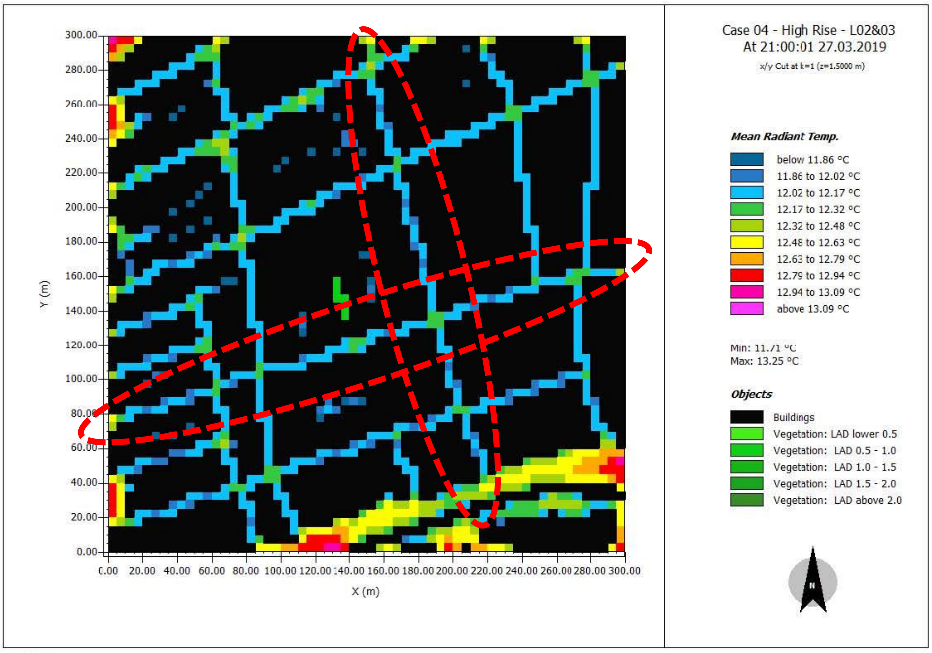
Simulated Mean Radiant Temperature for Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 04- High Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (i) at the Day Time 13:00:01h.

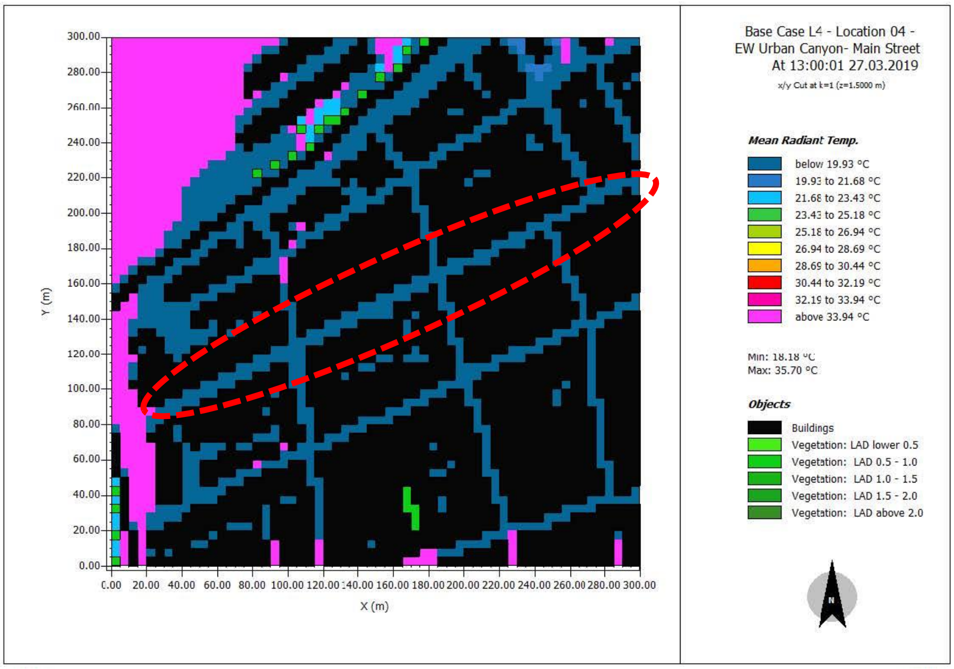


Simulated Mean Radiant Temperature for the Base Case L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

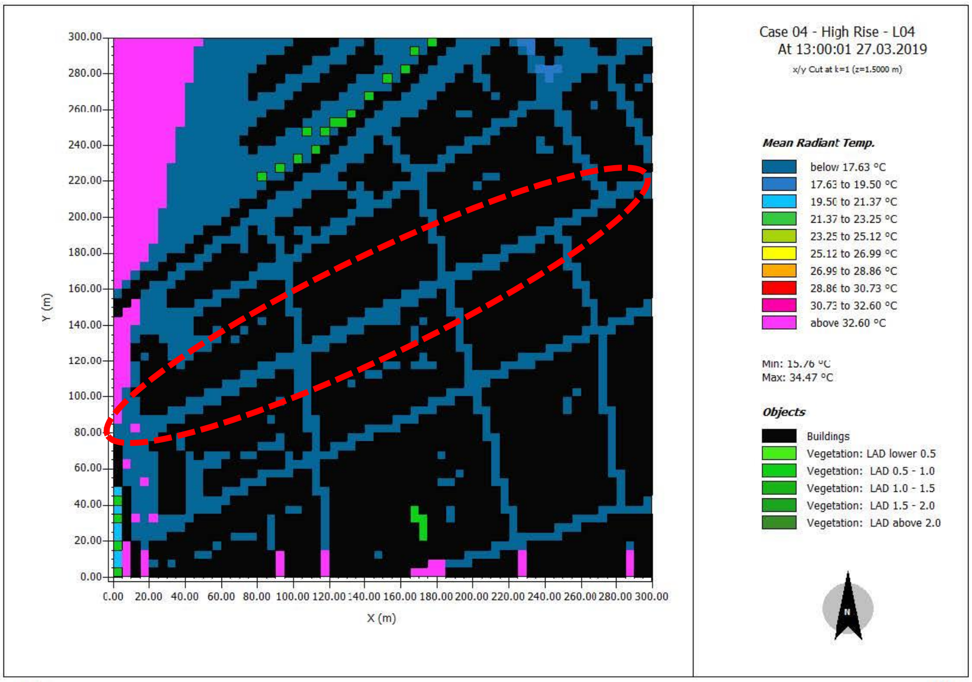


Simulated Mean Radiant Temperature for Case 04 –High Rise – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street (ii) at the Night Time 21:00:01h.

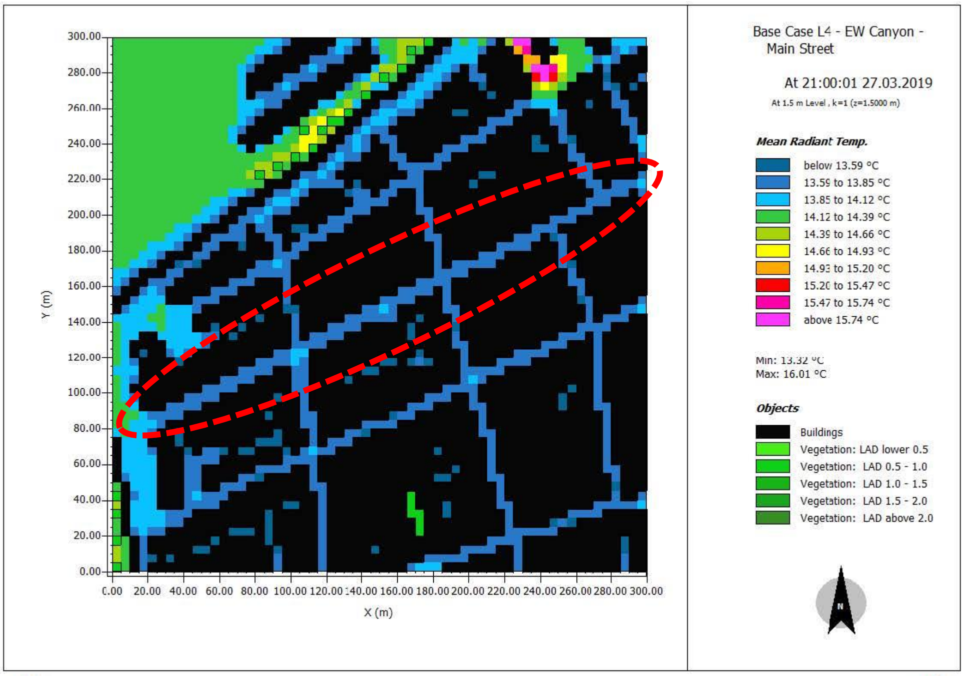
Location 04 – EW Canyon (Main Street)



