

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

B.M.L. Mendis

(169181F)

Master of Spatial Planning Management and Design

Department of Town and Country Planning

University of Moratuwa
Sri Lanka

November 2020

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

Balapuwaduge Marian Lakmini Mendis

(169181F)

Thesis/ Dissertation Submitted in partial fulfillment of the requirements for the degree
Master of Spatial Planning Management and Design

Department of Town and Country Planning

University of Moratuwa
Sri Lanka

November 2020

DECLARATION

“I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

Also, I hereby grant to University of Moratuwa the non-exclusive right to reproduce and distribute my dissertation, in whole or in part in print, electronic or other medium. I retain the right to use this content in whole or part in future works (such as articles or books).

Signature :.....

Name of the student : B. M. L Mendis

Batch : 2016/2018

Date :

CERTIFICATION

I certify herewith that, B. M. L Mendis , Index No 169181F of the 2016/2018 batch, has carried out research for the Master of Spatial Planning Management and Design dissertation under my supervision.

.....

Signature of the Supervisor

Date:.....

.....

Head of the Department of Town
and Country Planning

Date:.....

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.

ACKNOWLEDGEMENT

First and foremost, I wish to express my sincere thanks to Dr. Rangajeewa Rathnayake, Head of the Department, for providing me with all the necessary facilities for the research and for continuous encouragement.

Secondly, would like to acknowledge my research supervisors Dr. Chethika Abenayaka and Dr Amila Jayasingha for the continues guidance and their valuable support to complete this research successfully.

Further, I would like to offer my thanks to the Senior Lecturer Mrs Malani Herath, and the course Coordinator, Senior lecturer, Dr. Suresh Shanaka of Town and Country Planning, University of Moratuwa for their continuous guidance and valuable support during this study.

Moreover, I would like to offer my special thanks to Dr.R.M.K.U.Rajapaksha, Head of the Department in the Department of Architecture, University of Moratuwa to make arrangement to issue climatic data measuring equipments. Prof. R. Emmanuel, Senior Lecture of University of Glasgow in England and Dr. Narein Perera , Senior Lecture, Department of Architecture, University of Moratuwa for their kind assistance and guidance during this research. Further, I offer my heartiest thanks to Mr Lahiru Wimalarathna, Architect, Planner Yasiru Rathnayake, Planner Naduni Wijewardena, Planner Sukhitha Ranasingha and Mr.Chathura, Technical officer, Department of Architecture, University of Moratuwa for their numerous assistants to measure the outdoor thermal comfort and their valuable Technical assistance and numerical support to successful this Research.

I would like to show gratitude to Mr Chaminda, Computer Lab officer, Department of Town and country Planning, University of Moratuwa to given his support for the Technical assistant.

Finally, I would like to express sincere gratitude to my Family for their encouragements and guidance given in numerical way throughout this research.

TABLE OF CONTENT

DECLARATION	i
CERTIFICATION.....	ii
ABSTRACT.....	iii
ACKNOWLEDGEMENT	iv
TABLE OF CONTENT	v
LIST OF FIGURES.....	xii
LIST OF TABLES	xxi
CHAPTER ONE: INTRODUCTION	1
1.1 Background of the Study	1
1.2 Research Problem	2
1.3 The Significance of the Study	2
1.4 Objectives and Aims.....	3
1.5 The Method of Study.....	3
1.5.1. Colombo as a Case Study	3
1.5.2. Data collection methods.....	7
1.5.3. Urban Simulation Tools.....	8
1.6 Scope Limitations to the Study.....	9
CHAPTER TWO: BACKGROUND / LITERATURE REVIEW.....	10
2.1 Urban Development/ Urbanization and Climate Change	10
2.1.1. Urban Heat Island Scenario (UHI)	11
2.1.2. Historical Studies relevant to the Urbanization and Climate.....	13
2.1.3. Tropical Studies relevant to the Urbanization and Climate.....	14

