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The Department of Architecture and Built Environment
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Improving Environmental Condition of Workspaces of Multi-Storey Ready-Made Garment Factories in Bangladesh

Md Mohataz Hossain
BArch, MArch

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ABSTRACT

This research aims to identify viable design strategies that can improve the indoor thermal comfort within the workplaces of existing multi-storey ready-made garment (RMG) factories in the tropical climate of Bangladesh. The research framework was initially developed through literature reviews and a feasibility study on the applicability of a passive design approach within an existing RMG factory. The principal research follows the empirical case study approach collecting environmental data for three types of workspaces (i.e. cutting, sewing and finishing sections) and subjective responses from the workers, designer and owners of three multi-storey case study buildings during the three main climatic seasons (i.e. cool-dry, hot-dry and warm-humid seasons) of Bangladesh. In addition to field studies, a validated simulation study is also completed in one of the case study buildings.

Analyses of the subjective votes established workers' preferred thermal comfort range for temporal varieties of the climate and suggested that the distance between their workstation and ventilation-inlets should be maintained within 12m to 18m for more personalised control on their comfort avoiding the ceiling fans. Analyses of the environmental data from all case study buildings indicated that the limited effective openings of the existing windows and the ventilation strategy being limited to only occupied hours influence the thermal environment of RMG workspaces. Building owners saw value in implementing two solutions (i.e. altering existing window type to one with a higher effective opening area and utilising a night-time ventilation strategy with thermal mass) immediately in their existing buildings as well as new buildings. Simulation results confirmed that these two interventions can provide reductions of up to 23% of working hours when high temperature is experienced. Moreover, designing stack induced ventilation through shafts and changing functional arrangement can provide additional air speed (increase of up to 0.45 m/s) improving workers' thermal comfort.

Though this research includes limited number of case studies in sub-urban context lacking the representation of the total building stock of Bangladesh, the research methodology and key findings can still be used as a reference by architects and engineers involved in refurbishing existing workspaces or designing new RMG factories in Bangladesh and similar tropical regions. Findings can be adopted by owners and workers of the case study building for improving their workspaces. The thermal comfort guidelines and workable strategies can also serve as a reference for updating the existing building code of Bangladesh by extending the scope of the study.

PUBLICATIONS AND DECLARATION

The following joint publications were simultaneously produced by the author as the outcome of this doctoral study. Hence, some of the figures and words of the thesis chapters, as indicated below, may be similar as the published papers.

Published:

Publication details	Thesis chapters
HOSSAIN, M. M., FORD, B. & LAU, B. 2014. Improving Ventilation Condition of Labour-intensive Garment Factories in Bangladesh. *30th International PLEA Conference*. CEPT University, Ahmedabad, India.	Chapter 6
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HOSSAIN, M. M., LAU, B., WILSON, R. & FORD, B. 2016. Air Temperature vs Energy Efficiency of Workspaces: A field investigation in garment factories during cool-dry season. *15th International Conference on Sustainable Energy Technologies – SET 2016*. Singapore.	Chapters 7, 8 and 9
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LIST OF ACRONYMS

AC: Air Conditioned

ACH: Air Change per Hour

AH: Absolute Humidity

AV: Air Velocity

AVFR: Air Volume Flow Rate

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

AT: Air Temperature

BEPZ: Bangladesh Export Processing Zone

BGMEA: Bangladesh Garment Manufacturers and Exporters Association

BIDS: Bangladesh Institute of Development Studies

BNBC: Bangladesh National Building Code

CFD: Computational Fluid Dynamics

CIBSE: Chartered Institution of Building Services Engineers

CO: Carbon monoxide

CO_2: Carbone dioxide

CS: Cutting Section

CSK: Cotton 'Salwar Kameez'

DHW: Domestic Hot Water

DT: Dynamic Thermal

DTV: Day-time Ventilation

E: East

GDP: Gross domestic product

GHG: Green House Gas

GT: Globe Temperature

HVAC: Heating, Ventilation and Air Conditioning

IAB: Institutes of Architects, Bangladesh

IEB: Institutes of Engineers, Bangladesh

IES-VE: Integrated Environmental Solutions (Virtual Environment)

IGBC: Indian Green Building Council

IAQ: Indoor Air Quality

ILO: International Labour Organization

ISO: International Organization for Standardization

ET: Effective Temperature

F: Female

FS: Finishing Section

FSST: Full Sleeve Short T-Shirt

M: Male

MRT: Mean Radiant Temperature

N: North

NT: Neutral Temperature

NTV: Night-Time Ventilation

NV: Naturally Ventilated

OAV: Overall Acceptability Vote

OHS: Occupational Health and Safety

OT: Operative Temperature

PDEC: Passive Downdraught Evaporative Cooling

PHS: Predicted Heat Strain

PMV: Predicted Mean Vote ndex

POE: Post Occupancy Evaluation

PPD: Predicted Percentage Dissatisfied

RH: Relative Humidity

RC: Reinforced Concrete

RCC: Reinforced Cement Concrete

RMG: Ready-made garment

S: South

SD: Standard Deviation

SET: Standard Effective Temperature

SS: Sewing Section

SST: Short Sleeve T-Shirt

ST: Surface Temperature

TA: Thermal Acceptability

TCR: Thermal Comfort Range

TSV: Thermal Sensation Vote

TPV: Thermal Preference Vote

TCV: Thermal Comfort Vote

UHI: Urban Heat Island

W: West

WBGT: Wet Bulb Globe Temperature

WMO: World Meteorological Organisation

WFR: Window-to-floor Ratio

WWR: Window-to-wall Ratio

NOMENCLATURE

ΔS_h = Change in stored heat of body (W)

ΔS_b = Change in heat stored in the building (W)

ΔT = Temperature difference between indoor temperature and outdoor temperature (°C).

Δp = Pressure difference between the bottom and top stack with fixed discharge coefficient

ρ_i = Density of the air inside the building (kg/m^3)

A = Effective inlet or outlet area (m^2)

A_i = Total area of the inlets

A_o = Opening area

A_s = Surface area (m^2)

$AT_{\_out}$ = Outdoor Air Temperature

AV (n/s) = Air Velocity (from north/south direction)

AV (e/w) = Air Velocity (from east/west direction)

AV (u/d) = Air Velocity (from up/down direction)

C_d = Conduction (W)

C_v = Convection (with respiration) (W)

Clo = Clothing insolution

E_v = Evaporation (with respiration) (W)

g = Acceleration due to gravity ($10m/s^2$),

H = Stack height measured between the centre of the inlet and the centre of outlet (m)

M = Metabolic heat production (W)

Met = Metabolic rate

N = Number of air change per hour

Max =Maximum

Min = Minimum

Q_e = Evaporative heat loss (W)

Q_i = Internal heat gain (W)

Q_c = Conduction heat gain or loss or heat flow rate by conduction (W)

Q_s = Solar heat gain (W)

Q_v = Ventilation heat flow (gain or loss) (W)

R = Correlation coefficient

RH_{in} = Indoor Relative Humidity

RH_{out} = Outdoor Relative Humidity

Rd = Net radiation exchange (W)

T_{mrt} = Mean Radiant Temperature

T_{op} = Operative Temperature

T_{wbgt} = Wet Bulb Globe Temperature

T_w = Wet Bulb Temperature

T_{nwb} = Wet Bulb Temperature - Naturally Aspirated

T_i = The indoor temperature (°C) often taken as the upper adaptive comfort band

T_{a_in} = Indoor air temperature

T_{a_out} = Outdoor air temperature

T_a = Air temperature

T_g = Globe temperature

t_i = Indoor air temperature

T_o = The outdoor temperature (°C)

t_o = Outdoor air temperature

q = Ventilation rate (m^3/s)

q_c = Air flow rate required for cooling (m^3/s)

q_s = Stack air flow rate (m^3/s)

U = Transmittance, u-value ($W/m^2 K$)

V = Volume of the building or room or zone (m^3)

v = Velocity of the air (m/s)

CHAPTER 1. INTRODUCTION

This chapter introduces the main subject of the research. The main research question, aim and objectives are outlined and the novelty and significance of the research are highlighted. Moreover, the overall research methodology and thesis structure are presented.

CHAPTER 1. INTRODUCTION

1.1. Introduction

This chapter introduces the main subject of the PhD thesis. The main research questions, aim and objectives of the research are stated. The overall research methodology to achieve the aim and objective is presented. The novelty and significance of this research are also highlighted in this chapter. The chapter concludes with the thesis structure to guide the reader with an overview of the thesis contents.

1.2. Research Background

The readymade garment (RMG) sector is a fully export oriented industry and Bangladesh is one of the largest RMG exporters in the world after China (BRAC EPL, 2013, Absar, 2001, p.3). During 2007, this RMG sector of Bangladesh was flourishing with 4,000 garment factories employing approximately 2.5 million people, of which 80% were women (IFC, 2007, p.1). Labowitz (2016) reported that this growing number of garment factories in Bangladesh passed 7000 in numbers after the year of 2015. This sector plays an essential role in the economy of Bangladesh, accounting for more than 80% of the total export earnings (Rahman et al., 2007, p.3) and nearly 10% of total Gross domestic product (GDP) (i.e. 221.4 Billion US$ in the year of 2016) of Bangladesh (World-Bank, 2017, IFC, 2007, p.1).

Among all textile products, the RMG products of the global renowned clothing brands are produced in RMG factories which are mostly human labour intensive (Sarkar and Akter, 2008, Hossain, 2011, p.43). Employers involved in production work for 10-12 hours a day in workspaces which include cutting, sewing and finishing sections (Zohir and Paul-Majumder, 2008). The activities within the production spaces are the significant part of the total chain of process completed within the RMG industry, i.e. from RMG sample pattern and fabric spreading to finishing, inspection and shipment of the end product (Prokaushali Sangsad Limited, 2007, Paul-Majumder and Begum, 2006). In the tropical climatic context of Bangladesh, most of the workers in RMG factories suffer from discomfort in their workspaces and a range of health problems due to the high indoor temperature and poor air distribution (Fatemi, 2014).

A previous survey conducted by the Bangladesh Institute of Development Studies (BIDS) in 17 factories in the years of 1990, 1997 and 2003 revealed that artificial lighting operated 10-12 hours a day and created an excessive amount of heat (Paul-Majumder, 2003). The majority of factories had ironing and sewing on the same floor, which caused higher indoor temperatures (Paul-Majumder, 2003). The study also collected feedback on the ventilation performance and many respondents reported this to be poor. These workspaces, with a deep floor-plate and low ceiling heights, usually employ forced cross-ventilation using extract fans located on the external walls. However, the existing active ventilation strategy is unable to provide the workers with necessary thermal comfort, even in the presence of a significant difference in 'wind pressure coefficient' between the inlets and outlets (CIBSE, 2005, Fatemi, 2014).

Recent research has shown that the physical working environment and long working hours of a RMG factory have an impact on female workers' health (Ali and Islam, 2017). Domat et al. (2013) also demonstrated that there is a significant impact of workspace conditions on the well-being and health of RMG factory workers. In particular, the poor environment inside these factory buildings has a harmful impact on workers' health and causes health related hazards (Wilson and Corlett, 2005, p.809, Zohir and Paul-Majumder, 2008, p.98). The previous studies by Paul-Majumder (2003) and Mridula and Khan (2009) revealed that the more common illnesses among the garment workers were headache, general anaemia, weakness, fatigue, poor appetite and vomiting tendency. Workers' thermal discomfort also hampers their work efficiency (Fatemi, 2014), resulting in additional workload to meet production targets without any financial benefit.

More recently, 414 garment workers were killed in 213 factory fires between the years of 2006 and 2009. Moreover, according to the Bangladesh Fire Department, a further 79 workers lost their lives in 2010 in 21 separate recorded incidents (Campaign, 2012, p.1). During fire incidents, trapped smoke inside the poorly designed factory buildings is one of the main reasons of fatalities (Akther et al., 2010) which is also correlated to the efficiency of ventilation. After an incident involving the massive collapse of a RMG factory building, known as the 'Rana Plaza tragedy' which resulted in the death of 1134 workers in April 2013, a new 'alliance' and 'accord' between RMG factories and

International organisations , such as International Labour Organization (ILO), German Society for International Cooperation, etc., have been formed for joint ventures evaluating the fire and structural safety in existing RMG factory buildings (Sabet and Tazreen, 2013, p.1). However, none of the recent collaborative projects directly included the initiative of improving thermal environment of RMG factories. There is also a lack of local legislation and regulatory design standards addressing the thermal environment within garment factories.

While considering the energy scenario, only 43% of the total population of Bangladesh has access to electrical energy grid (Hossain, 2016, p.1). The daily peak electricity output totals around 6,350 MW against a peak demand of 7,518 MW, leaving a demand-supply gap of 1168 MW (BRAC EPL, 2013, p.25). According to a study undertaken by the 'Ministry of Energy & Mineral Resources', energy is one of the most costly inputs of the production process accounting for about 20% of the final garment product cost (Prokaushali Sangsad Limited, 2007, p.16). A study also reported that industrial buildings have significant energy consumption (28%) in the Dhaka region in 2009-2010 (BBS, 2010, p.185). Considering the global context, a recent study shows that the building sector is one of the major consumers of energy, responsible for 20.1% of global demand and 30-40% of world's total Green House Gas (GHG) emission (EIA, 2017, UNEP, 2007, p.4).

In this case, passive design solutions for factory buildings may not only reduce energy consumption but also contribute to a decrease in carbon emissions. However, there are limitations to the implementation of a wide range of passive environmental design and energy efficient strategies for improving employee comfort in existing RMG factory buildings. For example, they may not be feasible due to disruption of the ongoing production process or due to structural limitations of the factory buildings. Typically, however, minor or intermediate interventions in existing buildings may be possible (Ford, 2010) and particularly in RMG factories, they may improve the thermal environment of workspaces subject to factory owners' agreement. A recent parametric study by Chowdhury et al. (2015) considered the thermal performance of RMG workspaces with respect to use of different building materials. However, this appears to be an absence of studies based on field evidence from RMG factories that

quantify the issues surrounding existing thermal conditions in different production workspaces (explained in Sections 2.5-2.7 and 4.3.4). Understanding the current conditions during the different climatic seasons that commonly prevail in tropical climates, such as those observed in Bangladesh, is a valuable starting point for identifying feasible solutions designed to improve the indoor thermal performance of both existing and new RMG factory workspaces.

Considering the current conditions within RMG factories in Bangladesh, this research was formulated to identify viable climate responsive design strategies that can improve the existing environmental conditions of the workspaces and extend the thermal comfort of the workers within the existing RMG factories of Bangladesh.