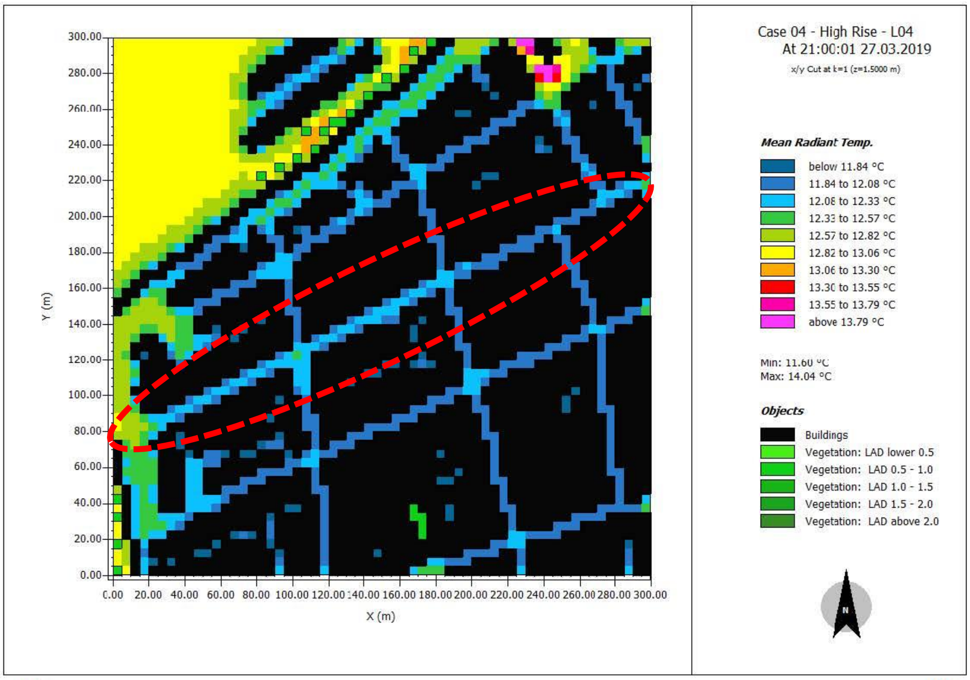
Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 04 – High Rise – Location 04- EW Canyon –Main Street (i) at the Day Time 13:00:01h.

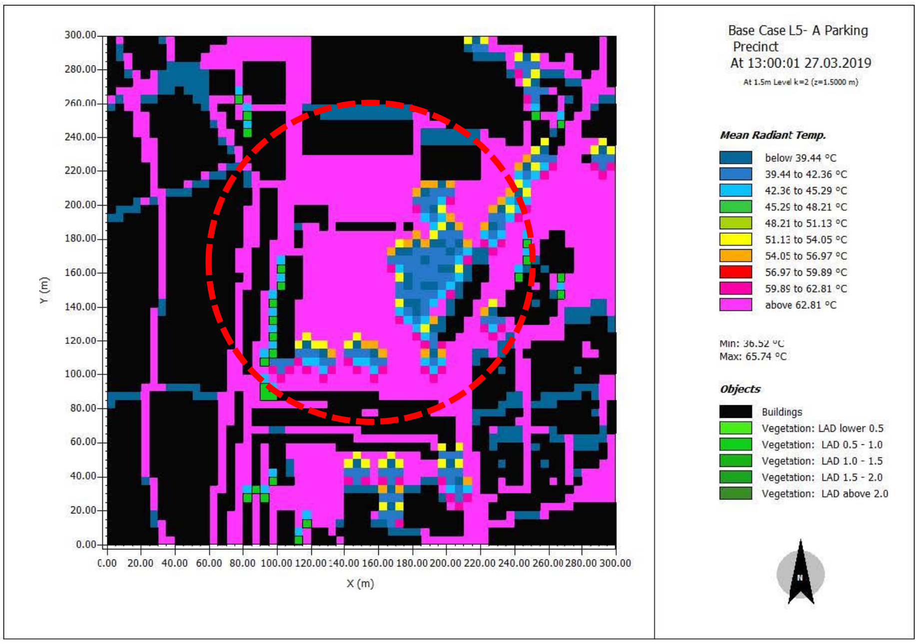


Simulated Mean Radiant Temperature for the Base Case L4 –04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

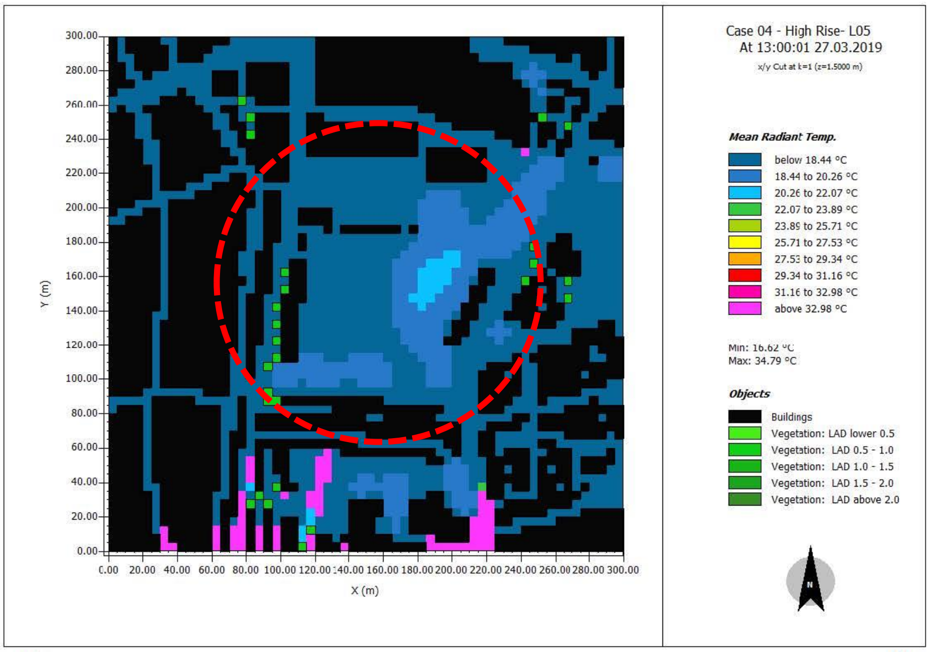


Simulated Mean Radiant Temperature for Case 04– High Rise – Location 04- EW Canyon –Main Street (ii) at the Night Time 21:00:01h.