2.2 Outdoor Climate and Comfort.....	23
2.2.1. Outdoor thermal Comfort in Tropics.....	24
2.2.1.1. Psychological Reasons.....	25
2.2.1.2. Thermo-physiological Differences.....	26
2.2.1.3. Heat balance differences.....	27
2.2.2. Factors Influencing Thermal comfort in Tropical Climates.....	28
2.2.2.1. Air Temperature.....	28
2.2.2.2. Mean Radiant Temperature (T _{mrt}).....	29
2.2.2.3. Humidity.....	32
2.2.2.4. Wind Speed.....	33
2.3 Urban Geometry and Built Form and the Microclimate.....	34
2.3.1. Definition of the Urban Geometry.....	34
2.3.2. Urban Form / Built Form.....	35
2.3.2.1. Definition and Classification of Urban Form/ urban built form.....	36
2.3.3. Urban Canyon.....	37
2.3.3.1. Classifications of the Urban Canyon.....	38
2.3.3.1.1. Aspect Ratio.....	38
2.3.3.1.2. Orientation of Streets.....	40
2.3.3.1.3. Sky View Factor (SVF).....	40
2.4 Public Life and Urban Geometry and Form.....	42
2.4.1. Public Life and Urbanization.....	42
2.4.2. Public Life and Street Urban Canyon.....	42
CHAPTER THREE: RESEARCH DESIGN.....	48
3.1. Selection of the Case study.....	48
3.2. Site Selection.....	48
3.2.1 Pedestrian Movements and Patterns.....	49

3.3 Selection of different Built Form at the Study Area.....	51
3.3.1 Selected Different Built Form Elements	52
3.3.1.1 An Urban Plaza	53
3.3.1.2. East –West Canyon	54
3.3.1.3. North - East Canyon.....	56
3.3.1.4. Parking Precinct	57
3.4. Obtaining weather data required for estimating thermal comfort levels at the five-selected locations.	58
3.5. Simulating the micro-climatic condition of the five- selected sites.	62
3.5.1. Selection of the simulation tool.	62
3.5.2. Executing Numerical Modeling utilizing the ENVI- met 4.1 software....	62
3.5.3. Envisaging the scenarios for simulation.	64
3.5.4. Measured and Simulated Data Analyzing to compute thermal comfort level of users.	71
3.5.4.1. Computing Thermal Heat Index.....	71
3.5.4.2. Analyzing Tools for Simulated data for Existing scenario and envisaged scenarios	72
CHAPTER FOUR: RESULTS AND ANALYSIS	73
4.0 Introduction to Chapter.....	73
4.1 Existing status of climatic conditions and Built Form	73
4.1.1. Climatic data for Colombo.....	73
4.1.1.1 Air Temperature	73
4.1.1.2 Relative Humidity	74
4.1.2. Weather measurements, Building Height data and Photographs obtained at the Field Survey.	75
4.1.2.1 Location 01- Urban Plaza.....	75

4.1.2.1.1 Location 01- Urban Plaza - Photographic Survey	76
4.1.2.1.2 Building Heights of Surrounding Buildings.....	77
4.1.2.1.3. Location 01- Urban Plaza - Field Measurements of the weather condition.....	78
4.1.2.2 Location 02 - East –West Canyon –(A) <i>Prince Street</i>	80
4.1.2.2.1. Location 02- East –West Canyon –(A) – Prince Street- Photographic Survey	81
4.1.2.2.2. Building Heights of Surrounding Buildings.....	82
4.1.2.2.3. Location 02 – East – West Canyon – (a) Prince Street – Field Measurements of the weather condition.....	83
4.1.2.3. Location 03 - North -South Canyon – <i>02nd Cross Street</i>	85
4.1.2.3.1. Photographic Survey	86
4.1.2.3.2. Building Heights of Surrounding Buildings.....	87
4.1.2.3.3. Location 03 - North -South Canyon – <i>02nd cross street</i>	88
- <i>Field measurements of the weather condition</i>	88
4.1.2.4. Location 04 - East –West Canyon – (B) <i>Main Street</i>	90
4.1.2.4.1. Photographic Survey	91
4.1.2.4.2. Building Heights of Surrounding Buildings.....	92
4.1.2.4.3. Location 04 - East –West Canyon – (B) Main street.....	93
- Field Measurements of the weather condition	93
4.1.2.5. Location 05 – A Parking precinct - <i>Gunasinghapura bus stand</i>	95
4.1.2.5.1. Photographic Survey	96
4.1.2.5.2. Building Heights of Surrounding Buildings.....	97
4.1.2.5.3. Location 05 – A Parking Precinct - Gunasinghapura bus stand ..	98
- Field measurements of the weather condition.....	98
4.1.2.6. The Reference Point – Charmer’s Granaries Land at Pettah	100