1.3. Research Questions, Aim and Objectives

After formulating the conceptual framework of this PhD research (explained in Sections 4.3 and 5.3), the following was identified as the main research question:

> *"What are the viable design strategies that can improve the thermal comfort and indoor environmental condition of workspaces within existing RMG factories in the tropical climate of Bangladesh?"*

To obtain answers to the main research question, the following three associated sub-questions were addressed in this research:

Sub-question A: *What are the factors that influence the thermal environment within workspaces in RMG factories and how do these vary between the seasons of Bangladesh?*

Sub-question B: *What are the thermal comfort guidelines and the workable design strategies to minimise the environmental issues within these workplaces?*

Sub-question C: *To what extent are the workable design strategies beneficial in terms of improving workers' thermal comfort within the workspaces?*

Since the main aim of this research was to investigate the workable design solutions for improving the indoor environmental conditions within RMG factories' workspaces, five objectives were set to answer the above sub-questions. Objectives 1-3 seek to answer *Sub-question A*, and Objectives 4 and 5 seek to answer *Sub-questions B* and *C respectively*. The five objectives are:

Objective 1: *To identify the environmental design parameters that influence the indoor thermal comfort of workspaces, including those of RMG factories, in a tropical climate.*

Objective 2: *To identify and assess the feasibility of passive design strategies in existing multi-storey RMG factories of Bangladesh.*

Objective 3: *To identify the key parameters that influence the thermal environment of workspaces in existing RMG factories during the climatic seasons in Bangladesh.*

Objective 4: *To identify thermal comfort guidelines and workable design strategies to minimise the issues (based on Objective 3) within RMG workspaces.*

Objective 5: *To explore the environmental benefits of applying the workable design strategies in existing RMG factories.*

1.4. Research Methodology and Rigour

This section presents a brief overview of the research methodology. A detailed description of the research methodology, used for this PhD research, can be found in Chapter 5. The review of relevant research methods, such as field monitoring, survey and simulations, and the justification for the methods used in this research are also discussed in Chapter 4.

This research revolves around an empirical case study approach and considers a number of case studies to achieve an in-depth set of field observations (Groat and Wang, 2013) and a simulation study addressing the main research question (including three sub-questions) and five objectives (Section 1.3). Figure 1-1 illustrates the flow diagram of the total research methodology, highlighting the methods and corresponding research objectives.

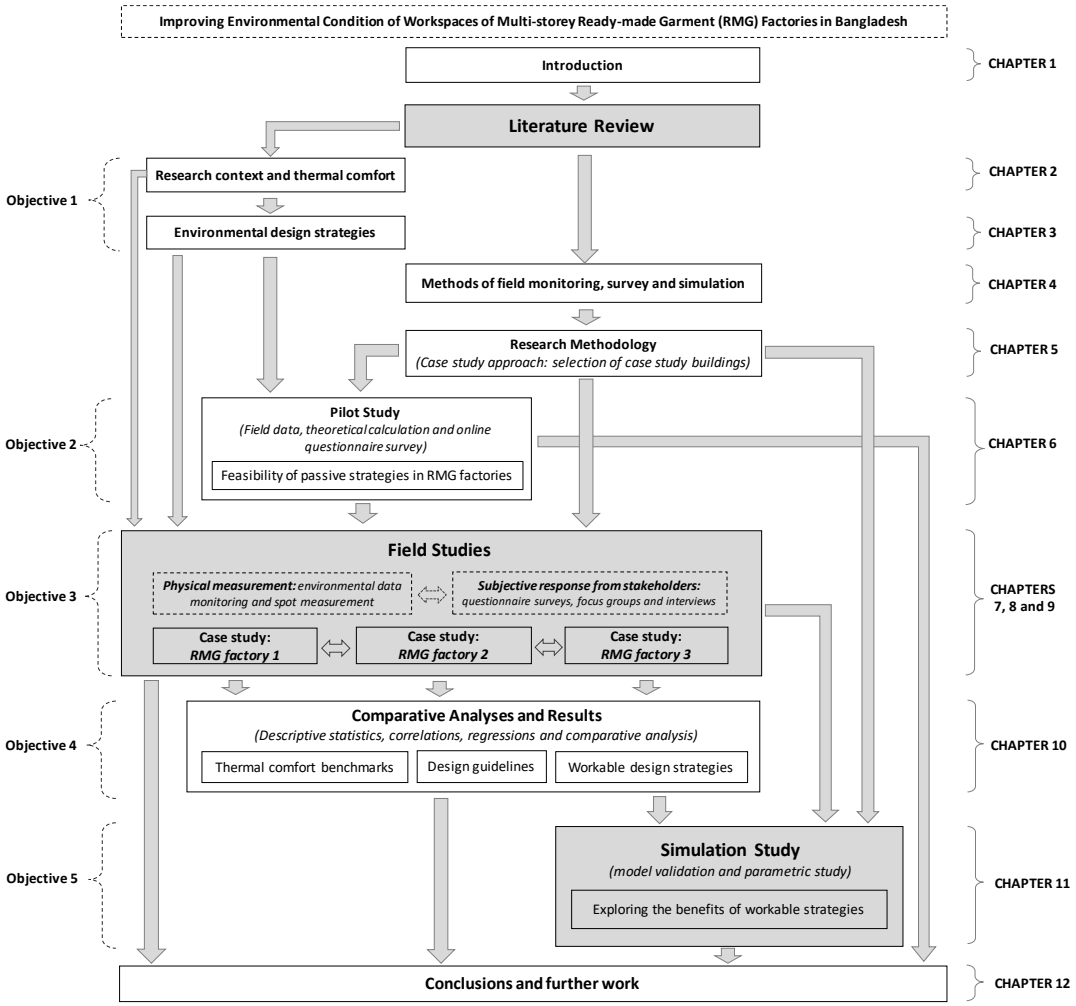


Figure 1-1: Flow diagram of the research methods and thesis chapters

To maintain the rigour of this research method, triangulation among three phases, i.e. theoretical studies, field studies (including physical measurement and subjective responses) and simulation studies, was applied in this study (Section 5.3).

As the first phase of this research, literature reviews were conducted to address the first research objective and a theoretical foundation on thermal comfort, climate responsive design and passive strategies in workspaces in the tropical regions were developed. Further literature review was undertaken identifying suitable methods to conduct the field investigations and simulation study. Due to a lack of published evidence on passive design strategies, specifically for existing RMG factories in Bangladesh, a further theoretical study was necessary to address the research objective 2. Hence, a feasibility study was conducted coupled with a pilot study to test the viability of applying passive design strategies within existing RMG factories in the

context of Bangladesh. Moreover, the limitations of the methods identified during this pilot study were also addressed in the next two phases.

The second phase includes in-depth field studies in three case study buildings (i.e. *RMG factory 1*, *RMG factory 2* and *RMG factory* 3) during three climatic seasons (i.e. cool-dry, hot -dry and warm-humid) in Bangladesh. The field investigations consist of physical measurements, subjective response collection from stakeholders, field observations and the collection of photographic evidence. The physical measurement includes continuous monitoring and spot measurements of both the indoor and outdoor thermal environment in selected RMG factories' workspaces. The factory workers from workspaces (i.e. cutting, sewing and finishing sections), owners and managing directors and designers of the selected RMG factories were considered as the stakeholders for a subjective response collection. To acquire subjective data, a structured questionnaire survey and six focus group discussions undertaken with 908 and 49 workers (in total) respectively were used to gather thermal comfort perception and adaptive measures adopted at workstations during the different seasons. The data were then analysed statistically to identify common design parameters influencing their thermal environment, the targeted thermal comfort conditions and associated design guidelines and strategies. Three semi-structured interviews with the factory owners and directors were completed to identify workable design strategies for the three case study buildings. However, only an informal discussion with an architect of case study building-1 was feasible. This phase addressed research objectives 3 and 4.

The third phase includes a simulation study to address research objective 5. A Dynamic Thermal (DT) and a Computational Fluid Dynamics (CFD) simulation model of *RMG factory 3* were developed using the simulation programme 'Integrated Environmental Solutions - Virtual Environment' (IES-VE, version 2017). This case study building is selected since this is the only purpose-built building having all the data required for a valid parametric study. The weather file and models were validated against the meteorological and field data. The simulation scenarios were formulated based on the workable design strategies identified in the previous phase and environmental benefits were quantified based on increased working hours within workers' targeted thermal comfort range and improved airflow profile within the workspaces.

1.5. Novelty and Significance

This research presents for the first-time field evidence that includes both physical measurement and subjective responses, to identify the common parameters influencing the thermal environment within three type of workspaces in existing RMG factories during the three climatic seasons in Bangladesh. This research proposed a number of workable design approaches, including passive stack ventilation as a novel solution, to minimise the existing issues. Based on a limited number of case studies and field data, the study also recommended the thermal comfort ranges preferred by the workers, preferable speed and direction of the airflow at their workstations and the threshold distance between a ventilation inlet and a workstation (potentially a new design guideline of ceiling height to floor-plate width ratio). Subsequently established workers' adaptive comfort conditions with personalised control over ventilation varying across the three climatic seasons and validated simulation studies represent the added value of this research.

Though the research includes only limited number of case study building, the impact of this research may still be significant, particularly on the RMG factory workers whose continuous exposure to poor thermal environment is evident. Effective implementation of passive ventilation strategies in RMG factories can increase the period of time during which a natural environment is provided for workers and reduce electricity energy consumption and consequent greenhouse gas emissions (Wijewardane and Jayasinghe, 2008). By adopting complementary passive design strategies, the whole building envelope can work as a 'climate modifier' to reduce the cooling load and improve indoor thermal comfort (Rajapaksha and Hyde, 2012). The methodology and key findings of this research can also be followed by architects and engineers with further investigation to refurbish an existing workspace or to design new multi-storied RMG factories with improved workplace conditions in Bangladesh and similar tropical regions (explained further in Section 12.4).

1.1. Scope and Limitations

The research described in this thesis focused on improving thermal comfort of workspaces within the multi-storey RMG factories in Bangladesh. Considering the

available time and budget of the research, only three case study buildings were selected each occupying a semi-urban context. Hence, the case studies are unable to represent the total RMG factory building stock of Bangladesh and results gained from this research are likely to be applicable only to the case study buildings or to buildings with similar form and morphological context experiencing the climate of Bangladesh. As a consequence, the implications of the results presented here on policy and practice are also limited.

The field studies were completed within a short period of time, around 10 days of monitoring and so provide only a representation of each climatic season in Bangladesh. Moreover, due to limited access to the factory buildings, the sample size for the comfort surveys varied across each season. Hence results such as thermal comfort ranges may not represent the whole year. Moreover, with only three interviews with the owners of the case study building being conducted, the results may not represent the perception of all owners of RMG building stock. Since the first two case study buildings were not purpose built and hence their architects could not be identified and given the unavailability of the architects of the third building, formal interviews with the designers could not be arranged. However, the informal discussion with the architect of the third case study building was included.

The workable design strategies presented in this research do not consider the cost and disruption associated with the retrofitting. Investigations around barriers to implementations of the proposed strategies in terms of their affecting indoor air quality, lighting and acoustics of existing workspaces are beyond the scope of this study. Further details can be found in Section 12.3.

1.2. Structure of the Thesis

This thesis is organised in twelve chapters. The flow of the chapters corresponding the research objectives and methodology is highlighted in Figure 1-1. Brief descriptions of all the chapters are provided below:

Chapter 1 introduces the main subject of the research. The main research question, aim and objectives are outlined and the novelty and significance of the research are

highlighted. Moreover, the overall research methodology and thesis structure are presented.

Chapter 2 provides a literature review to formulate a theoretical base on thermal comfort in RMG workspaces. Environmental conditions within RMG factories, climatic context, thermal comfort, relevant building regulations and the knowledge gaps are presented. The chapter also includes a review of similar empirical studies focusing on thermal comfort and performance of factory buildings, their methods and key learning for this thesis.

Chapter 3 presents a literature review on passive design strategies to build a theoretical foundation for this research. The review also includes learning from architectural precedents to identify the passive strategies and the associated design parameters that were already applied within the workspaces in tropical zones. A list of applicable design strategies is outlined at the end of this chapter to be referred to in the next steps of the research.

Chapter 4 presents a literature review focusing on the methods of field monitoring, survey and simulation studies adopted in previous empirical research. It identifies the methods and strategies considered suitable for conducting this PhD research including the field investigations and simulation study.

Chapter 5 presents the detailed account of the method adopted for this research. The case study buildings are also introduced in this chapter. The rationales and descriptions of all the methods implemented within this research are also presented.

Chapter 6 presents a feasibility study at the pilot study stage to test the applicability of the passive design strategies within existing garment factory buildings. Results from a theoretical analysis and an online questionnaire survey guide further analyses of this research and indicate the extended scope of main field studies.

Chapter 7 presents the results from the field studies conducted in the first case study building, *RMG factory 1*, during three climatic seasons in Bangladesh. Exiting issues related to thermal environment and a number of improvement strategies are

proposed at the end of the chapter based on the field evidence, including measured environmental data and workers' subjective responses.

Chapter 8 provides the results from the field studies conducted in the second case study building, *RMG factory 2*. Similar to previous chapter, exiting issues of thermal environment and a number of improvement strategies are proposed at the end of the chapter.

Chapter 9 presents the results from the field studies conducted in the third case study building, *RMG factory 3*. Similar to previous chapter, exiting issues of thermal environment and a number of improvement strategies are proposed at the end of the chapter.

Chapter 10 provides comparative analyses of field survey data from the three case study buildings with an objective to establish thermal comfort guidelines for RMG factory workers. Feedback from the building owners is described and workable design strategies are outlined.

Chapter 11 presents a simulation study used to quantify the effects of applying a number workable strategies in an existing RMG factory building. The validation process of climate data and an IES-VE simulation model is outlined. The simulation results are compared and benefits are highlighted.

Chapter 12 refers back to the five research objectives and describes the key findings showing how each of the objectives was achieved in this research. It also presents limitations of the study, its original contribution to knowledge, the implications of the research to policy and practice and recommended further research arising from this research.

CHAPTER 2. LITERATURE REVIEW: RESEARCH CONTEXT AND THERMAL COMFORT

This chapter provides a literature review to formulate a theoretical base on thermal comfort in RMG workspaces. Environmental conditions within RMG factories, climatic context, thermal comfort, relevant building regulations and the knowledge gaps are presented. The chapter also includes a review of similar empirical studies focusing on thermal comfort and performance of factory buildings, their methods and key learning for this thesis.

CHAPTER 2. LITERATURE REVIEW: RESEARCH CONTEXT AND THERMAL COMFORT

2.1. Introduction

This chapter firstly reviews the workspace environment of RMG factory workers and the broader climatic zone under which Bangladesh is located. It sequentially provides a preliminary knowledge base by reviewing thermal comfort approaches and fundamental thermal performance aspects relevant to this research. Reviews of similar empirical studies focusing on thermal comfort and performance of RMG factory building, their methods and key learning for this research were also included. Then it concludes by reviewing the code and building regulations on thermal performance aspects.

2.2. Chapter Aim and Scope

The main objectives of this chapter to review previously published literature on workspace environment of RMG factory, climate and the context of Bangladesh, thermal comfort, thermal performance aspects and relevant building regulation. This knowledge base will act as a reference material for the next chapters.