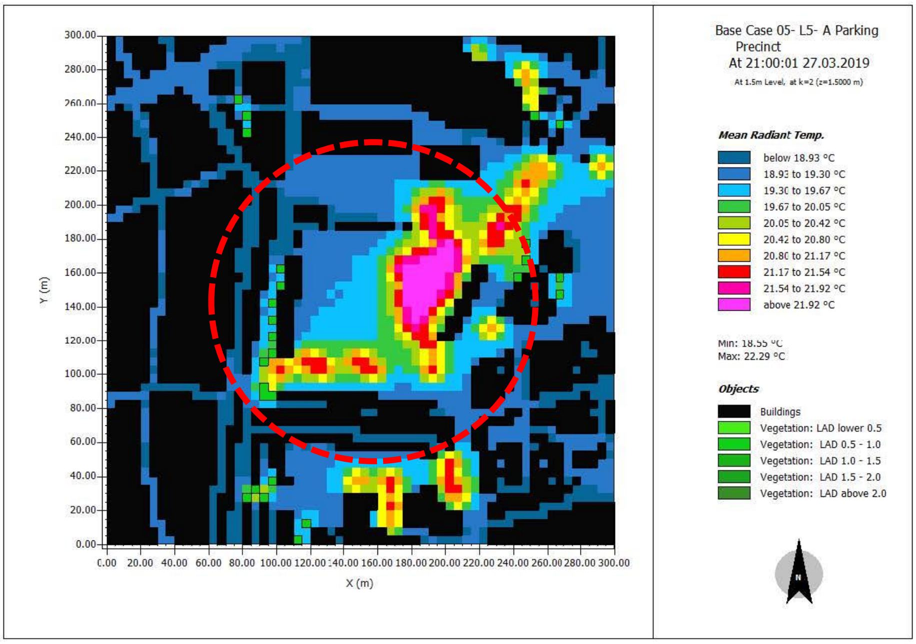
Location 05 – A Parking Precinct



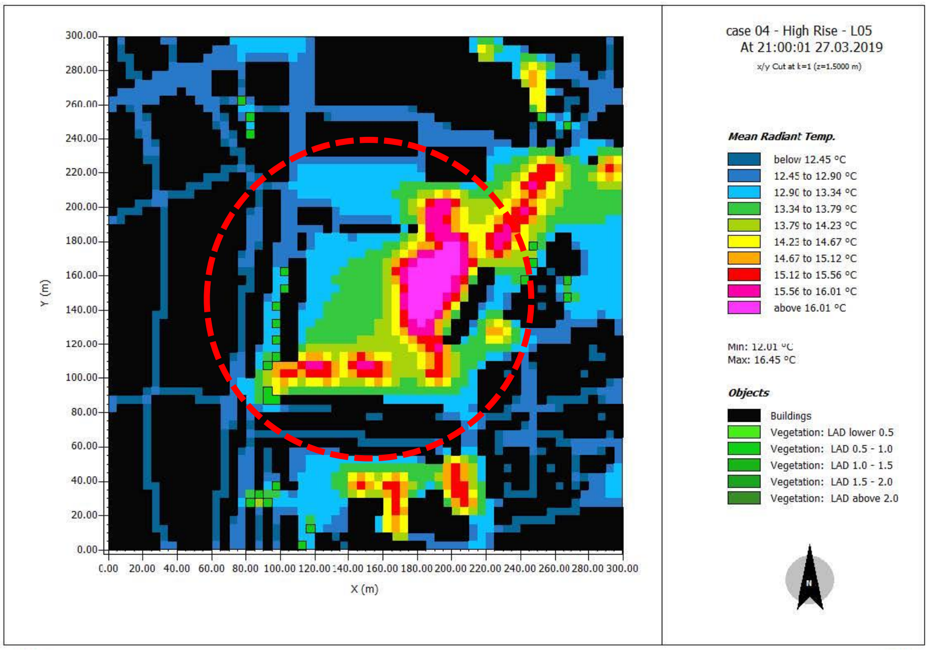
Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for Case 04 – High Rise – Location 05- A Parking Precinct (i) at the Day Time 13:00:01h.



Simulated Mean Radiant Temperature for the Base Case L5 –Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.



Simulated Mean Radiant Temperature for Case 04 – High Rise – Location 05- A Parking Precinct (ii) at the Night Time 21:00:01h.

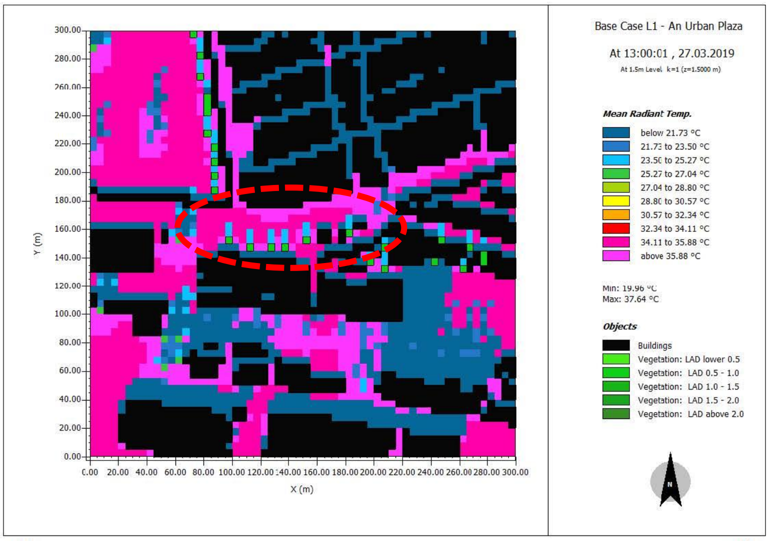
APPENDIX IX : MRT Distribution maps for Changing Surface Materials

Scenario – Case 08

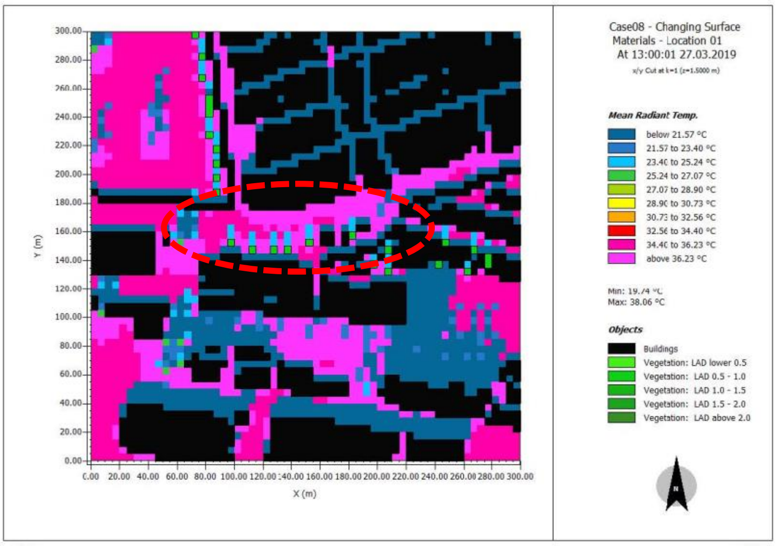
Simulated Mean Radiant Temperature were analyzed for the Case 08 – Changing Surface Materials of all different five built forms **at the Day time ,13:00:01h.**