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.	101
4.1.2.7.1 The summary of the Measured weather data from 11 a.m. to 13.00 p.m. (Session 01)	102
4.1.2.7.2. The summary of the Measured weather data from 16.00 p.m. to 18.00 p.m. (Session 02)	103
4.1.2.8. Summary of calculated Thermal Heat Index Difference (THI Difference)	104
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.	104
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.....	105
4.2 Interpreting the existing Thermal Comfort Levels.	106
4.2.1. Interpreting the existing thermal comfort levels around noon time. (11.00 a.m. to 13.00 p.m.)	106
4.2.1.1. Comparing the data on Average Air Temperature (C°).	106
4.2.1.2 Comparing the data on Average Surface Temperature (C°)	107
4.2.1.3. Comparing Thermal Heat Index (THI) of selected sites.	109
4.2.1.4. Comparing the THI Difference of selected sites.....	110
4.2.2. Interpreting the existing Thermal Comfort Levels at evening time. (16.00 p.m. to 18.00 p.m.).....	112
4.2.2.1. Comparing the data on Average Air Temperature (C°)	112
4.2.2.3 Comparing Thermal Heat Index (THI) of selected locations.....	115
4.2.2.4 Comparing the THI Difference of selected Locations	116

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.)	118
4.2.3.1. Comparison of Average Air Temperature.....	118
4.2.3.2. Comparison of Average Surface Temperature.....	120
4.2.3.4. Comparison of Thermal Heat Index Difference (THI Difference) ..	122
4.3 Computer Simulation Using with Numerical Modelling ENVI-met 4.0.	124
4.3.1. Air Temperature Analysis.....	124
4.3.1.1 Air Temperature Analyze for Existing Locations. (Base Cases)	124
4.3.1.2. Air Temperature Analysis for Envisaged Scenarios	131
4.3.2 Mean Radiant Temperature Analysis (MRT)	150
4.3.2.1 Existing scenario (Base case).....	150
4.3.2.2 Simulated Mean Radiant Temperature (MRT) of Envisaged Scenarios.	151
4.3.3 Predicted Mean Vote Analysis (PMV)	171
4.3.3.2 Predicted Mean Vote Analysis (PMV) for Envisaged Scenarios.....	173
CHAPTER FIVE: CONCLUSION.....	186
5.1 Key findings of the study	186
5.1.1. Summary of Findings for Empirical Data Analysis.....	186
5.1.1.1. Average Air Temperature.....	186
5.1.1.2. Thermal Heat Index Value (THI Value)	187
5.1.1.3. Thermal Heat Index Difference (THI Difference)	187
5.1.1.4. Surface Temperature	188
5.1.2. Summary of Findings of ENVI - met Computer based Simulation Data Analysis on envisaged planning interventions.....	188
5.1.2.1. Air Temperature	188
5.1.2.2. Mean Radiant Temperature (MRT).....	190