2.3. Workspace Environment of RMG Factories

The interaction between occupants and built environment takes place in numerous ways. The important aspects of an environment includes thermal environment (both inside and outside of the built environment), luminous environment, ventilation, noise or vibrations (CIBSE, 2015, ASHRAE, 2013). The human factors that are directly affected by the environmental condition are personal comfort, health, performance and Interactions (CIBSE, 2015). It is important for architects and building service engineers to integrate all environmental aspects to design comfortable and healthy environment for the occupants. Hence, this section focuses on reviewing the present condition of the RMG factory's workspaces and the potential impacts on clothing workers.

2.3.1. RMG production and main workspaces

Within the estimated RMG factories, workspace areas are the places where workers mostly get involved in tailoring works foe 10-12 hours as a part of the production chain process (Prokaushali Sangsad Limited, 2007, Paul-Majumder and Begum, 2006). The main production areas (i.e. workspaces) can be divided into three sections, Cutting Section (CS), Sewing Section (SS) and Finishing Section (FS), where the first step is cutting and the final steps are finishing and labelling (Hossain, 2011, Winefsky and Tenney, 2002). Figure 2-1 illustrates the overall production process and the three types of workspaces.

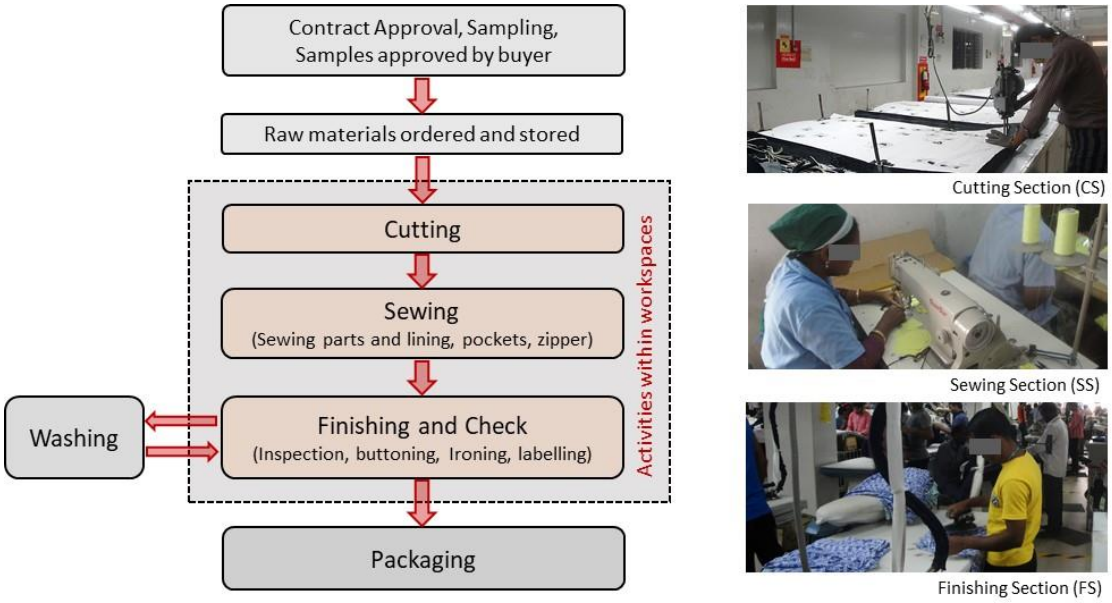


Figure 2-1: Production flow chart within workspaces of RMG factories

Among a limited number of studies, Paul-Majumder and Begum (2000) showed that the majority of the workers within the prduction workspaces of RMG factories, particularly in the SS, are women. From their lastest survey, it can be observed that the SS was hightly occupied area while the CS is less occupied workspace (Paul-Majumder and Begum, 2000, p.37). These workspaces were also reported as poorly ventilated, overcrowded and congested areas by the surveyed workers (Paul-Majumder, 2003, Paul-Majumder and Begum, 2006). The workers involved in ironing works within the FS (Figure 2-1) are exposed to very high heat caused from the hot water pipes near their workstations in addition to the artificial lights above their heads (Paul-Majumder,

2003, Hossain, 2011). Indoor AT is always found 3-4°C higher than outdoor AT in factory buildings (Khan et al., 2011). These studies indicates the poor thermal environments of RMG factories' workspaces. However, it demands further field evidence with quantitative data to get a clear image of the working environment.

2.3.2. The factory environment and the workers

The employees who are directly involved in the production related activities of a factory with limited or no administrative capacity are categorised as factory worker (Wijewardane and Jayasinghe, 2008). While considering their workspace environment, performance of physical and mental work of the workers becomes a priority that needs to be addressed (Robertson et al., 2008, Wong et al., 2003). Where excessive heat and cold diminish the performance of mental tasks, the overall optimum performance, both physical and mental, can only be achieved by ensuring thermal comfort to the workforce (CIBSE, 2015, Prokaushali Sangsad Limited, 2007). Venugopal et al. (2015) in their research evident that prolong exposure to heat in workplace have negative impact on workers' health and efficiency in tropical climate.

In case of RMG factory buildings in Bangladesh, Steinisch et al. (2013) reported that work related stresses and interpersonal resources are associated with workers' health. Workers' comfort, health, safety and performance can be directly influenced by the quality of the physical working environment (NAP, 2010, Ali and Islam, 2017, Ramsey et al., 1983). Poor environmental quality inside the building has harmful impacts on workers' health (Wilson and Corlett, 2005) resulting in a high incidence of illness (Zohir and Paul-Majumder, 2008, p.98). As demonstrated in Table 2-1, the most frequent incidence were physical weakness/fatigue (28%), headache (97%), respiratory problem (36%), vomiting (28%) and fainting (18%) (Mridula and Khan, 2009, p.13). In addition, Ahmed and Raihan (2014) showed that many skin related diseases are caused due to unhealthy working environment. These are likely to result from the hot indoor conditions of most factories, lack of proper ventilation, frequent electricity failure, and high humidity etc.

Table 2-1: Work related illness in RMG factories (Source: Mridula and Khan, 2009, p.13, Paul-Majumder, 2003)

Name of the incidence	Incidence of illness (%) (in the year of 2009)	Incidence of illness (%) (in the year of 2009)
Headache	57.0	97
Physical weakness/fatigue	42.4	28
Vomiting	24.8	28
Respiratory problem	11.3	36
Fainting	3.7	18

Previous theoretical studies and empirical evidence suggest that improving the indoor thermal environment can improve health and wellbeing of the workers at their workspace offering financial benefits to both workers and factory owners (Fisk, 2000, Hobday and Dancer, 2013, Mahbob et al., 2011). Among the environmental conditions, Hossain (2011) and Fatemi (2012) commenced field studies on illumination and thermal condition in a number of RMG factories in context of Bangladesh. In both cases, the authors conducted environmental data measurement and collected feedback from the workers. They showed that the environmental condition of the studied workspaces required improvement. It was also highlighted that improving the thermal condition of the workspace environment increases the efficiency of the workers and improving thermal environment reduces the number of errors up to 1.88% (Fatemi, 2014, p.149). It was indicated that ensuring comfortable temperature range to the RMG workers can reduce the total number of sickness from 760 to 676 (Fatemi, 2014, p.149). These studies indicate the significance of studying thermal environment of these workspace, however are unable to show credibility due to limited number samples and data collection (Section 4.5.7). Hence, further empirical research is required to explore the issues around thermal environment and design solutions for RMG factories' workspaces.

Mendell et al. (2002) demonstrated the significant research need of improving ventilation and thermal environment of workers' workspace to reduce the health hazards. Therefore, among the aspects of environmental conditions, this research focuses on indoor thermal environment of workspaces of RMG factories in context of

Bangladesh. Since, the climate and the context of Bangladesh are associated with the indoor thermal environment of workspaces, these will be reviewed in the next section.

2.4. Climate and the Context of Bangladesh

2.4.1. Classification of climate and the tropics

Danby (1963) emphasised on the importance of understanding climate as the crucial step for designing a building to target optimum thermal performance. Hence, this section will highlight the tropical climate and the context of Bangladesh.

A set of meteorological conditions, also known as the prevailing environmental conditions, of a region in a given time defines the weather and determines the climate (Hyde, 2000, Szokolay, 2008). The combination in time of weather conditions, features of a geographical location defines the climate (Szokolay, 2008). Climate of a region is measured by recording 30 years of weather conditions of the region, as defined by World Meteorological Originations (WMO, 2017). As the climatic elements, climatic conditions are mainly measured by solar radiation, outdoor Air Temperature (AT), rainfall, Absolute humidity (AH) or Relative Humidity (RH) and Air Velocity (AV) (Koch-nielsen, 2002, Oakley, 1961).

Radiation of a region is directly related to the position of the sun, sky condition and sunshine hours (alternatively cloud cover). Intensity of solar radiation is determined by latitude. The sun heats up the ground of the earth and atmosphere more quickly through clear sky than cloudy sky (Oakley, 1961, Szokolay, 2008). The closer a region is to the Equator, the greater its exposer to solar radiation and the greater the RH (Oakley, 1961, Hyde, 2000). Distance from the Equator is also linked to seasonal variations. The farther a region is located from equator, the greater the variations in the seasons.

The indication of the existence of heat is expressed as temperature (Szokolay, 2008, p.6). Temperature is the most typical component of tropical climate and is determined by AT. AT, measured by means of a dry-bulb thermometer and also known as dry-bulb temperature (Szokolay, 2008), generally rises during daytime due to radiation from the sun. On the other hand, AT decreases during night time due to outward radiations from

the earth towards the atmosphere, which is also faster in process in clear sky condition than overcast sky (Koenigsberger et al., 1973, Oakley, 1961, Galvin, 2016). AV, i.e. air speed and direction, is the concerned parameter to characterise air flow. Movement of winds in the tropical regions have direct relation with air pressure which is also related to temperature of the earth surfaces. Changes in wind pattern results in seasonal variations, such monsoon. Along with the wind, rain is another related part of the climate, which is conserved by the building designers (Oakley, 1961). In case of no rain, there is still certain amount of moisture always present in the air which is expressed by absolute humidity (AH) or RH. The *humidity* of air is an absolute expression of the moisture content or vapour pressure (CIBSE, 2015, p.1-3). RH is the ratio of vapour pressure to saturation vapour pressure at any given temperature. This element of climate is inversely associated with AT (Koenigsberger et al., 1973, Oakley, 1961, Galvin, 2016). Psychrometric chart is widely used to trace the relationship between the dry-bulb AT, RH and AH. The combined effects of all these elements of climate in different regions of the world result in different seasons in the tropics.

The climate can be classified in numerous ways. For instance, (Lippsmeier, 1969) divided the climatic zones as subtropics, hot humid, monsoon, savannah and hot arid zones (Hyde, 2000). One of the widely accepted climate classification was initially developed by Vladimir Köppen in 1900, known as Köppen climate classification, based on soils and vegetation (Kottek et al., 2006). The modified and most recent version is recognised as 'Köppen-Geiger climate classification'. Figures 2-2 and 2-3 show the climate maps highlighting the tropics and location of Bangladesh. As stated by Triantafyllou and Tsonis (1994), the main drawback of this map is that it does not consider RH and is only based on monthly average rainfalls and AT.

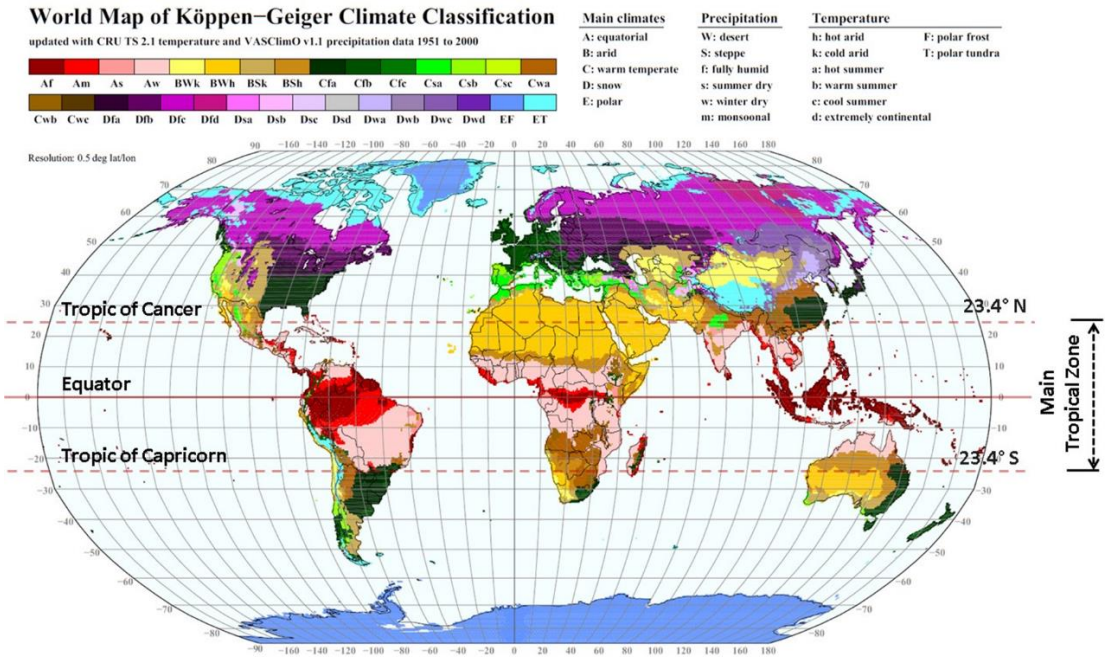


Figure 2-2: World map showing Köppen-Geiger climate classification (source: Kottek et al. 2006, p. 261, edited by the author)

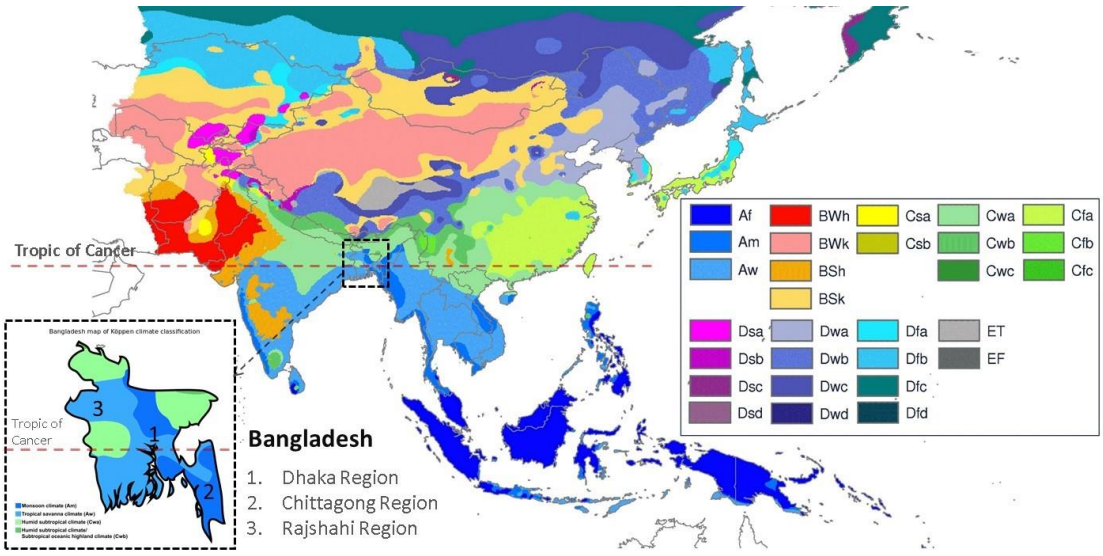


Figure 2-3: Location of Bangladesh in Köppen-Geiger climate map (source: Peel et al. 2007, p. 1639, edited by the author)

Since the thermal performance of a building actually deals with users' thermal comfort and response to climate, Szokolay (1991) introduced useful categories of tropical climate. They are hot dry, hot humid, moderate and cool. These characteristics are reflected throughout the seasonal and annual variations and widely accepted by building designers (Galvin, 2016, Maxwell and Drew, 1964, Koenigsberger et al., 1973).