Location 01 – An Urban Plaza

Base Case L1-Location 01 -An Urban Plaza

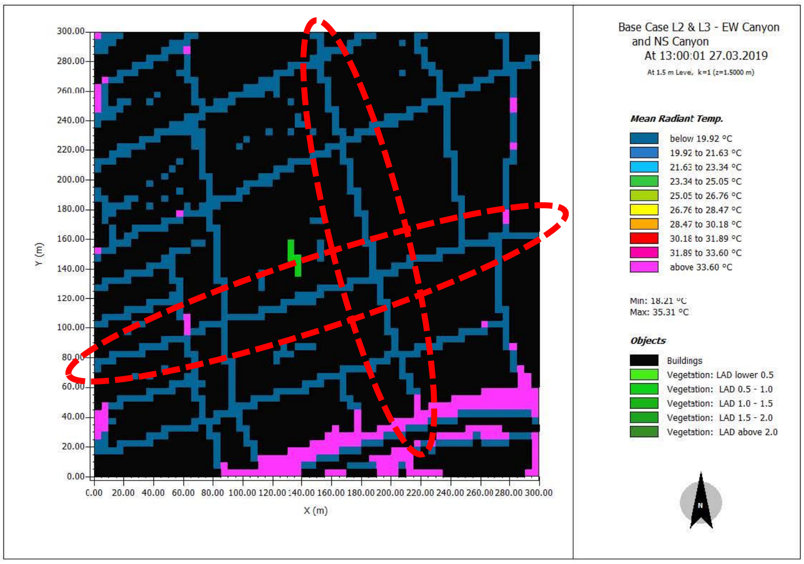


Case 08- Changing Surface Materials - Location 01 - An Urban Plaza, 13:00:01h

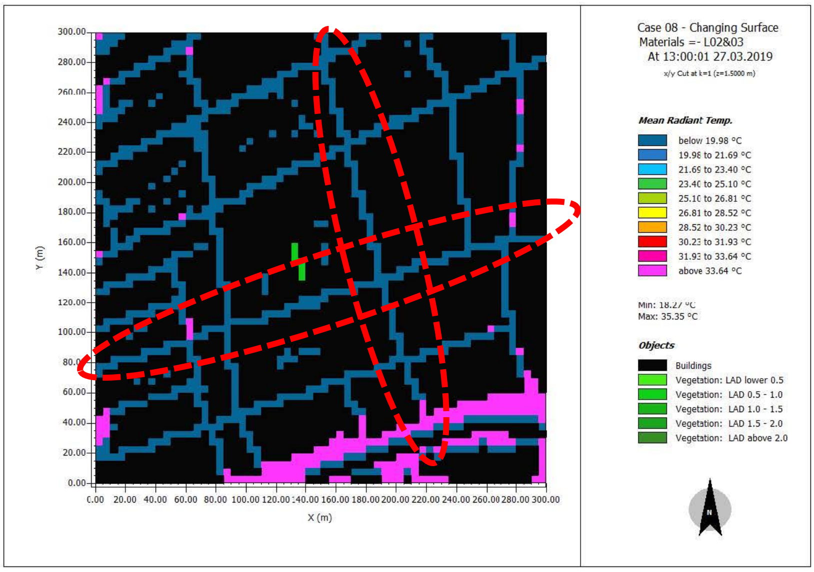


Location 02 & Location 03- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street.

Base Case L2&L3 – Location 02 & Location 03- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street , 13:00:01h

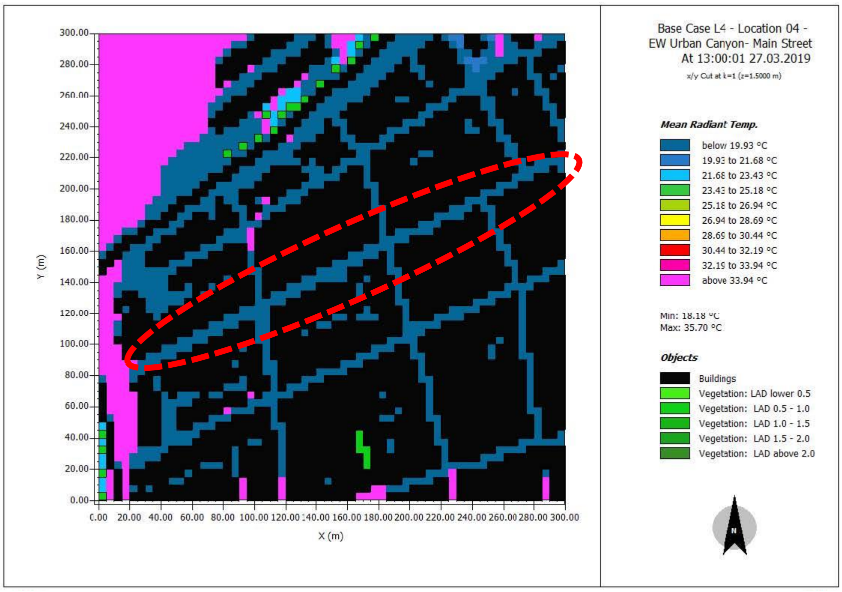


Case 08 – Changing Surface Material – L2&L3- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street, 13:00:01h

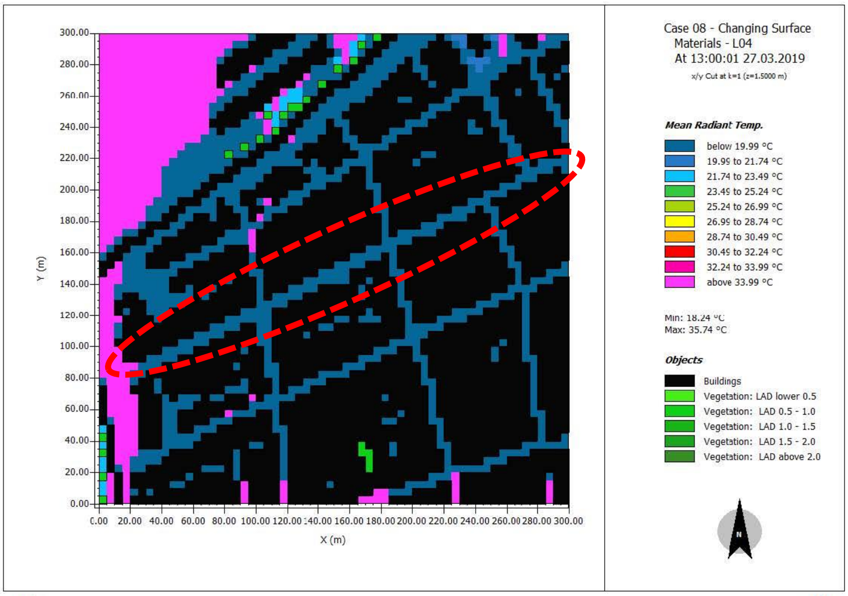


Case 08 – Changing Surface Material – L4- EW Canyon - Main Street.