5.1.2.3. Predicted Mean Vote (PMV).....	191
5.2 Significance of the study for Spatial Planning and Design	193
5.3 Limitations of the Study	194
5.4 Directions for Future Study	195
REFERANCE LIST	196
APPENDICES.....	199
APPENDIX I: Building heights were categorized according to the Urban Development Authority Guide Lines. (Appendix I – ‘C’ Form of Building Guide Plan, UDA)	199
APPENDIX II: Simulated Air Temperature Maps for the Increasing Building Height Scenario.	200
APPENDIX III : Simulated Air Temperature Maps for the Green Scenario	208
APPENDIX IV: Simulated Air Temperature Maps for Create Open Spaces (Case 06) Scenario.....	211
APPENDIX V: Simulated Air Temperature Maps for Creating Wind Corridors (Case 07) Scenario.....	212
APPENDIX VI: Simulated Air Temperature Maps for Changing Surface Materials (Case 08) Scenario.....	214
APPENDIX VII: Mean Radiant Temperature (MRT) Distribution Maps	222
APPENDIX VIII: Mean Radiant Temperature (MRT) Distribution Maps.....	226
APPENDIX IX : MRT Distribution maps for Changing Surface Materials Scenario – Case 08	258
APPENDIX X : Summary of simulated Air Temperature, MRT and PMV values for each Locations.	266

LIST OF FIGURES

Figure 01: Normalized difference built-up index (NDBI) maps of the CMA in (a) 1997; (b) 2007; and (c) 2017 (Ranagalage M.etal, 2017)	4
Figure 02 :Land surface temperature (LST) maps of the CMA in (a) 1997; (b) 2007; and (c) 2017 (Manjula Ranagalage, 2017)	5
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	11
Figure 04 Causes for UHIs	12
Figure 05: A Schematic View of Urban Air Temperature Profile	13
Figure 06: Historic air temperature trends in the CMR	19
Figure 07: Day time thermal comfort trends in the hottest month in Colombo	20
Figure 08: Night time thermal comfort trends in the hottest month	21
Figure 09: Typical” vs. “recent” a climate in Colombo city- Day Time	22
Figure 10: “Typical” vs. “recent” climate in Colombo city- Night Time	22
Figure 11: Thermal comfort effect of land use categories	24
Figure 12: Environmental inspiration is essential to gain Outdoor comfort.	25
Figure 13: Indoor and outdoor comforts varydue to the differences of clothing, activity levels and exposures times of the people.	26
Figure 14: Human energy balance: steady –stat condition.	27
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.....	29
Figure 16 : Impact of Solar Radiation in Dar es Salaam, Tanzania. (a) Yearly average, (b) a clear day.....	30
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.....	31
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.	32

Figure 19: The different levels of relative humidity due to the cooling effect of the wind.....	33
Figure 20: Urban geometry	35
Figure 21: Different Urban Forms	37
Figure 22: Urban Canyon.....	38
Figure 23: Radiation effect on an urban canyon reference to its aspect ratio	39
Figure 24: Orientation of Urban canyons.....	40
Figure 25: : The sky view factor in a symmetrical street canyon	41
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).....	42
Figure 27: Life in Urban street canyon	43
Figure 28: Street as a place of festivity	44
Figure 29: Street as a place for community activities	44
Figure 30: Street as a recreational area	45
Figure 31: Urban Open spaces act as Public Plaza . (Public Plaza in front of the Pettah Railway Station in Sri Lanka.	46
Figure 32: Urban Open spaces use for surface parking.	47
Figure 33:Pedestrian Movement and Pattern at Pettah.	49
Figure 34: Highly pedestrianized Urban Area as the selection of the case study	50
Figure 35: Location Map.....	51
Figure 36: Location Map with Different Built Form Elements	52
Figure 37: An urban Plaza – Station Plaza.....	53
Figure 38: East –West Canyon – a.) Prince Street	54
Figure 39: East –West Canyon – b.) Main Street.....	55
Figure 40: North –East Canyon – 02 nd Cross Street.....	56
Figure 41: Parking Precinct- Gunasinghapura Bus Stand.....	57
Figure 42: : Equipment utilized to measure weather parameters	59
Figure 43: Location Map for Field survey	61
Figure 44: Modelling of Base Case Location 01 – An Urban Plaza	67
Figure 45: Modelling of Base Case Location 02 & Location 03	68
Figure 46: Modelling of Base Case Location 04 – EW Urban Canyon – Main Street	69