Climate has the direct impact on the micro-climate of a building site. The geographic location defines the major climatic elements, such as solar radiation and prevailing wind, and thus determines how a building is going to respond throughout a year (Koch-nielsen, 2002, Oakley, 1961). The second affected part is the building envelope under which the design parameters and environmental strategies are directly related.

2.4.2. Climate in context of Bangladesh

While considering the climate of Bangladesh, analysis of meteorological data of the capital region named Dhaka shows that the prevailing outdoor AT varies between 12.3°C and 33.7°C at different times of a year. The whole year can be categorised into three climatic seasons as indicated in Table 2-2 and Figure 2-4(a). These are hot-dry, warm-humid (monsoon and post-monsoon) and cool-dry seasons with average ATs of 28.1°C, 28.8°C/26.6°C and 19.9°C respectively. The RH is relatively high with mean RHs of 79.2%/73.7% during the warm-humid season.

Table 2-2: Climatic characteristics for different seasons in Bangladesh (source: meteorological data of Dhaka- year 2013)

Climatic seasons		Months	Climatic characteristics*			
			Air Temperature (°C)	Relative Humidity (%)	Solar Radiation (Rad)	Wind speed (km/h)
Hot-dry		Mar-May	33.7 (max), 20.4 (min), 28.08 (avg)	64.8 (mean)	234 (avg)	5.2 (avg)
Warm-humid	Monsoon	Jun-Sep	32.1 (max), 25.9 (min), 28.8 (avg)	79.2 (mean)	177 (avg)	2.9 (avg)
	Post Monsoon	Oct-Nov	31.6 (max), 19.2 (min), 26.6 (avg)	73.7 (mean)	172 (avg)	1.3 (avg)
Cool-dry		Dec-Feb	28.1 (max), 12.9 (min), 19.9 (avg)	62.3 (mean)	166 (avg)	2.6 (avg)

** Here, max: maximum, min: minimum and avg: average*

Figure 2-4(b) presents daily climatic parameters for a representative day in each of the seasons. The data shows that prevailing outdoor AT and solar radiation rises to its maximum during the occupied hours (usually 08:00-19:00) of the RMG factories and there is a diurnal variation of around 14°C and 15°C, during hot dry and cool dry

seasons respectively. During warm humid season, especially during monsoon period (Table 2-2), the diurnal range is relatively low (around 6°C). These major differences of AT along with other variables should be in consideration while considering the thermal environment and design strategies suitable for RMG factories in Bangladesh. Further key design considerations for micro-climate conditions in context of Bangladesh are explained in Sections 6.4, 7.3, 8.3 and 9.3.

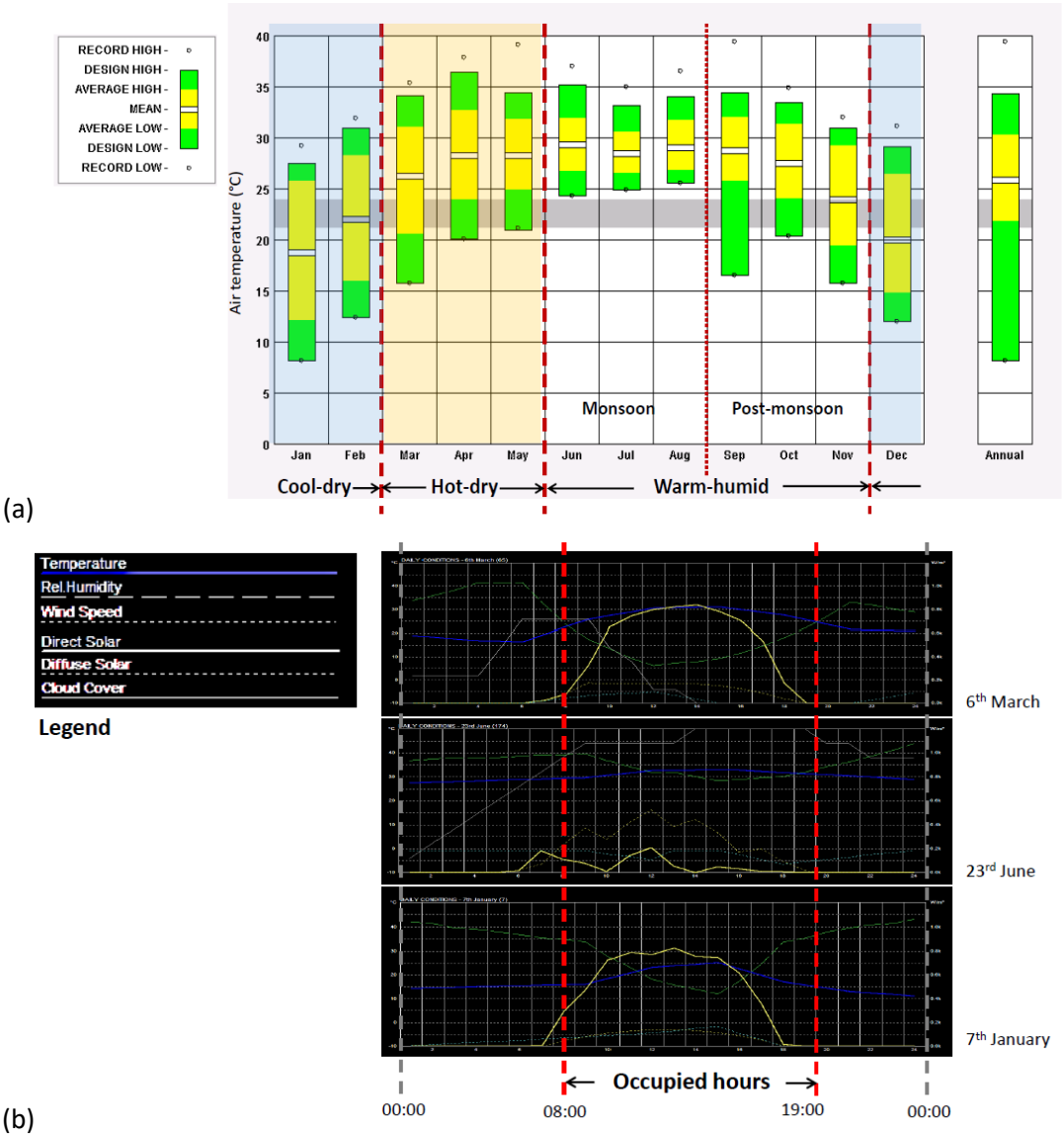


Figure 2-4: a) Annual AT profile with seasonal classification b) Climate data for representative days in each season (source: results from climate Consultant 4 and Autodesk weather tool 2011)

Since Bangladesh is located within the tropical zone, 22°-25° north from the equator (Figure 2-3) and has three distinct seasonal variations (i.e. hot-dry, warm-humid and cool-dry) (Figure 2-4), it is reasonable to observe all the environmental strategies

concerning the tropical climatic zones and their aspects associated to seasonal distinctions (explained in Chapter 3).

2.5. Thermal Comfort and RMG Factories' Workspaces

2.5.1. Factors affecting physiological thermal comfort

Thermal environments can be determined based on three broad groups, i.e. thermal comfort, thermal discomfort and thermal stress, which are all related to occupants' thermal perceptions and experiences (Race, 2006). Since thermal comfort is considered as the criterion to determine the thermal performance of a building (Wyon, 1974), it is important to understand the comfort guidelines for the occupants required for this study. In so doing, the designers can adopt certain strategies to make sure the indoor environment is comfortable for the occupants. Hence this section will provide an insight into the human thermal comfort and assessment process in context of tropical climate conditions.

The definition of thermal comfort can be derived from ASHRAE standard 55 and it is *"that condition of mind that expresses satisfaction with the thermal environment"* (ASHRAE, 2013). It is a person's sensation of warmth which, in other way, also called an absence of discomfort (CIBSE, 2015, Race, 2006). When a thermal environment potentially cause harmful medical situations, such as, dehydration, respiratory problem, hyperthermia or even fatalities, to the occupants due to high temperature, thermal stress is also a way of evaluating the environment (Race, 2006).

Among a range of previous research on determining human thermal comfort of human, Aulicems and Szokolay (2007) highlighted the 'heat balance model' and 'adaptive comfort model' as the two widely accepted methods. Both models consider a number of parameters that affect the thermal experience of the occupants within a building with an aim to find acceptability range of thermal comfort (de Dear and Brager, 2002, Brager and de Dear, 1998). Therefore, the thermal comfort ranges with suitable models (explained in Sections 2.5.1.1 and 2.5.1.2) need to be studied while considering to improve an existing thermal environment or designing a new one for a certain functional space. Particularly, for RMG factory building, it is important to establish the acceptable thermal comfort range for the production workers.

2.5.1.1. Heat Balance model

This model considers the heat exchange of the human body. It is also known as closed climate chamber method which involves measuring thermal perception of subjects placing them into a constant thermal environment. Numerous amount of models, such as Ole Fanger's Predicted mean vote index (PMV), Effective temperature (ET) scale and other studies before ASHRAE 55 guide, were developed based on this method. The heat exchange of body was followed by the recent PMV model. The human body continuously produces heat due to its metabolic process. This heat needs to be dissipated to the environment to maintain the core body temperature of 37°C while the skin temperature range can be 31-34°C. This heat exchange process can be depicted by the Figure 2-5 and Equation 2-1 (Szokolay, 2008, p.17).

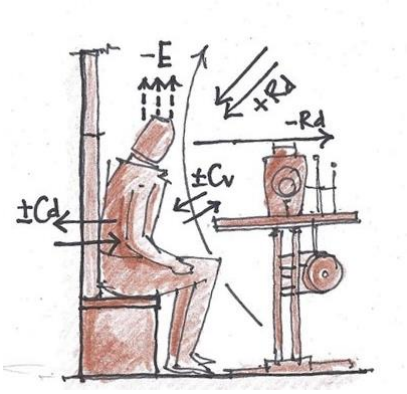


Figure 2-5: Human thermoregulatory system within an environment (source: author)

$$M \pm Rd \pm Cv \pm Cd - Ev = \Delta S_h$$

Equation 2-1

Where,

ΔS_h = change in stored heat of body

M = metabolic heat production

Rd = net radiation exchange

Cv = convection (with respiration)

Cd = conduction

Ev = evaporation (with respiration)

Table 2-3 illustrates the three group of variables that affect heat exchange process of human body, thus thermal comfort of occupants. In a workspace, thermal

environment mainly defined as function of four physical variables (i.e. AT, MRT, AV and RH) and two personal factors (i.e. activity level and clothing) (Frontczak and Wargocki, 2011, Gossauer and Wagner, 2007, Alwetaishi, 2016).

Table 2-3: Factor affecting thermal comfort (Szokolay 2008, p.17)

Environmental	Personal	Contributing factors
Air Temperature	Metabolic rate (or activity)	Food and drink
Humidity	Clothing	Body shape
Air movement	State of health	Subcutaneous fat
Radiation	Acclimatization	Gender and Age

Based on the Equation 2-1, PMV of the occupants on a given condition was predicted by another complex equation which mainly takes into accounts the factors, such as, clothing factor, clothing insulation, convective heat transfer coefficient, metabolic rate, vapour pressure of air, clothing thermal insulation, external work load, AT and air velocity (Aulicems and Szokolay, 2007, p.35). In a simple term, as a steady state model, PMV combines the effect of AT, humidity, Mean Radiant Temperature (MRT) and air movement along with activity level and clothing into single value on a thermal sensation scale (CIBSE, 2015, p.1-8). Table 2-4 shows the examples of various sensation and preference scales developed to evaluate thermal comfort based on this model.

Table 2-4: Popular scales to calculate (a) subjective warmth and (b) thermal preference (source: ASHRAE, 2010, as cited in CIBSE, 2015, p.1-4)

Index value	Thermal sensation and preference			
	(a) Subjective warmth scales		(b) Thermal preference scales	
	ASHRAE	**Bedford**	**Nicol**	**McIntyre**
	How do you feel just now?		*I would prefer to be:*	
+3	Hot	Much too warm	-	-
+2	Warm	Too warm	-	Much cooler
+1	Slightly warm	Comfortably warm	Cooler	Cooler
0	Neutral	Comfortable	No change	No change
-1	Slightly cool	Comfortably cool	Warmer	Warmer
-2	Cool	Too cool	-	Much warmer
-3	Cold	Much too cool	-	-

When it is concerned about ventilation, air quality becomes also an indirect but important factor for occupants. Smell and sensitivity to irritants are two ways that

people tend to evaluate the quality of air (Race, 2006). It is usually estimated by using the widely accepted 'seven point Bedford scale' (Wong and Khoo, 2003, Race, 2006).

As a function of PMV, Predicted Percentage Dissatisfied (PPD) is another criterion that estimate the percentage of a large group of occupants dissatisfied within the same given thermal environment. It is recommended to keep the percentage below 10% of a space (Figure 2-6) to ensure thermal comfort (CIBSE, 2015, p.1-9).

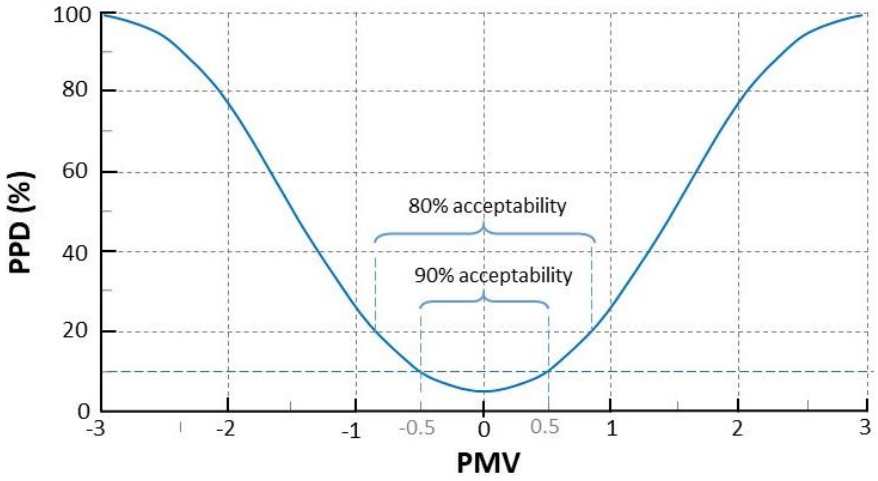


Figure 2-6: Relation among PMV, PPD and thermal acceptability (source: Alwetaishi, 2016, p.930, newly drawn by the author)

Rijal et al. (2002) suggested that the environment should be acceptable as comfortable to 80%-90% of the occupants. It should be around the central three scales (vote -1, 0 and +1) of ASHREA seven-point TSV scales (-3 to +3) (Figure 2-6).