Base Case L4 – Location 04 – EW Canyon Main Street, 13:00:01h

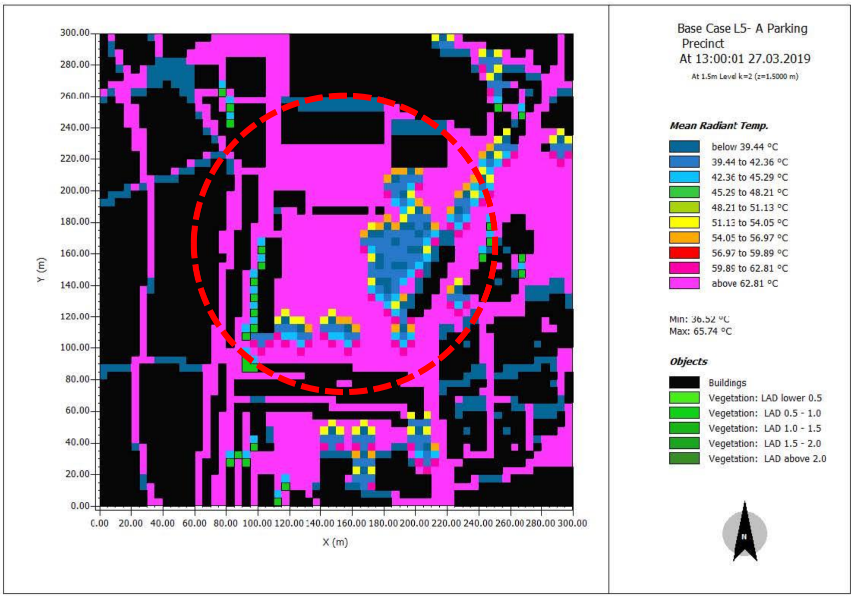


Case 08 – Changing Surface Material – L4- EW Canyon Main Street , 13:00:01h

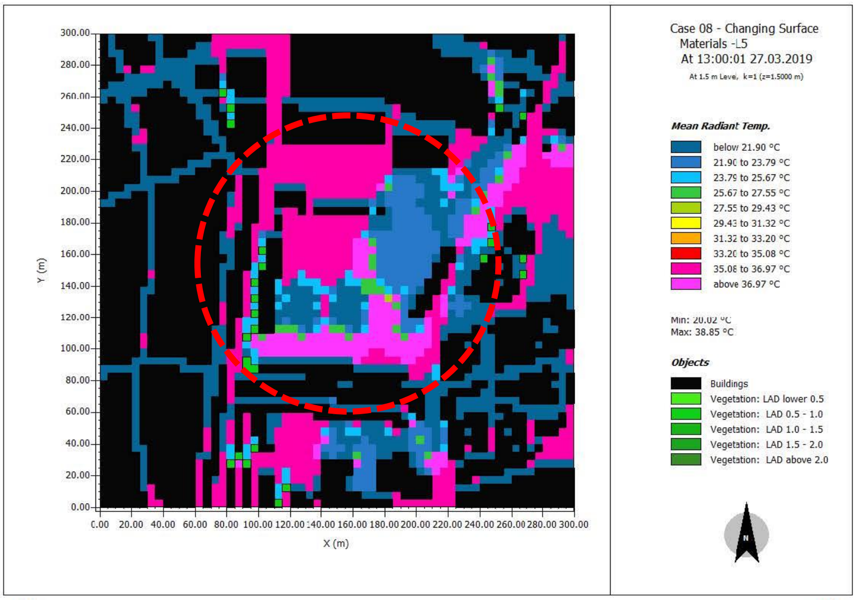


Location 05 - A Parking Precinct

Base Case L5- Location 05 – A Parking Precinct,13:00:01h



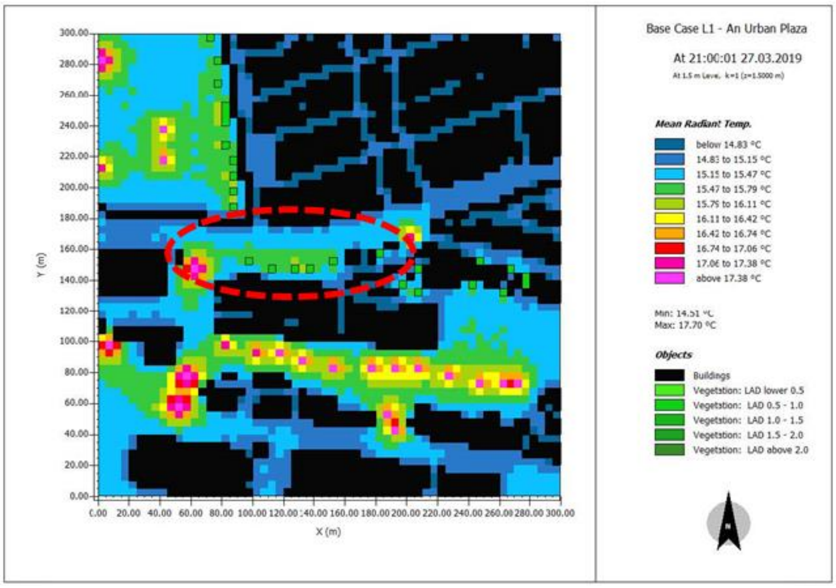
Case 08 – Changing Surface Material – L5- A Parking Precinct,13:00:01h



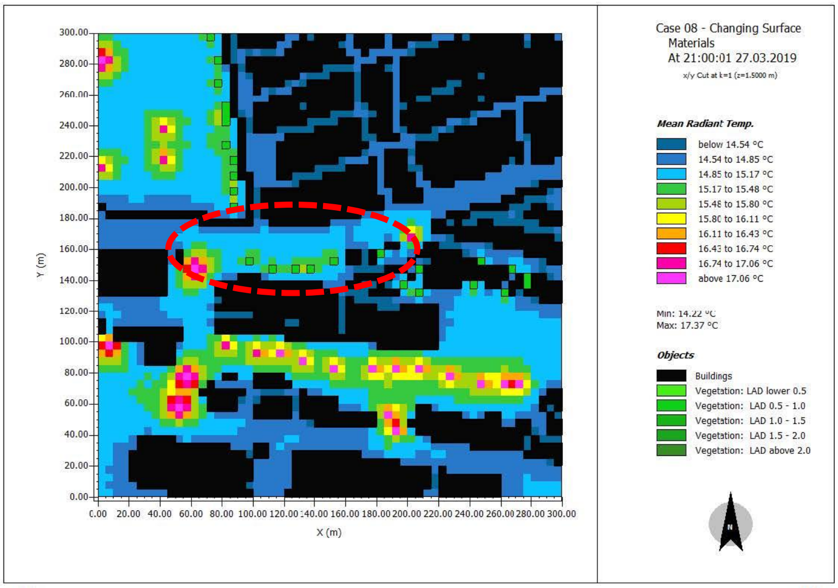
Simulated Mean Radiant Temperature were analyzed for the Case 08 – Changing Surface Materials of all different five built forms **at the Night time ,21:00:01h.**

Location 01 – An Urban Plaza

Base Case L1-Location 01 - An Urban Plaza, 21:00:01h

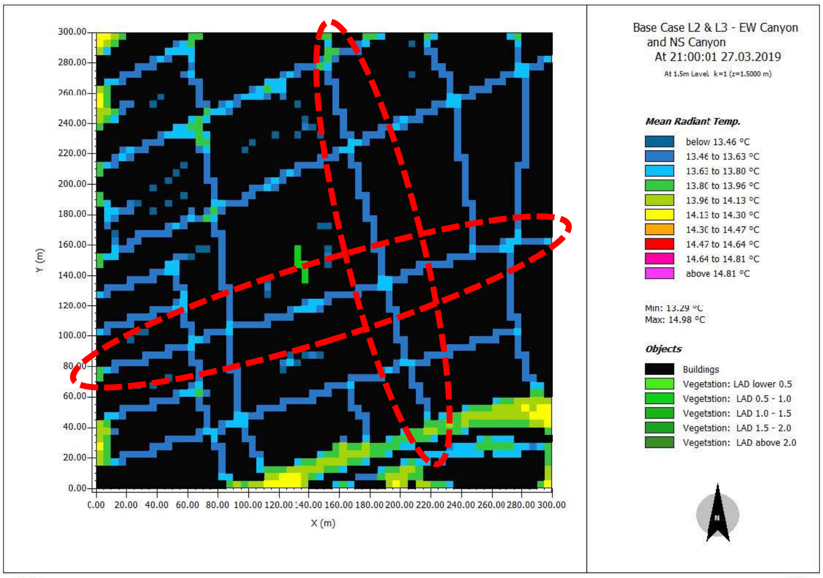


Case 08- Changing Surface Materials - Location 01 -An Urban Plaza, 21:00:01h

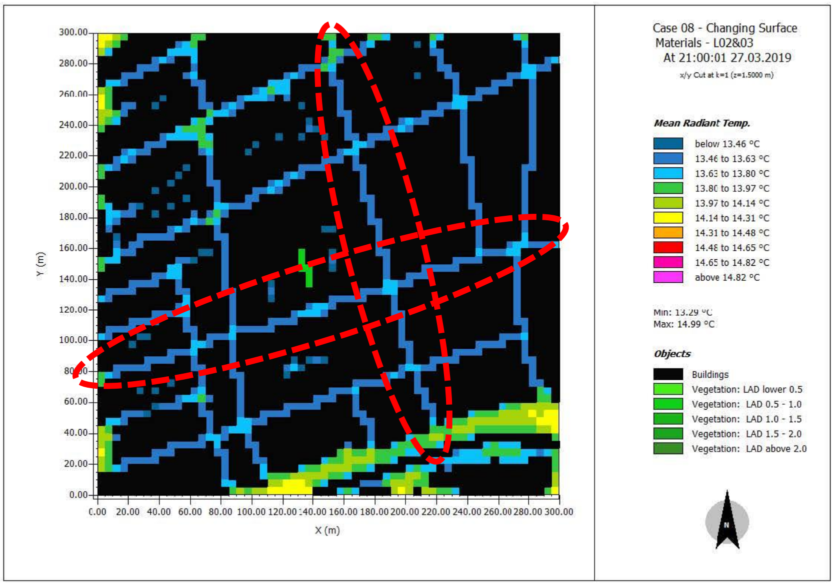


Location 02 & Location 03- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street.