Figure 47: Modelling of Base Case Location 05 – A Parking Precinct	70
Figure 48: Monthly Mean Temperature (Data from March 2018 to March 2019)... ..	74
Figure 49: Monthly Mean Relative Humidity	74
Figure 50: Field Survey Map – Location 01 – An urban Plaza.....	75
Figure 51: Photographic Survey – Location 01 – An urban Plaza.....	76
Figure 52: Building height Distribution Survey – Location 01 – An urban Plaza.....	77
Figure 53: Point of Filed Survey – Location 01 – An urban Plaza	79
Figure 54: Field Survey Map – Location 02 – East-West Canyon – Prince Street....	80
Figure 55: Photographic Survey – Location 02 – An urban Plaza.....	81
Figure 56: Building height Distribution Survey – Location 02 – East West (EW) Urban Canyon – Prince Street	82
Figure 57: Point of Filed Survey – Location 02 – East West Canyon – (a) Prince Street	84
Figure 58: Field Survey Map – Location 03 – North South Canyon –	85
Figure 59: Photographic Survey – Location 03 – North South (NS) Canyon – 02 nd Cross Street	86
Figure 60: Building height Distribution Survey – Location 03 – North South (NS) Canyon – 02 nd Cross Street	87
Figure 61: Point of Filed Survey – Location 03 – North South Canyon – 02 nd Cross Street.....	89
Figure 62: Field Survey Map – Location 04 – East West Canyon – Main Street.....	90
Figure 63: Photographic Survey – Location 04 – East West Canyon – Main Street.	91
Figure 64: Building height Distribution Survey – Location 04 – East West Urban Canyon – Main Street.....	92
Figure 65: Field Survey Map – Location 05 – A Parking Precinct.....	95
Figure 66: Photographic Survey – Location 05 – A Parking Precinct.....	96
Figure 67 : Building height Distribution Survey – Location 05 – A Parking Precinct.	97
Figure 68: Field Survey Map – Reference Point.....	100
Figure 69 : Average Air Temperature (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations	106

Figure 70: Average Surface Temperature (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations.	108
Figure 71: Calculated THI Values (C°) from 11.00 a.m. to 13.00 p.m. for all Five locations.	109
Figure 72: THI Difference from 11.00 a.m. to 13.00 p.m. for all Five location.....	111
Figure 73: Average Air Temperature from 16.00 p.m. to 18.00 p.m. for all Five locations.	112
Figure 74: Average Surface Temperature from 16.00 p.m. to 18.00 p.m. for all Five locations.	114
Figure 75: Calculated THI values from 16.00 p.m. to 18.00 p.m. for all Five locations.	115
Figure 76: Calculated THI Difference from 16.00 p.m. to 18.00 p.m. for all Five locations.	117
Figure 77: Average Surface Temperature for both Sessions for all Five Locations.	118
Figure 78: Average Surface Temperature for both Sessions for all Five Locations.	120
Figure 79: Average THI values for both Sessions for all Five Locations.....	121
Figure 80: THI Difference for both Sessions for all Five Locations	123
Figure 81: Simulated Air temperature map on ,L1-Location 01-An Urban Plaza At Day Time, 13:00:01h.	124
Figure 82: Simulated Air temperature map on ,L1-Location 01-An Urban Plaza at Night-time, 21:00:01h	125
Figure 83: Simulated Air temperature map on, L2 and L3 – Location 02- EW Canyon –Prince Street and Location 03-NS Canyon – 02 nd Cross Street at the Day-time, 13:00:01h.....	126
Figure 84: Simulated Air temperature map on, L2 and L3 – Location 02- EW Canyon – (A) Prince Street and Location 03-NS Canyon – 02 nd Cross Street at Night-time, 21:00:01h.....	127
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	128
Figure 86: Simulated Air temperature map on, L5– Location 05- A Parking Precinct at Day-time, 13:00:01h.....	129