2.5.1.2. Adaptive comfort model

'Adaptive' can be referred as the gradual reduction of occupants' response to repetitive environmental conditions along with all the experience the occupants go through to cope with the environment around an individual and a group (Brager and de Dear, 1998). The basis of the adaptive comfort model is field studies on human thermal comfort. The results of this model defers from that of closed chamber studies and establishes the greater tolerance of temperature changes by the occupants. Temperature changes affect the body heat balance. This adjustment involves additional behaviour to gain comfort, change in the metabolic heat production and adjusting the thermal environment for a certain extend (Alwetaishi, 2016).

Adaptive model support the concept that comfort depends on the state of mind of the occupant and influence by many other factors not considered by PMV model (Fountain et al., 1996). Three modes of adaptation are considered for adaptive thermal comfort model (Prosser, 1958, Brager and de Dear, 1998) and they are behavioural adjustments, physiological adaptation (acclimatisation) and psychological. Hence, through this model, a wider comfort range may be achieved compared to comfort temperature predicted by ASHRAE. However, if the indoor AT deviations exceeds 10°C due to seasonal variations, parts of the occupants are expected not to adapt with the environment in extreme seasonal variations (Humphreys et al., 2007).

2.5.1.3. Applicable comfort model

A Previous study shows that comfort studies in the field provide variations in temperature preference, whereas the studies based on 'comfort chambers' provide similar range of preference (Humphreys et al., 2007). This study suggests that comfort is context dependent. For instance, it was also found that occupants from warm-humid regions have higher thermal tolerance due to acclimatisation to high level of humidity and temperature (Mallick, 1996). Therefore, PMV method, based on which several international standards, such as ASHRAE design standard, established, did not represent the comfort conditions of occupants in the tropical climates with various seasonal changes (Brager and de Dear, 1998).

On the other hand, adaptive approach provides more precise estimation of thermal comfort range for the occupants of passive buildings (Orosa and Oliveira, 2011). It supports the concept of Neutral Temperature (NT) which is directly related to mean outdoor temperature (Szokolay, 2008, Nicol and Humphreys, 2002, de Dear et al., 1997). There are a number of equations provided by the pervious researchers where comfort temperature is as a function of outdoor air temperature. However, the shortcoming of these equations is the too much dependence on outdoor AT ignoring some of the important variables, such as radiant temperature, of PMV model (Halawa et al., 2014). A number of comfort studies in context of South Asia and Bangladesh established the usefulness of utilising Operative Temperature (OT) as a criterion, which combines the effect of AT and MRT and expresses into a single value (in °C) to estimate NT and preferred comfort range of occupants (CIBSE, 2015, Indraganti et al., 2014,

Shajahan and Ahmed, 2016). Mallick (1996) showed that increasing fan-speed setting and thus increasing air speed from 0 to 0.45 m/s could extend the mean comfort temperature from 28.9°C to 31.6°C in Bangladesh. Hence, AV is also required to be evaluated for any space as a part of comfort study. Further elaborations with relevant equations can be found in Section 5.5.8.

To sum up, where PMV method tends to provide narrow comfort ranges, adaptive method actually consider occupants' adaptive capacities to cope with wider range of thermal comfort respecting the seasonal changes. Adaptive thermal comfort model is certainly a better approach, however it recommends field studies based on person-environment system approach (de Dear, 2004, Humphreys et al., 2007, Nicol, 2004, Ferrari and Zanotto, 2012, Chang, 2016). Previous study suggests that PMV model is useful for preliminary prediction of thermal comfort of occupants. However, field studies are more reliable within the diversity of environments to determine the NT and comfort ranges corresponding to adaptive model before inclusion in relevant standards (Nicol and Humphreys, 2002).

2.5.2. Thermal comfort for factory workers

As mentioned in the previous section, thermal comfort criteria usually reflect the personal factors and a number of indoor environmental parameters including AT, RH, AV, GT, MRT, Effective temperature (ET) or Standard Effective Temperature (SET) and OT (Section 5.5.8).

For RMG factories, the personal factors, such as metabolic rate (Met value) and clothing (Clo) values can also be defined based on the type of activities within the workspaces. Mallick (1996) showed that Clo value varies between 0.35 and 0.5 for the common cloths of light summer in the tropical climate of Bangladesh. As illustrated in Table 2-5, 1.8 and 1.7 were estimated as met values for fabric cutting and stamping respectively, while 1.4 was estimated for bias cutting, sewing and button sewing activities (Gouvêa et al., 2006, p.5). 1.0 and 1.2 are likely met values for seated and standing workers respectively (Butera, 1998, p.41).

Table 2-5: Met values for various activities of workers (source: Gouvea et al 2006 and Butera 1998)

Activity	Met value*	Activity	Met value*
Fabric cutting	1.8	Button sewing	1.4
Stamping	1.7	Packing	1.4
Bias cutting	1.4	Resting (Seated)	1.0
Sewing	1.4	Standing	1.2

**Here, heat generation Met is 58.2Wm^{-2}*

A number of research in context of tropical climate proposed environmental parameters usually expressed in terms of thermal comfort range and neutral temperature. Table 2-6 shows the summary of the suggested neutral temperature and thermal comfort ranges found previous studies in tropical climate.

Within the limited number of studies on RMG factories, Fatemi (2014) has proposed a thermal comfort target for the warm-humid season of the Dhaka region. According to his study, workers can feel comfortable when subject to an AT between 28.5-33.0°C and RH between 56-72%, if the air speed can be maintained between 0.8-1.5 m/s. These AT and air speed ranges are higher than that assumed in Olgyay's comfort zone. If the air speed is less than 0.8 m/s, the comfort temperature needs to be reduced below 28.5°C and increasing the air speed perceptibly improves the thermal comfort condition (Fatemi, 2014, Humphreys, 1970). Chowdhury et al. (2015) in their study on RMG factories in the Dhaka region recommended 24-28°C as a minimum AT range when RH is below 65% and a mean air speed of is maintained. Based on laboratory (climate chamber) experiment, 25.6°C was found to be most appropriate AT for only sewing activity (Chowdhury et al., 2017a).

Table 2-6: Summary of studies on thermal comfort and key findings in tropical region

Region		Reference	Research methods	Thermal comfort threshold values		
				Neutral Temperature	Comfort Range	Air speed
Bangladesh	Dhaka (or Japan)	(Chowdhury et al., 2017a)	Laboratory experiment	25.6°C	25 - 26°C (RH: 60 ± 5%)	0.23 - 0.3 m/s
	Dhaka	(Tariq, 2014)	Field survey	30.20°C	29.89 - 30.54°C	-
	Dhaka	(Shajahan, 2012)	Field survey	31.5°C	29 -34°C	0
	Dhaka region	(Fatemi, 2012)	Field survey	-	28.5 - 33°C	0.8 - 1.5 m/s
	Dhaka	(Mallick, 1996)	Field survey	-	24 - 32°C	0
	Dhaka	(Ahmed, 1987)	Field survey	-	23.1 -28.6°C	-
Other countries	Singapore	(Wong et al., 2016)	Field survey	-	-	<1.6 m/s to avoid draughts
	North-East India	(Singh et al., 2010)	Field survey	27.1°C	> 29.1°C	-
	Hyderabad, India	(Indraganti, 2010)	Field survey	29.23°C (OT)	26 - 32.45°C	-
	Malaysia	(Ismail et al., 2009)	Field survey	-	>28°C 50-60% (RH)	-
	Colombo, Sri Lanka	(Wijewardane and Jayasinghe, 2008)	Field survey	26.0°C	> 29.5°C	0
	South China	(Yang and Zhang, 2008)	Field survey	28.3°C (OT)	25.0 - 31.6°C	
	Brazil	(Gouvêa et al., 2006)	Field survey	22.5°C (OT)	-	-
	Singapore	(Wong and Khoo, 2003)	Field survey	28.8°C (OT)	-	-
	Thailand	(Khedari et al., 2000)	Controlled field survey	-	26 - 36°C (RH: 50-80%)	0.2-0.3 m/s
	Jakarta, Indonesia	(Karyono, 1995)	Field survey	26.4°C (AT) 26.7°C (OT)	23.3 - 29.5°C (AT) 23.3 - 29.9°C (OT)	-
	Bangkok, Thailand	(Busch, 1992)	Field survey	28.5°C (ET)	-	-
	Singapore	(de Dear et al., 1991)	Climate chamber	28.5°C	-	-
	Roorkee, India	(Sharma and Ali, 1986)	Field survey	-	21°C - 30°C	-
	Singapore	(Ellis, 1953)	Field survey	26.2°C (ET)	-	-

A number of other research studies have investigated thermal comfort in industrial and other types of building in the tropics. For instance, Khedari et al. (2000) established a ventilation comfort chart for the warm humid climatic context of Thailand. The study recommended that an air speed between 0.2-3.0m/s is maintained if the indoor AT and RH varies within the ranges of 26-36°C and 50-80%. Their study observed that the air speed may need to exceed 3m/s by increasing the ventilation flow rate, if the AT increases above 34°C. However, to avoid disturbance due to noise level from fans, the air speed is to be maximum 3m/s. Moreover, these recommendations need to be set

against other considerations, for example for industrial buildings in the tropics, the air speed is to be below 1.6m/s to avoid discomfort due to draughts (Wong et al., 2016). Matthews and Nicol. (1995) indicated the optimum AT comfort temperature target can be set as low as 26.1°C if the indoor mean GT climbs as high as 32.52°C in textile factories during the hot-dry season in northern India. Chowdhury et al. (2017b) predicted the heat stress experienced by Bangladeshi RMG workers over the course of a full year. Their results revealed that the Wet Bulb Globe Temperature (WBGT) and Predicted Heat Strain (PHS) exceeded the standard comfort range during the months of May-August. Taken as a whole, these studies indicate the significant impact of ventilation in improving the thermal comfort and reducing the heat stress of RMG workers by enhancing air speed.

Kang and Lee (2008) revealed that windows with proper louvres can control the air flow direction and contribute to improving the thermal comfort of factory workspaces. Because of AV profile within the workspace is an essential contributor to the thermal comfort of RMG workers, it will form an important component of the investigations. Based on the above studies, this research should include a preliminary assessment of thermal comfort condition of RMG factories' workspaces and should follow the criteria (assumed comfort ranges) shown in Table 2-7**.**

Table 2-7: Preliminary assessment criteria for thermal comfort of RMG factories

Parameter	Preliminary Assessment criteria
Comfort range (AT and RH)	The indoor environment will be evaluated targeting an AT range of 24-28.5°C as general thermal comfort band for all climatic seasons where the average air speed is assumed below 0.2m/s. It will also be evaluated over a moderate AT range of 28.5-33°C for all climatic seasons where the average AV is assumed above 0.2 m/s. In both cases, acceptable RH is below 65%.
Air speed	Preferable air speed range will be considered as 0.8-1.5 m/s to evaluate only the air circulation profile within a workspace.

Other literature review suggest that there is a lack of field survey based thermal comfort studies in terms of integrating them into real building design and practice (Rupp et al., 2015, Ferrari and Zanotto, 2012). In particular, above literature reviews recommends a need for conducting new comfort studies within existing RMG factories

to evaluate the thermal comfort neutrality and preferred comfort ranges of RMG factory workers for cutting, sewing and finishing activities to use it for architectural design in Bangladesh. Moreover, Table 2-6 also indicates the lacking of thermal comfort studies in various climatic seasons of Bangladesh. Chapter 10 will address this knowledge gap through a statistical analysis of field data.

2.6. Thermal Performance Aspects of RMG Factory Buildings

After knowing about the climatic context and indoor thermal comfort requirements. It is essential to consider a number of climate adjustment strategies for designing a climate responsive building and moderating the indoor environment for occupants' thermal comfort. Where it is concerned about the tropical climate, designers usually consider passive design strategies (explained in Chapter 3). Before that, it is important to understand the thermal behaviour of building to apply the design strategies.

2.6.1. Thermal performance of a built environment

Flow of heat within a building, from zone of higher temperature to that of lower temperature, is occurred in three different ways within the materials and built environment. They are conduction, convection and radiation (CIBSE, 2015, p.3-4, Szokolay, 2008, p.8). *Conduction* occurs by the movement of molecular substance with a body or bodies, such as the building materials. *Conductivity* is the widely known property of the material, measured as the heat flow density (W/m K) (Szokolay, 2008, p.9). *Convection* is defined as the flow of heat by the movement of fluid, for example, air or liquid, and can be occurred between gaseous material to solid body or vice versa (Szokolay, 2008, p.9, CIBSE, 2015, p.3-4). It depends on the area of contact, temperature different between surface of the solid body and fluid and *convection coefficient* (measured unit is W/m^2 K). On the other hand, thermal *radiation* occurs from an emitting body of warmer surface to another cooler surface through a certain range of wavelengths. Reflectance, absorbance and emittance of the emitting and receiving surfaces determine the radiation process.

The building can be considered as thermal system with a sequence of input and output, similar to heat balance system of a human body (Section 2.5.1.1). It can be shown in a

notional building with the Figure 2-7 and can be expressed by the Equation 2-2 (Szokolay, 2008, p.35).

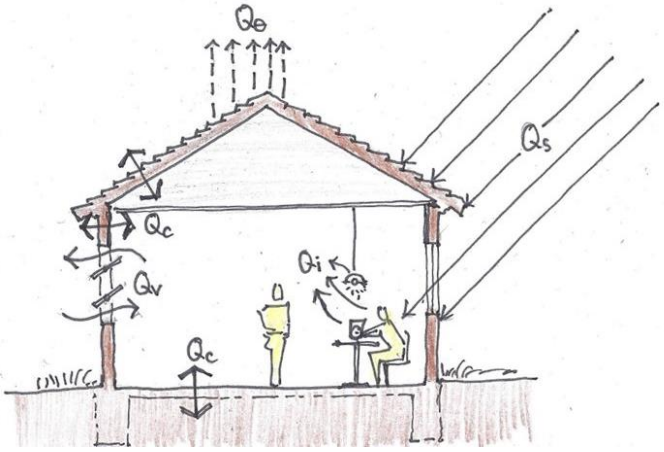


Figure 2-7: Thermal behaviour of a building (source: author)

$$\mathrm{Qi} + \mathrm{Qc} + \mathrm{Qs} + \mathrm{Qv} + \mathrm{Qe} = \Delta \mathrm{S}_b$$

Equation 2-2

Here, ΔS_b = change in heat stored in the building

Qi = internal heat gain

Qc = conduction heat gain or loss

Qs = solar heat gain

Qv = ventilation heat gain or loss

Qe = evaporative heat loss.