Base Case L2&L3 – Location 02 & Location 03- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street , 21:00:01h

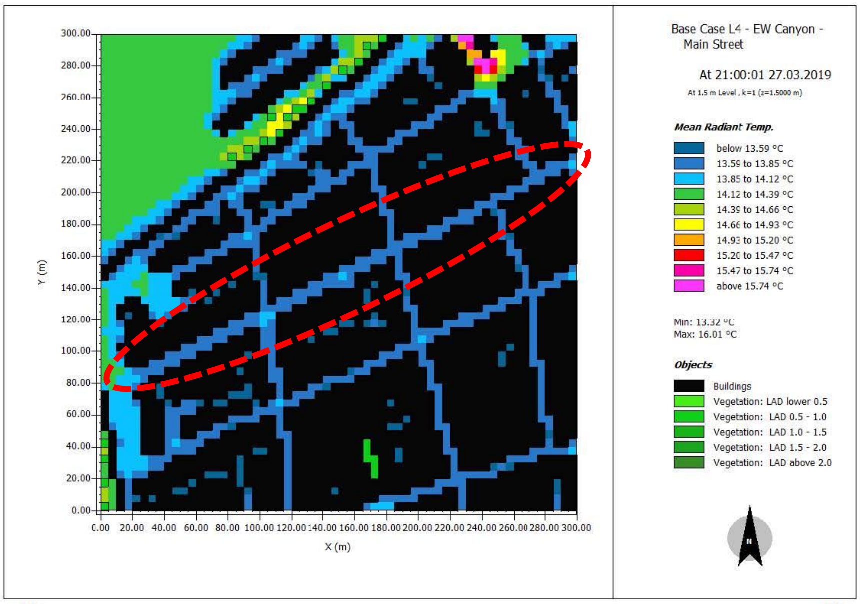


Case 08 – Changing Surface Material – L2&L3- EW Canyon –Prince Street and Location 03-NS Canyon – 02nd Cross Street, 21:00:01h

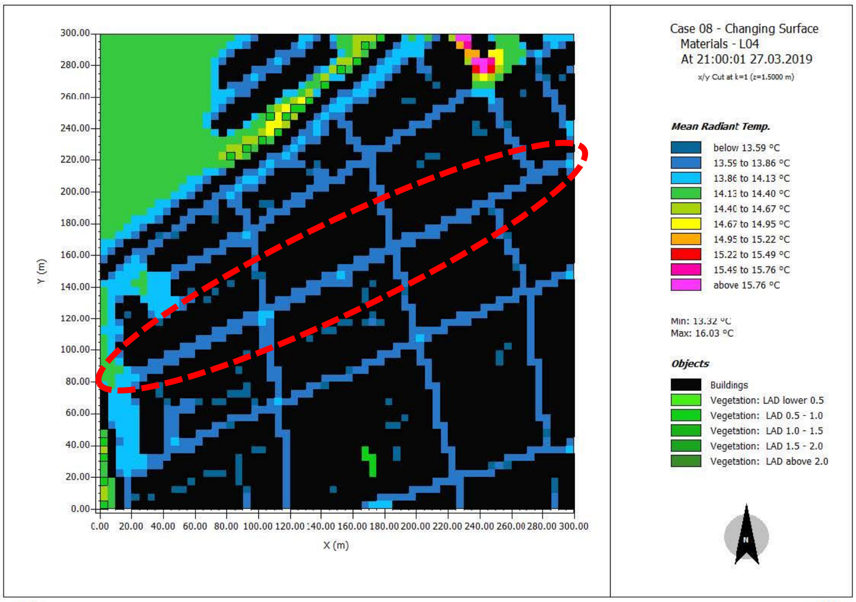


Location 4- EW Canyon - Main Street.

Base Case L4 – Location 04 – EW Canyon Main Street, 21:00:01h

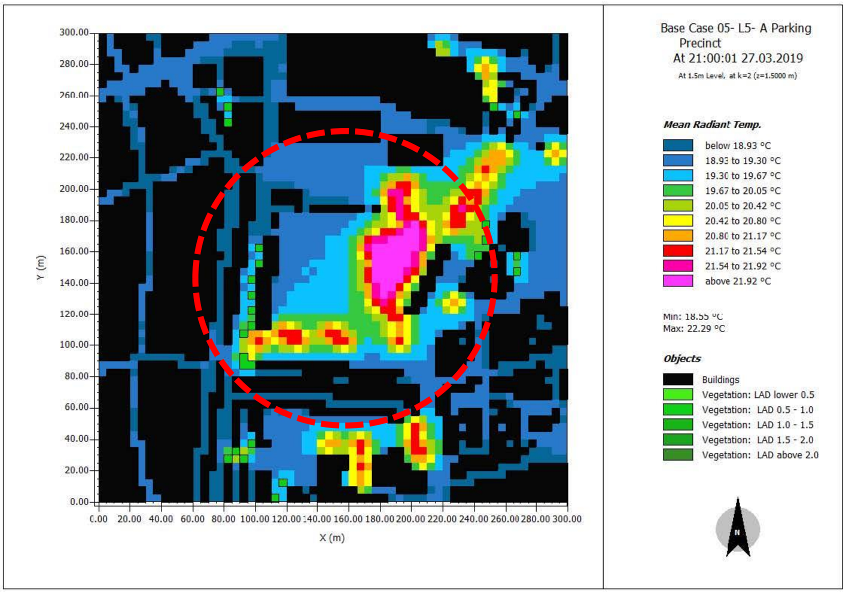


Case 08 – Changing Surface Material – L4- EW Canyon Main Street , 21:00:01h

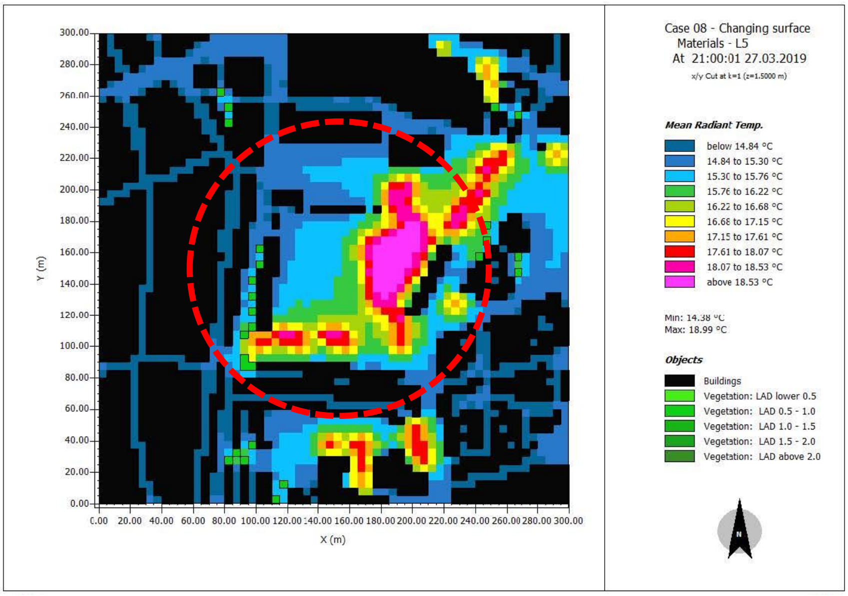


Location 5- A Parking Precinct

Base Case L5- Location 05 – A Parking Precinct, 21:00:01h



Case 08 – Changing Surface Material – L5- A Parking Precinct, 21:00:01h



APPENDIX X : Summary of simulated Air Temperature, MRT and PMV values for each Locations.