Figure 87 : Simulated Air temperature map on, L5– Location 05- A Parking Precinct at Night-time, 21:00:01h	130
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.....	131
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	132
Figure 90: Case 05 – Green – Increasing existing Tree Canopy width two times for the Location 01 – An Urban Plaza	133
Figure 91: Case 05 – Green – Increasing existing Tree Canopy width by twice for the Location 05 – A Parking Precinct.	134
Figure 92: Case 05 – Green – Increasing existing Tree Canopy by twice for the both Location 01 and Location 05.....	135
Figure 93: Case 05 – Green – Adding More Trees and More green for the Location 01- An Urban Plaza	135
Figure 94: Case 05 – Green – Adding More Trees and More Green for the Location 05- A Parking Precinct	136
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.....	136
Figure 96: Case 05 – Green – Adding a Tree Line for the both sides of Location 04 – Along the main Street.....	137
Figure 97: Case 05 – Green – Adding Tree Line for the both sides of Location 04 – Along the main Street.....	138
Figure 98: Case 06 – Create Open Spaces (Case 06) scenario.....	139
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.	140
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	140
Figure 101: Creating Wind Corridors Scenario- Case 07 – a.) Creating Openings at Existing Harbor wall.	141

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	142
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.	142
Figure 104: Creating Wind Corridors Scenario- Case 07 – b.) Removing existing Harbor wall.....	143
Figure 105: Air Temperature Analysis on b) Removing the existing harbor wall for creating wind corridors. Data were taken on Receptor point N1.....	144
Figure 106: Air Temperature Analysis on b.) Removing the existing harbor wall for creating wind corridors. Data were taken on Receptor point N2.....	144
Figure 107: Air Temperature Analysis on both a and b options for creating wind corridors on Receptor point N1	145
Figure 108: Air Temperature Analysis on both a and b options for creating wind corridors on Receptor point N2.....	145
Figure 109: Changing Surface Materials scenario (Case 08).....	147
Figure 110: Changing Surface Materials scenario (Case 08) at Day time, 13:00:01h	148
Figure 111: Changing Surface Materials scenario (Case 08) at the Night Time, 21:00:01h.....	149
Figure 112: Changing Surface Materials scenario (Case 08) at both Day time, 13:00:01h and the Night Time, 21:00:01h	149
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.	150
Figure 114: Simulated Mean Radiant Temperature for increasing Building Height Scenario at the Day Time 13:00:01h.....	152
Figure 115 : Simulated Mean Radiant Temperature for increasing Building Height Scenario at the Day Time 21:00:01h.....	152
Figure 116: Simulated Mean Radiant Temperature for increasing Existing Tree Canopy by twice Scenario at the Day Time 13:00:01h.....	153
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.	154

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.....	155
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.	156
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.....	157
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.....	158
Figure 122 : Simulated Mean Radiant Temperature for the Case 05 – Adding Tree Line along the Main Street at the Day Time13:00:01h.	159
Figure 123: Simulated Mean Radiant Temperature for the Case 05 – Adding Tree Line along the Main Street at the Night Time 21:00:01h.....	159
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.....	160
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.....	161
Figure 126: Simulated Mean Radiant Temperature for the Case 06 – Create an Open Space scenario at the Day Time 13:00:01h.....	162
Figure 127 : Simulated Mean Radiant Temperature for the Case 06 – Create an Open Space scenario at the Night Time 21:00:01h.	163

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.	164
Figure 129: Simulated Mean Radiant Temperature for the Case 07 – Create Wind Corridors scenario at the Day Time 13:00:01h	165
Figure 130 : Simulated Mean Radiant Temperature for the Case 07 – Create Wind Corridors scenario at the Night Time 21:00:01h.....	165
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.....	166
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	167
Figure 133 : Simulated Mean Radiant Temperature for the Case 08 – Changing Surface Materials scenario at the Day Time 13 :00:01h	168
Figure 134 : Simulated Mean Radiant Temperature for the Case 08 – Changing Surface Materials scenario at the Night Time 21:00:01h.....	169
Figure 135: PMV values of the Existing Scenario at the Day time, 13:00:01h	172
Figure 136 : PMV values of the Existing Scenario at the Day time, 21:00:01h	172
Figure 137 : PMV values of Changing Building Height Scenario at the Day time, 13:00:00h.....	173
Figure 138: PMV values of Changing Building Height Scenario at the Night time, 21:00:00h.....	174
Figure 139 : PMV values of Green Scenario at the Day time, 13:00:00h.....	175
Figure 140 : PMV values of Green Scenario at the Night time, 21:00:00h	175
Figure 141 : values of Green Scenario – Adding Tree Line for the Location 04 – EW Canyon – Main Street at the Day time, 13:00:00h.....	176
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.....	177
Figure 143 : PMV values of Green Scenario – Case 06 – Create an Open Space at the Day time, 13:00:01h.....	178