When the sum of all heat flow is zero, thermal balance of the building occurs. The indoor temperature will increase, if the sum is greater than zero. The building will cool down, if the sum is less than zero. By adopting appropriate design strategies (explained in Chapter 3. the heat flow can be controlled or moderated in the tropical climate targeting the design indoor condition for occupants' comfort.

Thermal performance of a built environment, hence, depends on the regulating factors of the building and the surrounding context. The key factors include the location of the site, morphological context, micro-climate conditions with the daily and seasonal variations, function of the building, building envelop and most importantly the comfort criteria for the occupants of the building (Hyde, 2000).

When it is about controlling external heat from the sun, building orientation and shape are the first design parameters to be considered (Bainbridge and Haggard, 2011). For instance, if an east-west elongated rectangular building in context of Dhaka, Bangladesh, is considered, east, west and south facades of the building are exposed to the sun for a longer period of the year, particularly during winter solstice, while north façade is not exposed to sun any time of the year (Figure 2-8). However, during winter the solar radiation from the south side may be desirable while building needs to be protected from rest of the year.

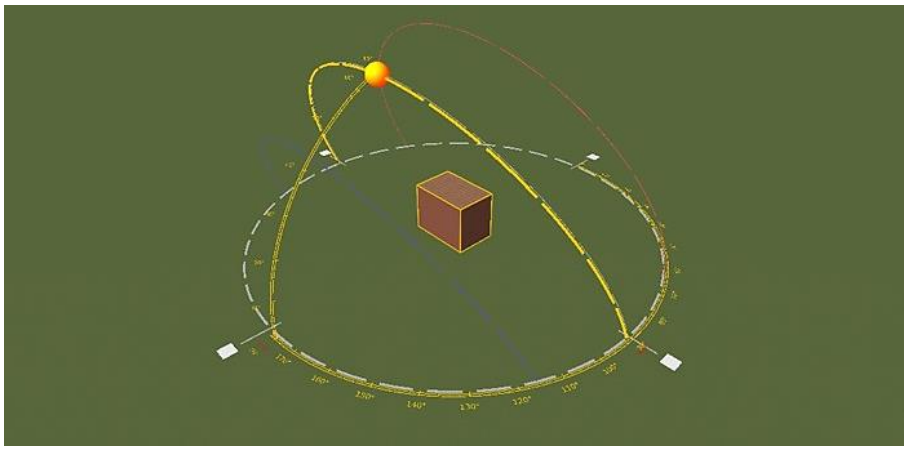


Figure 2-8: Sun path diagram over a rectangular building in context of Dhaka (source: author)

Building orientation and shape also determines the wind pattern across the building in a specific site context (Givoni, 1994). In addition to direct wind, natural air movement though a building can be achieved though pressure difference between inside and outside of the building, even in an urban context (Santamouris, 2005). Hyde (2000) suggested that increasing air movement and controlling the external heat in warm seasons of tropical climate depend on the careful design of the building envelope.

Table 2-8 shows a number of key design strategies and parameters for optimising the thermal performance of a building in the tropics. Aflaki et al. (2015) showed that ventilation shafts, window-to-wall ratio (WWR) and building orientation are the effective design parameters to utilised both stack and wind driven ventilation and improve thermal comfort for occupants in the tropics. In particular, window configurations and indoor segmentations plays a significant role in optimising the indoor thermal performance (Prianto and Depecker, 2003). As a strategy of building cooling, increasing WWR can improve the ventilation rate of a building, however also

increase the exposure to the solar heat (Liping and Hien, 2007). Mallick (1996) referred that thermal mass, building orientation and air flow through windows are direct effect on thermal comfort of occupants in context of Bangladesh.

Table 2-8: Key design strategies and elements for optimising thermal performance of a building (source: Aflaki et al 2015, Prianto and Depecker 2003, Hyde 2000)

Controlling from heat gains		**Provision of cooling**	
Strategies	**Architectural design parameters**	**Strategies**	**Architectural design parameters**
i) Controlling direct solar radiation	- Surrounding buildings - Building orientation - Form and shape of the building - Window configuration and location - Shading design and balcony - Internal divisions (Partitions, floor and ceiling) - External walls - Roof and facade material - Occupancy and functional layout	i) Flow of air (wind and stack induced)	- Surrounding buildings - Building orientation - Functional layout and segments - Window aperture/size and location - Shading location and Louver angle - Construction material (thermal mass) - Integrated mechanical ventilation
ii) Control of conduction heat gain		ii) Utilising night ventilation and thermal mass	
iii) Control of internal heat gain		iii) Evaporative cooling	
iv) Prevention of ventilation and infiltration gain		iv) Mechanical dehumidification	

Further review on these design parameters are presented in Chapter 3.

2.6.2. Thermal performance studies on factories

There is a limited number of empirical research on thermal performance aspects of factory buildings in the tropics. Table 2-9 highlights the key findings of these research. The studies considered both single and multi-storey factory buildings. A few studies indicated that the common shape of multi-storied RMG factories in Bangladesh is rectangular or 'shoe box' (Naz, 2008, Hossain, 2011, Fatemi, 2012) where building envelope play an important role for thermal performance. The key building envelopes that can be considered particularly for RMG factories include openings, external walls and roof (Chowdhury et al., 2015). Chowdhury et al. (2015) also showed that the external walls and roof with various thickness and materials make significant impact on indoor AT fluctuations within workspaces.

Table 2-9: Summary of research on thermal performance and design strategies of factory buildings

Research topic	Reference	Research method	Key learning
Effect of two type of roofs on thermal performance	(Chowdhury et al., 2017c)	Simulation study	A green roof construction can create 2.5-3.5°C lower indoor AT than a non-green roof of a RMG factory during summer in Bangladesh.
Indoor environmental quality of Green Buildings	(Ravindu et al., 2015)	Field study (case studies)	Thermal comfort, ventilation, and ability to control indoor environment of the green factory were comparatively less satisfactory in Sri Lanka. Energy-saving features may be cause of poor thermal performance.
Thermal performance of Building envelope of RMG factory	(Chowdhury et al., 2015)	Laboratory and simulation study	Fluctuation of indoor AT in upper floors is relatively higher, 3.8 ◦C to 7.6 ◦C, than that of lower floors within a RMG factory in Bangladesh.
Existing Indoor thermal condition	(Khan et al., 2011)	Field study (case studies)	Indoor AT of case study factories is always higher than outdoor AT (day and night time) in Bangladesh
Effect of naturally ventilated (NV) cavity roof	(Susanti et al., 2011)	Numerical simulation study	This type of roof may improve indoor thermal environment of factories without complicated installations.
Effect of energy efficient design approach on thermal performance	(Chowdhury and Alam, 2011)	Simulation study	Increasing the opening ratio on roof for enhanced daylight can cause negative effect on indoor AT in a RMG factory of Bangladesh.
Effect of Louver ventilator on natural ventilation	(Kang and Lee, 2008)	Laboratory and simulation study	Aligning the outer louver blades with the approaching wind can guide ventilation and increase the air flow rate in a factory building.
Reduction of heat gain by roof cavity	(Susanti et al., 2008)	Laboratory experiment	Roof cavity can induce natural air flow and protect factory from solar heat gain. However, air flow also influenced by the opening size in the cavity.
Energy efficient design approach	(Naz, 2008)	Field and simulation study	Hollow core floor slab can maintain a stable indoor AT (25-30°C) which is significantly lower compared to that with the traditional construction material within the SS of RMG factory in Bangladesh.

These empirical studies demonstrated the effect of various material of the external wall, floor and roof, which are directly associated with reducing solar heat gain (Table 2-8), on indoor thermal performance of factory buildings. However, they lack studies

on ventilation strategies and relevant design parameters, such as window and passive vents, integrated mechanical or hybrid ventilation and viability of these features in context of RMG factories in Bangladesh. Chapter 3 will explain further regarding these features.

2.7. Codes and Building Regulations on Thermal Performance

Thermal performance aspect takes a significant part within the 'code of conducts' that are maintained by the RMG factories as a prerequisite compliance set by the international buyers (clothing brands) (Haider, 2007). The 'code of conducts' include International Labour Organization (ILO) core labour standards, Employment conditions, Occupational health and safety (OHS) and other regulations. The compliance of workplaces' thermal environment falls under the category of OHS which are always being improved following the existing standards and legislations (Baral, 2010). However, many of these standards are not usually contextualised and are not viable in context of Bangladesh (Hossain, 2011, Ahmed, 2011, Haider, 2007).

Table 2-10 illustrates the summary of existing building regulations regarding thermal performance aspect of RMG workspaces. All these regulations lack specific guidelines for thermal comfort and design strategies for RMG factories in Bangladesh. Even some of the existing standards may not be viable for all archetype of factories. For instance, the local building regulations the 'Bangladesh National Building Code 2006' only describes the relationship between the 'opening area' and 'floor area' for naturally ventilated (NV) buildings which may not applicable to buildings with wide floor plates with forced ventilations.

Table 2-10: Summary of building regulations on thermal performance aspects

Local Regulations	Reference	Existing guidelines related to thermal performance aspects		
		Thermal comfort and ventilation	**Environmental design parameters**	**Comments**
Bangladesh National Building Code	(Islam and Hossain, 2013, HBRI & BSTI., 2006, part.4, HBRI, 2015, p.8-114)	• For air conditioned (AC) Building: 25-26°C (AT) 50-60% (RH) 1-2°C (AT swing) • ΔT < 5°C • Ventilation rate: 12.5 l/s per person (NV), 8-10 ACH or 17.5 l/s per person (Mechanically ventilated (MV or AC building).	• Window-to floor ratio (WFR) = 4:100 (NV building). • Vent-to-floor ratio = 1:75 (MV building). • Ceiling height ≥ 3.5m • MV shaft-width (minimum) = 1.5, 3, 4, 5 and 6.5m for buildings of 3, 4, 5, 6 and over 6.5 storeys respectively. • Setback between two elongated buildings = 0.5 x building height.	- No retrofitting strategies. - No guidelines on width of NV workspace and building.
Building construction regulations	(Ministry of Housing of Govt. of Bangladesh, 2008)	-	-	No specific environmental design guidelines.
Bangladesh Export Processing Zone (BEPZ) planning guideline	(BEPZA, 2009)	NV recommended	• Ceiling height ≤ 3m • WFR = 1:10	No other specific guidelines on thermal comfort.

The brief review of the existing relevant code and standards and the associated knowledge gaps are shown in Table 2-11. Ahmed (2011) undertook a study in context of Bangladesh and suggested that more research on garment factories' environment and energy efficiency with considering the local climatic context and the adaptive environment for local population are necessary to review and establish local code or standards.

Table 2-11: Summary of existing legislations on thermal performance aspects

Local Legislations and standards	Reference	Existing guidelines related to thermal performance aspects		
		Thermal comfort and ventilation	Environmental design parameters	Comments
International Labour Organization (ILO) Core Labour standards	(ILO, 1998, p.58, ILO, 2013)	- Natural cross ventilation - Air flow rate: of 8-12 l/s per person.	*Worker density:* 2m^2 per worker.	No other specific guidelines.
Bangladesh Factory Law 1965	(Chowdhury, 2003, ILO, 1965, p.7)	- Comfort range to be prescribed by the local government. - *Ventilation:* 10m^3/worker.	*Density:* 2.25m^2/worker *Volume of space*: 14m^3/worker Separating the space with high AT by insulation. - insulating the roofs by air space or double roof.	No other specific guidelines on thermal comfort.
Occupational Health and Safely (OHS) Code of Conduct	(Sarkar and Akter, 2008)	-	-	No specific guideline.
Employment Code of Conduct	(Kaufman et al., 2004, Lum, 2003)	-	-	No specific guideline.
The Bangladesh Factories Rules, 1979	(Chowdhury, 2003)	- Adequate ventilation for fresh air (to be prescribed by government). - AT for comfort and safety (not specified).	-	No specific guideline.
Bangladesh Labour Act 2006	(GoB, 2006)	Adequate ventilation and comfortable AT.	-	No specific guideline.

International standards from other countries were also reviewed. The guidelines from the UK and USA, i.e. CIBSE 2015, ASHRAE 55, were already indicated in Sections 2.5. CIBSE (2015) recommends comfort target of AT ranges for winter (19-21°C) and summer (23-26°C) which are more applicable to cold countries. Code for Environmental Sustainability of Buildings (Singapore) recommends OT range (24-26°C), RH (below 65%) and mean air speed (0.6m/s) (BCA, 2012, p.41). It also provides general guideline on U-value of facades (less than 2W/m^{2}K). No design guideline for naturally ventilated RMG factories was found. Indian Green Building Council (IGBC) has the rating system for factory buildings and point up to the value of 5 are provided if certain ranges of PMV values (within 0-1.8) are achieved inside an unconditioned workspace (IGBC, 2014, Council, 2009). No significant passive design guideline was found.

A number of joint collaborative projects are undergoing between Bangladesh and developed countries to improve the existing condition of RMG sector. The baseline surveys under this joint collaborative project, 'Alliance for Bangladesh Worker Safety', were conducted to assess and retrofit a number of existing RMG building in terms of fire and structural safety (Alliance for Bangladesh Worker Safety, 2016). However, indoor environmental condition is out of its framework. 'Accord on fire and building safety in Bangladesh' considers the issues on Worker-led health and safety (Raina and Jennings, 2013, Accord, 2013). However, workers' health is also affected by indoor thermal environment, lighting and acoustics which have not been included in the accord. Furthermore, the ongoing project that focuses on improving social and environmental standards in the textile industries still does not include thermal environment of RMG factories in the agenda (GIZ, 2017).

From the review of local building regulations focusing on thermal performance aspects, it can be generally observed that they lack design guidelines promoting climate responsive RMG factories and do not include any numerical data based on empirical evidence. This research, therefore, will consider the knowledge gap found in this section and gather empirical evidence accordingly.

2.8. Summary

Based on the literature review on RMG workspace environment, climate, thermal comfort, thermal performance aspects of factory building and regulations, this chapter provided an insight of the overall research context. Among a number of environmental aspects, thermal environment of RMG factories is taken into consideration for this research considering the significance of it on workers' health and comfort. Climate is the major challenge of Bangladesh, since the country is located within the tropical zone with its three types of seasonal variations over a year. Environmental design strategies should be adaptable enough to cope with the temporal variations of climate of Bangladesh as well as 'high temperature' issues for workers' physiological comfort.

Among the thermal comfort approaches, PMV method is useful for preliminary assessment of thermal performance of RMG factories. However, adaptive comfort model is also useful since it considers the impact of seasonal changes on human

acclimatisation with the outdoor climate. Previous studies on thermal comfort indicates the shortcoming of consistent design guidelines in various workspaces. A thermal comfort range were assumed for RMG factory based on the previous studies. However, further field investigations on RMG factory workers' thermal perception in difference climatic seasons of Bangladesh are also essential (presented in Chapter 10).

Literature reviews on thermal performance aspects of building regulations indicated the lack of research on passive design strategies for RMG factories and associate parameters. Similarly, regulatory frameworks also lack detail design guidelines on thermal comfort and environmental parameters, particularly for RMG factories.