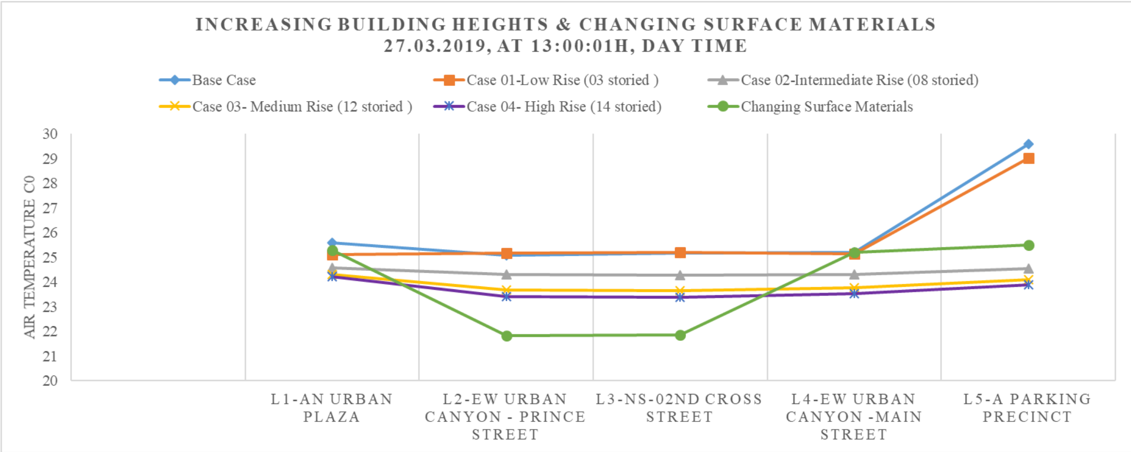


Figure 153: Air Temperature of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h .

Source: Author

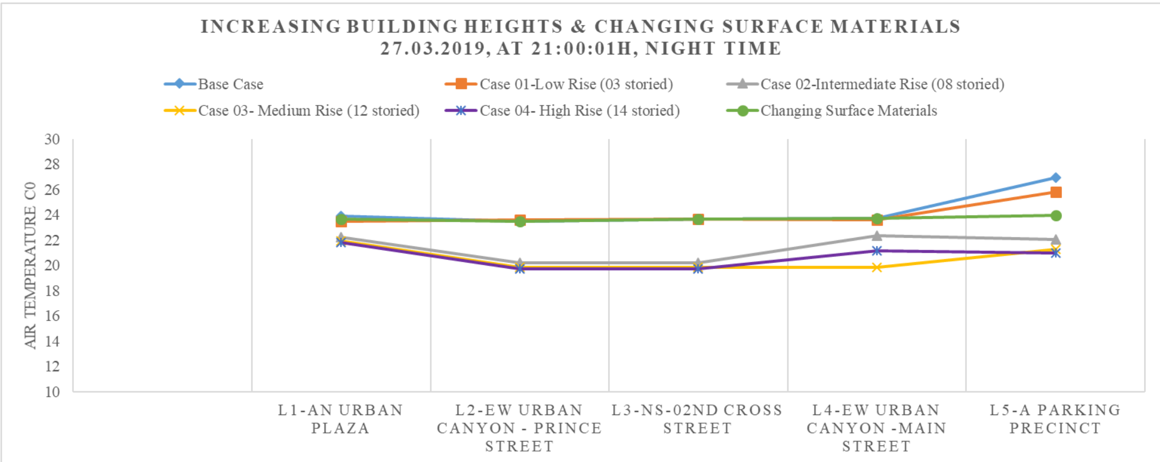


Figure 154: Air Temperature of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h

Source: Author

Figure 155 : MRT of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h

Source: Author

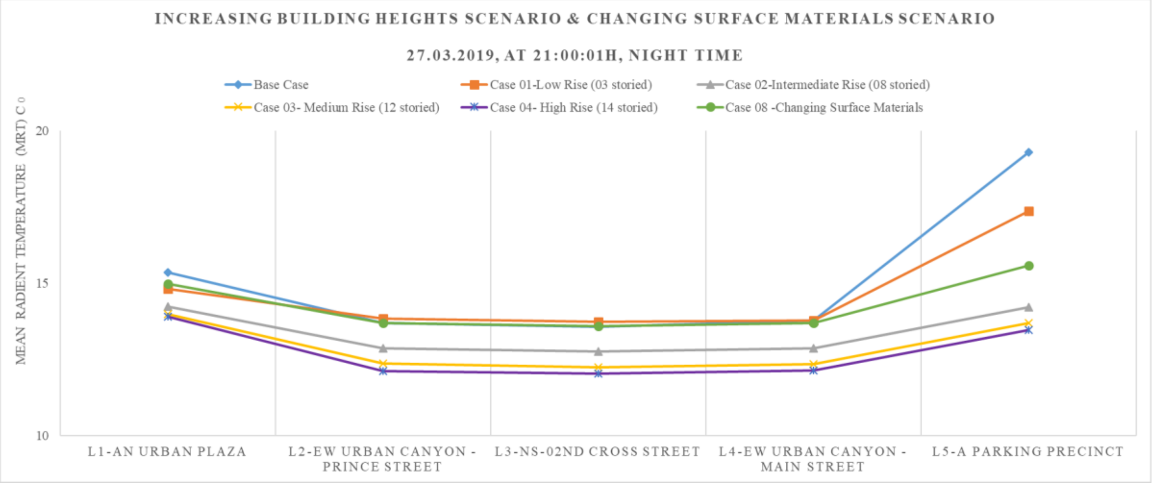
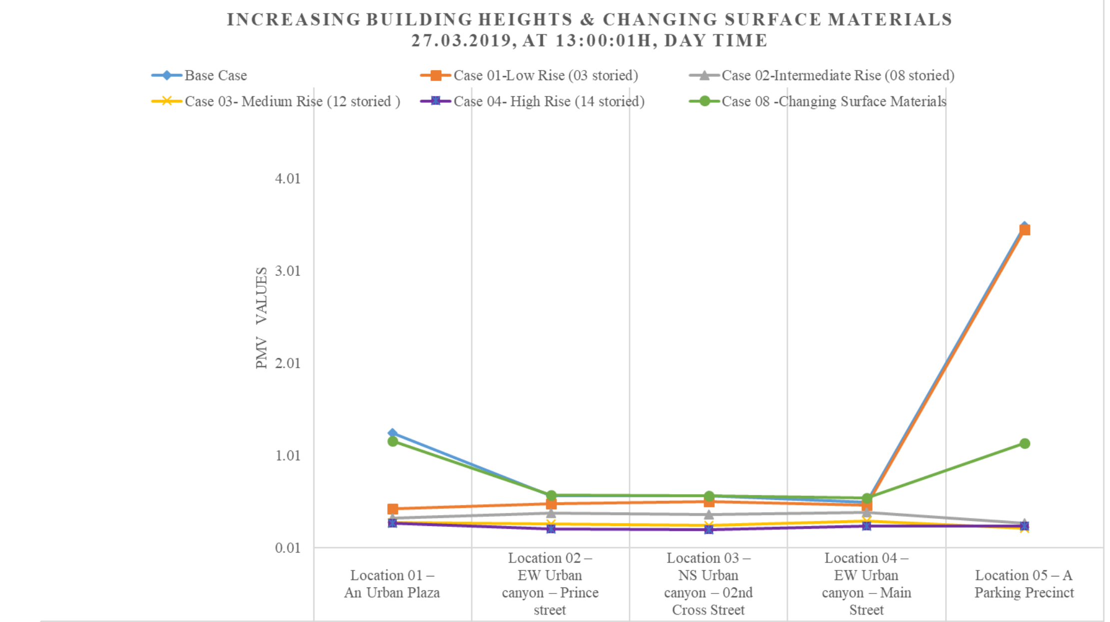