Figure 144 : PMV distribution of Existing Scenario – Base Case L2&L3 at the Day time, 13:00:01h.....	179
Figure 145: PMV distribution of Green Scenario – Case 06 – Create an Open Space at the Day time, 13:00:01h.....	179
Figure 146: PMV values of Green Scenario – Case 06 – Create an Open Space at the Night time, 21:00:01h	180
Figure 147 PMV distribution of Existing Scenario – Base Case L2&L3 at the Night time, 21:00:01h.....	181
Figure 148 : PMV distribution of Green Scenario – Case 06 – Create an Open Space at the Night time, 21:00:01h.....	181
Figure 149 : PMV values of Case 07 – Create wind corridor scenario at the Day time, 13:00:01h.....	182
Figure 150 : PMV values of Case 07 – Create wind corridor scenario at the Night time, 21:00:01h.....	183
Figure 151 : PMV values of Case 08 – Changing Surface Materials scenario at the Day time, 13:00:01h.....	184
Figure 152: PMV values of Case 08 – Changing Surface Materials scenario at the Night time, 21:00:01h.....	185
Figure 153: Air Temperature of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h	266
Figure 154: Air Temperature of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h.....	266
Figure 155 : MRT of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h.....	267
Figure 156: MRT of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h	267
Figure 157 : PMV values of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Day time, 13:00:01h. , Source: Author.....	268
Figure 158: PMV values of Increasing Building Height Scenario and the Changing Surface Materials scenario at the Night time, 21:00:01h , Source: Author	268
Figure 159: Air Temperature for Green scenario at the Day and Night Time.	269
Figure 160: Air Temperature for Green scenario at the Day and Night Time.	269

LIST OF TABLES

Table 01: Descriptive statistics of the retrieved LST values in CMA (°C).	5
Table 02: Annual Average Air Temperature of Colombo (1982-2012)	6
Table 03: Recent tropical UHI studies	16
Table 04: South Asian literature in past reviews.....	18
Table 05: Impact of wind speed for the human body.....	34
Table 06 : Thermal Sensation Scale,.....	72
Table 07: Field Measurements – Location 01 – An Urban Plaza	78
Table 08: Field Measurements obtained from Hobo meters– Location 01 – An urban Plaza	79
Table 09: Field Measurements – Location 02 – East West Canyon – (a) Prince Street	83
Table 10: Field Measurements obtained from Hobo meters– Location 02 – East-West (EW) Canyon – (A) Prince Street	84
Table 11: Field Measurements – Location 03 – North South Canyon – 02 nd Cross Street.....	88
Table 12: Field Measurements obtained from Hobo meters– Location 03 – North South Canyon – 02 nd Cross Street.	89
Table 13: : Field Measurements – Location 04 – East West (EW) Canyon – Main Street.....	93
Table 14: Field Measurements obtained from Hobo meters– Location 04 – East West (EW) Canyon – Main Street.....	94
Table 15: Field Measurements – Location 05 – A Parking Precinct	98
Table 16: Field Measurements obtained from Hobo meters– Location 05 – A Parking Precinct.....	99
Table 17: Field Measurements obtained from Hobo meters– Reference Point	101
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).....	102

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)..... 103

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)..... 104

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)..... 105

Table 22: The albedo of applied materials for all Five locations..... 148

Table 23: Thermal Sensation Scale..... 171