The fundamental information and reviews on climate, thermal comfort, design strategies and other contents presented in this chapter will always be referred back in Chapters 2 - 11. Next chapter (Chapter 3) will focus on reviewing passive design strategies and architectural precedents as an extension of the Section 2.6 of this chapter.

CHAPTER 3. LITERATURE REVIEW: ENVIRONMENTAL DESIGN STRATEGIES

This chapter presents a literature review on passive design strategies to build a theoretical foundation for this research. The review also includes learning from architectural precedents to identify the passive strategies and the associated design parameters that were already applied within the workspaces in tropical zones. A list of applicable design strategies is outlined at the end of this chapter to be referred to in the next steps of the research.

CHAPTER 3. LITERATURE REVIEW: ENVIRONMENTAL DESIGN STRATEGIES

3.1. Introduction

The previous chapter provided a literature review on the workspace environment, climatic context, thermal comfort, and thermal performance aspects of RMG factory buildings. This chapter focuses on further reviewing the passive design strategies that are practised in the vernacular as well as contemporary workspaces and architecture in the tropics. Through a number of case studies, an insight is provided into the environmental strategies and related design parameters, such as the design elements achieving the passive ventilation and optimum thermal performance, proven to be the prime design solutions. These parameters will be considered as the potential design solutions for improving the existing RMG factories in Bangladesh.

3.2. Chapter Aim and Scope

The primary intention of this chapter is to review generic passive design strategies and their application within a range of selected case studies (i.e. buildings with workspaces), in the context of Bangladesh as well as other countries in tropical regions (as a continuation of Section 2.6). The literature reviews are sought to highlight a number of important design elements and strategies that may support the next steps of this research.

3.3. Climate Responsive Design and Passive Strategies

The cursory exploration of the concept of 'climate responsive design' concedes the significant relationship between designing building form and moderating indoor climate for users' comfort and well-being (Hyde, 2000). Beyond applying the law of thermodynamics to ensure climate responsiveness, the spectrum of thermal and visual delight are also sought by the architects (Hyde, 2000, Danby, 1963). Particularly in tropical climates, Hyde (2000) suggested that buildings can be designed in numerous ways to optimise the relationship between climate, site and users' thermal delight.

As defined by Krishan et al. (2001), passive design strategy is the way for designers to moderate or moderate the heat gains and provide a certain extend of cooling to a

building. By adopting these strategies in the design process, designers give building the provisions to naturally cope with the temporal varieties of seasons of the given climate (Szokolay, 2008). The primary climate adjustment strategies for moderate and hot humid climates, as stated by Hyde (2000), are the air flow, solar gain, thermal mass and evaporative cooling. However, there are more climate specific strategies and the major challenge is to integrate these strategies into the building and context.

Hyde (2000) emphasised on prioritising the strategies since the impacts of individual strategies may vary with respect to the site, micro-climate, building orientation and internal functional layout. Hence, the chapter will elaborate on both the generic design strategies, such as strategies to control of heat and provision of cooling to a notional building (Table 2-8), as well as the design strategies actually applied in a number of case study buildings (i.e. precedents) within the tropical regions, including Bangladesh.

3.4. Strategies for Controlling Heat Gains

High indoor temperature of indoor spaces due to heat gains is a major challenge during the warm seasons of tropical climate (Equation 2-2). The heat gain control strategies are considered to regulate the heat stored in the building (ΔS_b) and keep the AT of indoor spaces suitable for the occupants. The major sources of heat gains and the possible control strategies will be discussed in Sections 3.4.1 – 3.4.4.

3.4.1. Protection from direct solar radiation

For the period of year with high temperature, the building should be protected from incident solar radiation. By studying the sun-path diagram in reference with the building and site, the potential period can be determined when the sun should not be welcome (Szokolay, 2008). Through a geometrical calculation, shading devices can be designed to protect the glazing areas from direct radiations. It is less challenging to design shading devices for building facades with windows facing towards equator (e.g. south facade in case of Bangladesh). However, the angle of the sun from the east and west is relatively low, and a building is exposed to these sides over the year. Hence, the windows with glazing are usually avoided or enough buffer and vertical shading devices are provided to control the solar radiation.

3.4.2. Control of conduction heat gain

As referred by Koenigsberger et al. (1973) and Szokolay (2008), conduction heat gain depends on the heat flow rate through opaque building elements exposed to the sun or heat sources, such as, external wall or roof, of given area and the material properties and difference between sol-air temperature of the sun-lit surface and indoor AT. Sol-air temperature depend on the surface temperature of the exposed wall and outdoor AT. For example, the outdoor AT can be the same but the sol-air temperature of every facade of a building can be different due to different surface temperature. The equation can be depicted by the Equation 3-1.

$$Q_c = A_s \times U \times \Delta T$$

Equation 3-1

Here, Q_c = heat flow rate by conduction

A_s = surface area (m^2)

U = transmittance, u-value (W/m^2 K)

ΔT = temperature difference between indoor temperature and outdoor sol-air temperature (°C).

However, if the element of the building is transparent, e.g. windows, it is more likely to be considered as direct solar heat gain (as shown in Section 3.4.1) instead of conduction heat gain and is expressed by a different equation where the property of the glazing material as well as the fraction of incident solar radiation transmitted into a space are important determinants (Szokolay, 2008). While considering only conduction heat gain, the measures should be a careful selection of building materials focusing on the insulating properties and less exposed area of the element to the heat source such as the sun (Koenigsberger et al., 1973, Szokolay, 2008). It is desirable to provide building facades with minimum exposure to direct sun (Section 3.4.1).

In a given surface area, the next treatment should be the reduction of conductivity of the opaque element of the building by increasing the thickness of the element with layers or providing insulations within layers. However, location of the insulating materials also determines whether the building will act as lightweight or heavyweight

construction. As referred by Szokolay (2008), putting insulation towards inner surface of the heavyweight construction will lead the building acting like a lightweight construction (i.e. less thermal mass), while putting that towards outside will keep the similar thermal mass with less conductive heat gain. This treatment may be applicable to not only new buildings but also existing buildings.

3.4.3. Control of internal heat gains

Internal heat gains are defined as gains from the sources inside a built environment, for example, lighting, occupants, equipment etc., and the calculation of this kind of heat gain is made by multiplying each individual load by its running time (CIBSE, 2015, p.5-64, Szokolay, 2008). Internal heat gains can be controlled by moderating the occupancy and functional layouts. Segmentation of spaces is a way to isolate the overly heated equipment, such as fusing and ironing machine in a garment factory, from rest of the indoor spaces. Proving separate ventilation mechanism to flush out hot air separately, rather than spreading it, is one of the way of reduce indoor high temperature (Figure 3-1). Any equipment that uses energy in an indoor space tends to emit heat to the space. This heat emission can be reduced by choosing energy efficient equipment. For utilising the passive means, placement of the equipment near natural cross ventilation (explained later in Section 3.5.1) and otherwise, use of integrated mechanical extract fans next to the high heat generating equipment are possible measures to control internal gain within a space (Szokolay, 2008).

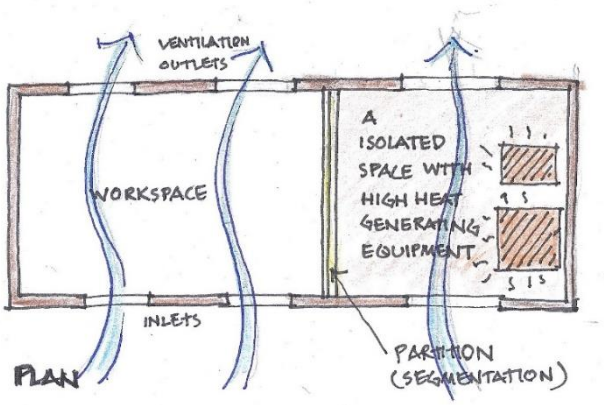


Figure 3-1: Internal heat gain and control strategy (source: author)

Rennie and Parand (1998) referred that electric lighting in a deep non-domestic building can be a serious reason of hot working environment. Daylight inclusion to the

space and reduction of electric lights to an efficient manner can also help to reduce indoor heat gain (Hossain and Ahmed, 2012, Hossain, 2011). For instance, reducing the number of lights, providing supplementary lights can potentially reduce the electric energy consumption as well as reduce heat emission inside the production spaces of garment factories (Hossain, 2011).

3.4.4. Prevention of ventilation and infiltration gain

Building façade treatment, window design, orientation of the windows in terms of exposure to direct outdoor wind, air-tightness of the opening and the operation schedule are associated with the ventilation heat flow (CIBSE, 2015). Building form and orientation can influence the ventilation flow by creating pressure difference between two building facades (Szokolay, 2008). Location of external building elements such as wing wall, vegetation, fences have effects on this.

Ventilation heat flow (Q_v) can be determined by the Equation 3-2 (Koenigsberger et al., 1973, p.76).

$$Q_v = 1300 \times q \times \Delta T$$

Equation 3-2

Here, q = ventilation rate (in m^3/s)

ΔT = difference between indoor and outdoor AT (K).

1300 = volumetric specific heat of air (J/m^3 K)

Ventilation flow rate (q) through an opening depends on the velocity of the air (v) and the opening area (A_o) and can be expressed by the Equation 3-3 (Szokolay, 2008, p.15).

$$q = v \times A_o$$

Equation 3-3

The number of times the total building volume is exchanged per hour is named as the Air Change per Hour (ACH). If the number of ACH can be known as N, the ventilation flow rate (q) in m^3/s can also be depicted by the Equation 3-4 (Szokolay, 2008, p.42).

$$q = \frac{N \times V}{3600}$$

Equation 3-4

Where, V is the volume of the building or room (in m^3) and 3600 is the number of seconds in an hour.

As referred by Szokolay (2008), supplying fresh air, flushing out indoor hot air while outdoor air is cooler than the indoor air and physiological cooling for occupants are main objectives of ventilation (explained in Section 3.5.1). For physiological cooling, Air Volume Flow Rate (AVFR) is related to the air velocity (m/s). Otherwise, if outdoor AT is greater than the indoor AT, ventilation and infiltration gain will occur (Figure 3-2).

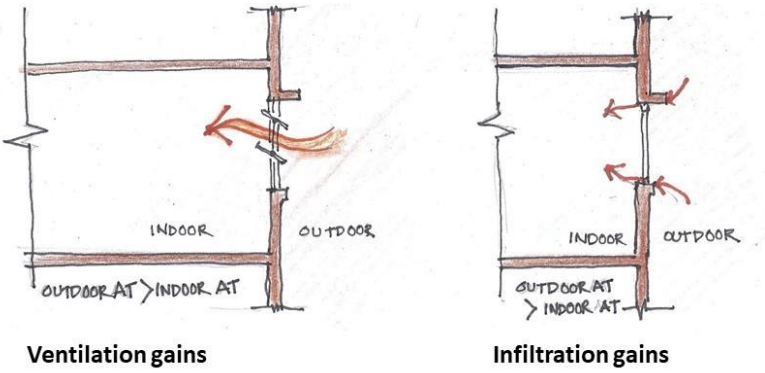


Figure 3-2: Ventilation and infiltration gain (source: author)

Window's effective opening area determine the air volume flow rate. The schedule of opening windows during the time when outdoor is hotter than inside can lead to ventilation gain.

3.5. Strategies for Cooling a Built Environment

In addition to heat gain control strategies, it is important to provide a building with sufficient provision of cooling to work against all the heat gains (Equation 2-2) and maintain the thermal balance within the building. This section provides an insight into a number of cooling strategies relevant to this research context.

3.5.1. Flow of air

Air flow strategy can be used for building cooling as well as physiological cooling (Hyde, 2000). By supplying cooler air from outside to indoor spaces, the cooling process of

indoor space of a building can be faster (CIBSE, 2015). In the tropics, physical comfort predominantly depends on sufficient provision of ventilation and 'comfort air flow' over the body of the occupants (Maxwell and Drew, 1964, Oakley, 1961).

As a major cooling technique throughout the world, ventilation is based on fundamental mode of convection where outdoor AT is lower than indoor AT (Santamouris and Ashimakopoulos, 1996, CIBSE, 2015). The major mechanisms of natural forces are pressure differences induced by wind and temperature gradients, known as stack effect (Figure 3-3) (Santamouris and Ashimakopoulos, 1996, Szokolay, 2008). When it is concerned about the natural wind effect, the pressure on the building depends on prevailing outdoor wind speed and its direction to the building and shape of the building (CIBSE, 2005). Mechanical forces, such as use of fan, can also generate pressure and air flow can be achieved.

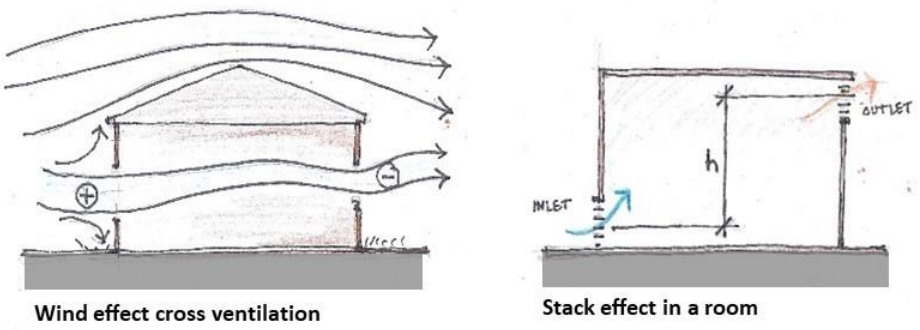
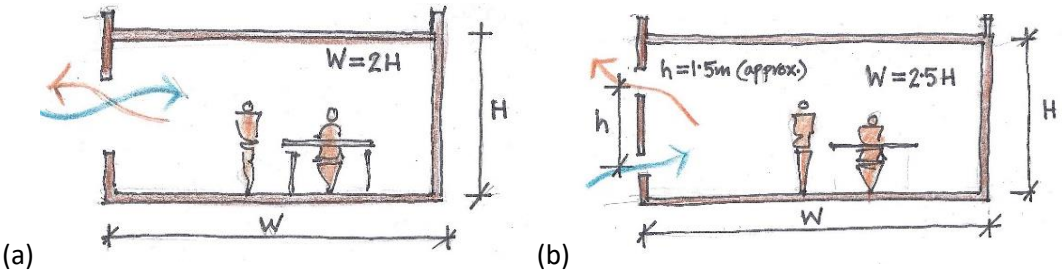


Figure 3-3: Ventilations induced by wind effect (cross ventilation) and stack effect (source: author)

It is important to be aware of the *rule of thumb* for determining the effectiveness natural ventilation. According the CIBSE (2005), ventilation can be initially categorized into single sided ventilation, cross ventilation and stack ventilation.

Single sided ventilation may be useful in cool season where wind turbulence works as natural force. In this case, the threshold width (W) of the space is twice of the floor-to-ceiling height (H) (Figure 3-4). If two openings are provided, stack effect takes place. The threshold width of the space is 2.5 times of the floor-to-ceiling height and separation between two openings should be minimum 1.5m (Figure 3-4) (CIBSE, 2005, p.15).