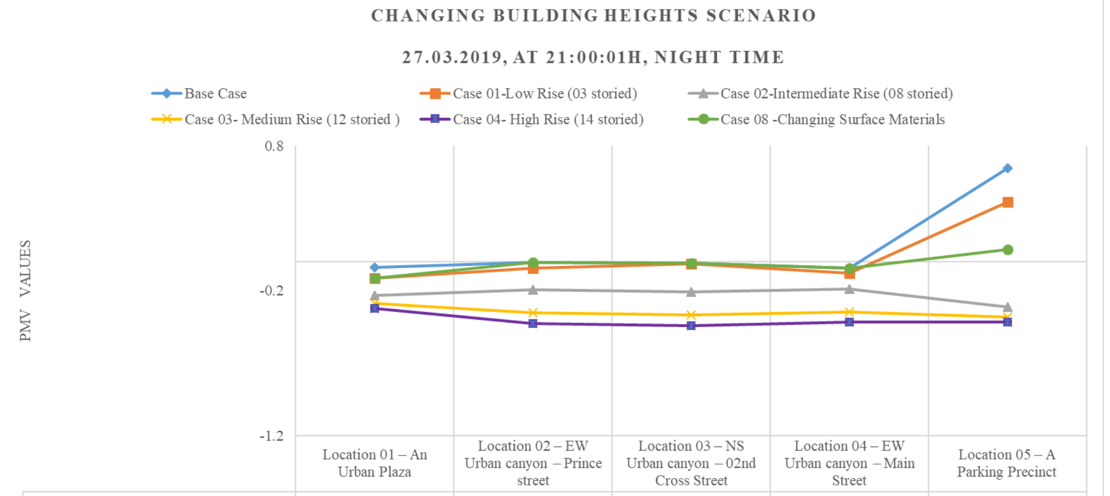
Figure 156: MRT of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h

Source: Author



	Location 01 – An Urban Plaza	Location 02 – EW Urban canyon – Prince street	Location 03 – NS Urban canyon – 02nd Cross Street	Location 04 – EW Urban canyon – Main Street	Location 05 – A Parking Precinct
Base Case	1.2548	0.5718	0.5704	0.5012	3.4977
Case 01-Low Rise (03 storied)	0.4296	0.4854	0.5101	0.4739	3.456
Case 02-Intermediate Rise (08 storied)	0.3333	0.3858	0.3722	0.3941	0.2775
Case 03- Medium Rise (12 storied)	0.2863	0.2637	0.2499	0.2958	0.2216
Case 04- High Rise (14 storied)	0.2713	0.2155	0.2024	0.2423	0.2473
Case 08 -Changing Surface Materials	1.163	0.57691	0.57555	0.54724	1.1433

Figure 157 : PMV values of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h**. ,** *Source: Author*



	Location 01 – An Urban Plaza	Location 02 – EW Urban canyon – Prince street	Location 03 – NS Urban canyon – 02nd Cross Street	Location 04 – EW Urban canyon – Main Street	Location 05 – A Parking Precinct
Base Case	-0.037163	-0.0053961	-0.00708	-0.045042	0.64552
Case 01-Low Rise (03 storied)	-0.11217	-0.041429	-0.015021	-0.076576	0.41407
Case 02-Intermediate Rise (08 storied)	-0.23161	-0.19076	-0.20698	-0.18586	-0.31408
Case 03- Medium Rise (12 storied)	-0.28819	-0.34904	-0.36809	-0.34722	-0.38084
Case 04- High Rise (14 storied)	-0.32058	-0.42358	-0.44249	-0.41574	-0.41648
Case 08 -Changing Surface Materials	-0.11109	-0.0059407	-0.0068424	-0.045218	0.085022

Figure 158: PMV values of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h , *Source: Author*

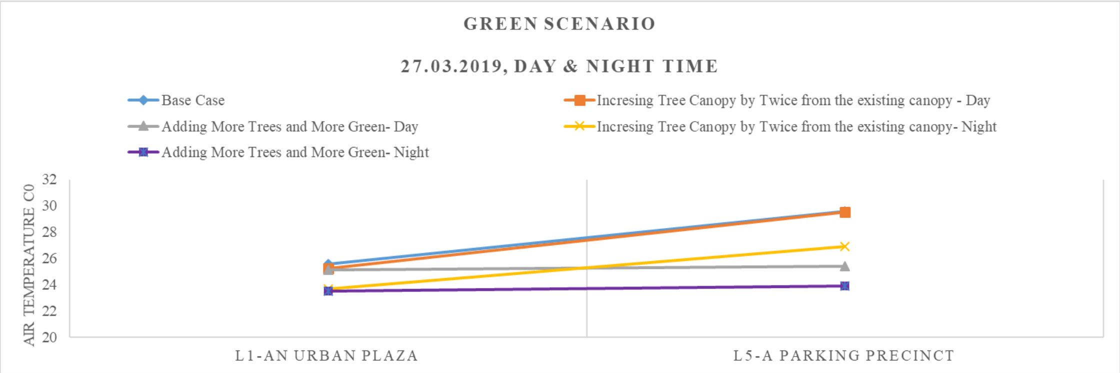


Figure 159: Air Temperature for Green scenario at the Day and Night Time.

Source: Author

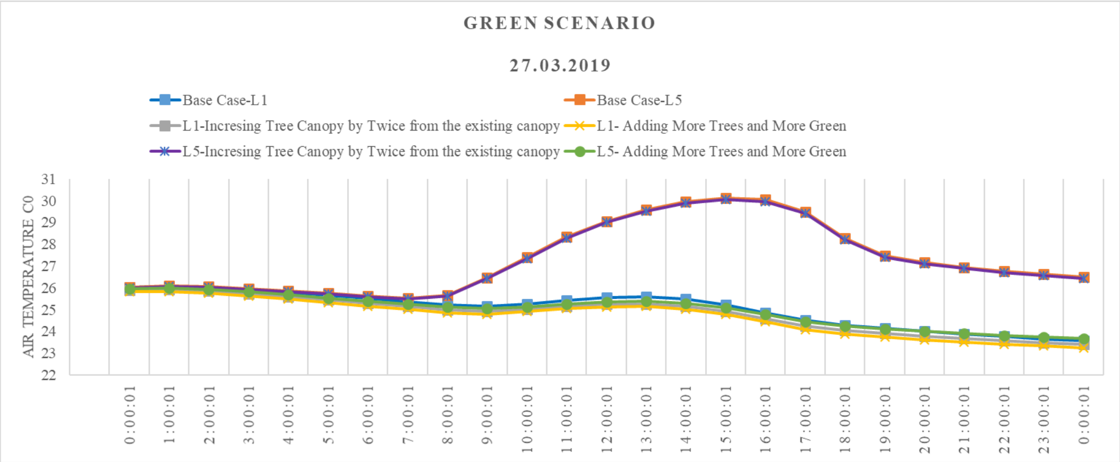


Figure 160: Air Temperature for Green scenario at the Day and Night Time.

Source: Author