(a) (b)

Figure 3-4: Single sided ventilation with (a) single opening and (b) double opening (source: author)

During humid seasons of tropical climate, it is more desirable to provide cross ventilation. Openings are located in both side of a space where openings near windward and leeward sides (Figure 3-3) can be considered as inlets and outlets respectively (Oakley, 1961, CIBSE, 2015). Cross ventilation is usually a wind driven strategy and the threshold distance between the two building facades is 5 times the floor-to-ceiling height as the *rule of thumb*, as shown in Figure 3-5 (CIBSE, 2005, p.16).

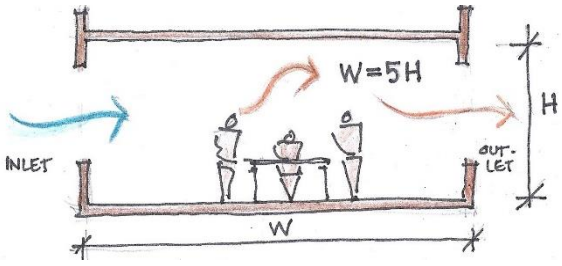
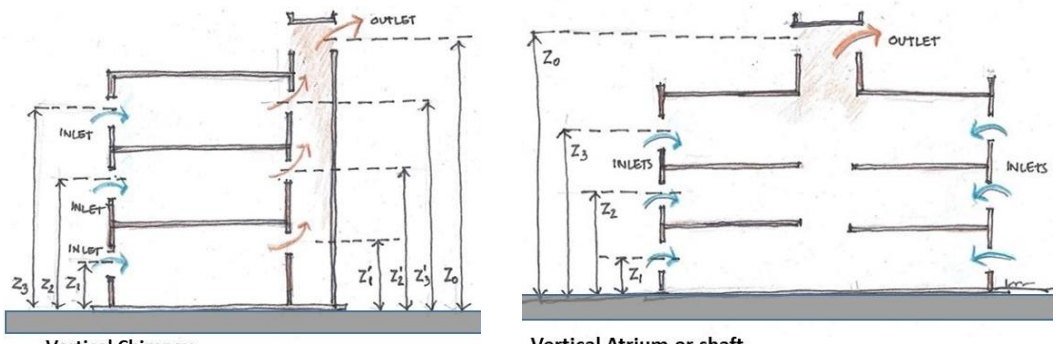


Figure 3-5: Cross ventilations (source: author)

Stack induced ventilation occurs by having density difference due to temperature stratification throughout a room height (Goodfellow and Tahti, 2001). By this process cooler air is pulled from the sides and the heated air naturally evacuated through a vertical and upward flow pathway (CIBSE, 2005, Szokolay, 2008). This process also can provide cross ventilation inside a space if the *rule of thumb,* shown in Figure 3-5, are maintained. This type of ventilation can be achieved by attaching an external vertical chimney or adding centrally located atrium or shaft (CIBSE, 2005, Lush and Meikle, 1988). Chimney is more applicable to narrow spaces maintaining the threshold width (Figure 3-5). Atrium ventilation concept is more appropriate for industrial building since there is an advantage of getting wider floor plate pulling the air from both side and maintaining the same rule of thumb (Figure 3-5). Here, two important parameters are the size of the inlets and outlets and stack height (z) (Figure 3-6). To avoid large size of opening and to achieve desire air flow rate, the stack outlet should be located

at least one floor above the top floor (CIBSE, 2005, p.17). During the warm seasons of a tropical region, it is also important to have high value of ΔT to induce the air flow (detail has been explained in Section 5.4.5).



(a) Vertical Chimney (b) Vertical Atrium or shaft

Figure 3-6: Stack ventilation (a) vertical chimney and (b) vertical shaft or atrium (source: author)

On the other hand, for physiological cooling of the occupants, it is essential to maintain required air velocity inside the building while passive ventilation through inlets is provided. Figure 3-7 shows that increase of ventilation flow rate corresponding to AT difference between indoor and outdoor can increase the sensible cooling of occupants (CIBSE, 2005, p.39). Since it was also found that increasing air speed up to 1.5m/s can elevate the cooling effect of garment factory workers up to 3°C resulting in being comfortable in an environment with higher AT (Fatemi, 2014), it is reasonable to focus on air flow patterns and air speed through the inlets for this research.

Third-party content

Figure 3-7: Effect of temperature difference and air change rate on sensible cooling capacity of ventilation air (height of space taken as 2.75 m) (source: CIBCE 2005, p.39)

Particularly for industrial building, windows and other openings, such as doors are also are also considered as significant building parameters that influence ventilation

process (Goodfellow and Tahti, 2001). Design strategy should include careful selection and location of appropriate type of windows from the range of options, such as vertical/horizontal pivot, top/bottom/side hung, side hung, sliding louvers etc. along with associated site context. In so doing, these windows can be operated by the occupants effectively ensuring uniform ventilation within the space (CIBSE, 2005, Santamouris, 2005). Another significant measure is reducing internal obstructions, such as internal partition, furniture, doorway etc. so that the internal spaces can be segmented according to air flow requirement and uniformity of air velocity can be maintained. The air movement can also be enhanced by using mechanical fans such as extractors, ceiling fans, wall mount fans etc.

3.5.2. Thermal mass and night ventilation

Specific heat is widely used to specify the magnitude of different building materials for better performance of a building, as *density* and *specific heat of materials* determine the thermal mass of the building (Rennie and Parand, 1998, p.25). If a building is constructed with the materials of higher density and specific heat capacity, such as concrete, bricks and tiles etc., it is considered as a heavyweight building. Heat retention and release process of this type of buildings are relatively slow due to having thermal mass. Thermal mass can be added in a lightweight building or can be increased by adding layers of dense materials at the internal surfaces of heavyweight building (Szokolay, 2008). By applying thermal mass in a NV building, indoor thermal performance of becomes relatively stable in terms of less fluctuation of indoor AT (CIBSE, 2015).

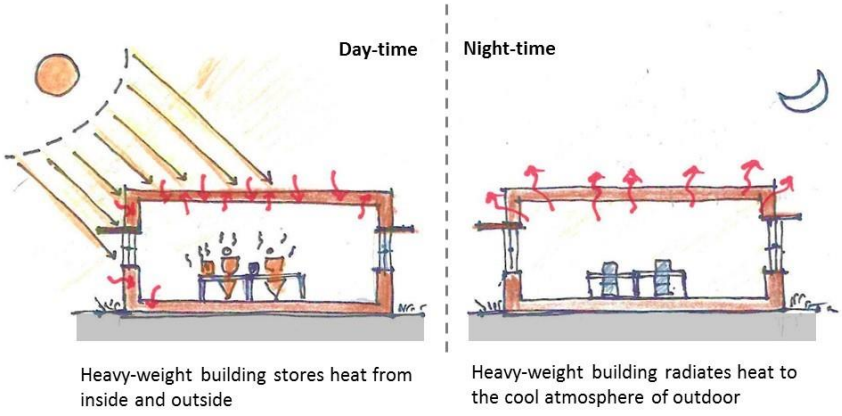


Figure 3-8: Effect of thermal mass within a heavy-weight building (source: author)

Thermal mass responds in buildings under a daily cycle where it typically absorbs heat during daytime and releases heat during night time (Figure 3-8). This process can be enhanced with the increase of time lag by giving enough provision of cooling through the night-time ventilation (NTV) which can be natural or mechanical ventilation. In so doing, the thermal mass will be capable of absolving more internal peak temperature from the indoor spaces and decrease cooling load (CIBSE, 2005, Santamouris and Ashimakopoulos, 1996, Givoni, 1994).

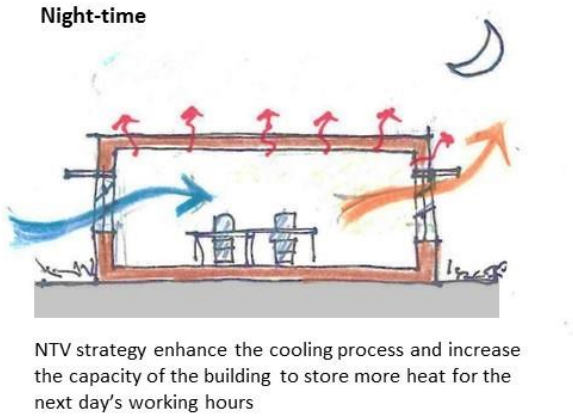


Figure 3-9: Combined effect of NTV and thermal mass (source: author)

NTV is an operation strategy, rather than mode of ventilation (CIBSE, 2005). Combined with thermal mass this strategy takes the advantage of diurnal variations in temperature within a day and provide cooling to the building during night which results in additional physiological cooling or comfort to the occupants during working hours (Figure 3-9). However, appropriate control over night ventilation may be required

during cool seasons of tropical zone to avoid subsequent discomfort of the following morning. Since previous research showed that night time ventilation is useful even in humid season, it will be reasonable to explore the application of it RMG factories in context of Bangladesh.

3.5.3. Evaporative cooling

Evaporative cooling is a mechanically controlled strategy that can be integrated with other passive strategies. It uses water to provide cooling within an indoor space. In a direct evaporative cooling, outdoor hot air enters through perforated wet surface and reduce the AT. In this process water absorbs the heat from the outdoor air utilising high latent heat of water and evaporate increasing the RH in the air (Koenigsberger et al., 1973, Szokolay, 2008) This mechanism is more applicable to the hot-dry climates where both advanced active and passive mechanism can be integrated (Ford, 2010). This strategy may not be desirable in humid seasons of Bangladesh due to existence of high RH in the indoor air and it may lead to additional thermal discomfort (shown in section 6.6).

3.5.4. Mechanical dehumidification

Dehumidification can be integrated with evaporative cooling and is applicable in humid season, when the high amount of RH is an issue. This is also called indirect evaporative cooling. In this process, the air is dried, by passing though chemical sorbents such as silica gel or mechanical device called dehumidifier, before the cool air enters into an occupied space (Szokolay, 2008). It may be applicable during humid season. However, this mechanism is relatively costly due to its dependence on mechanical means. Particularly for industrial buildings, this strategy is used to control dampness to protect products (Goodfellow and Tahti, 2001, p.717).

3.6. Learning from Precedents

Sections 2.6, 3.4 and 3.5 provided an insight of basic passive design strategies and associate design parameters. However, reviewing a number of precedents (i.e. case study buildings) would be an effective approach to understand the application of these passive design strategies appropriate to a given climate. Traditional architecture represents the strategies developed by native users over years making relationship

between culture, climate and building form (Hyde, 2000). Hence a traditional architecture can be examined as a precedent for the learning purpose. On the other hand, contemporary architecture can epitomise the adaptation of traditional design approaches to the contemporary setting by architects. Figure 3-10(i-ii) shows an example of the similarities of opening design pattern (e.g. horizontally two layers of opening in each floor level) among a traditional rural workspace and a modern non-domestic building in the same climatic context of Bangladesh. On the other hand, it is astonishing to observe that the windows of a typical multi-storied garment factory in Bangladesh (Figure 3-10.iv) loosely resemble the architecture of 20th century's Cotton Mill in England (Figure 3-10.iii), from completely different climatic contexts. These observations also trigger a review of architectural case studies of similar climatic context, as a step-in learning about and generating new environmental design ideas for the RMG factories studied in this thesis.



Figure 3-10: (i) Vernacular architecture in Bangladesh (ii) Modern architecture in Bangladesh (iii) Mons Mill in England and (iv) a typical garment factory in Bangladesh (source: photos taken by A. Al-Muhaymin and the author; Winter 1970)

Zarzar and Guney (2008) have reviewed a number of research studies and established the importance of studying architectural precedents prior to any design work. Studying precedents through a number of case studies not only helps to understand the

evolutionary model of certain architectural features, but also offer choices of how these may be reinterpreted in modern design. Following this approach, case studies were reviewed to learn further about the major design strategies adopted in different regions of tropical zone, including Bangladesh, and support the next steps of research.

3.6.1. Selected precedents

Five case study buildings, from both traditional and contemporary examples, from a total of 30, were selected to explore the application of environmental design strategies in the tropical zone (i.e. tropical, dry and moderate climatic context) representing the warm-humid, hot-dry, and moderate cool seasons respectively. Selection of the buildings covered a range of types, for instance, 400 years old traditional 'handloom weaving workspaces, multi-storied buildings with natural and active ventilation, adopted passive ventilation strategies, both retrofitted and new buildings, regional and international context, purpose-built buildings etc. The selected 5 case studies are as follows (Table 3-1 and Figure 3-11):

Table 3-1 Selected case study buildings for review

No.	Name of the precedent	Location	Building Character	Storey
i.	Traditional Handloom-workspaces	Demra, Dhaka, Bangladesh	400 years old traditional building	Single storey
ii.	National Parliament Building	Dhaka, Bangladesh	Purpose-built master Architecture	Multi-storey
iii.	Torrent research building	Ahmedabad, India	Retrofitted building	
iv.	East-gate Centre	Harare, Zimbabwe	Purpose built	
v.	Green Building Museum	Hangzhou, south China	Purpose built with green technology	

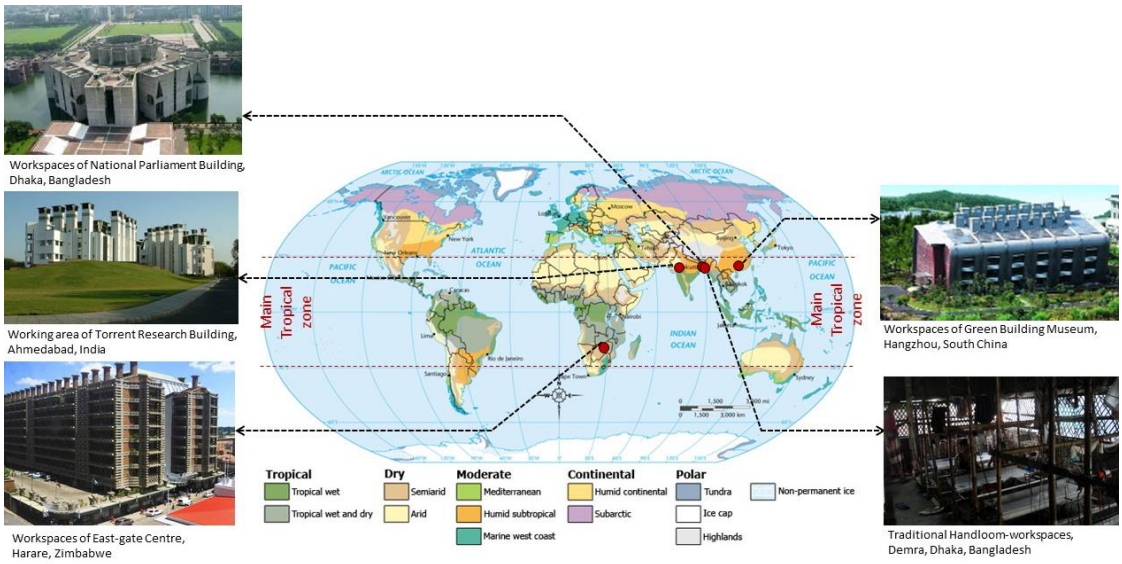


Figure 3-11: Location of the case studies in the tropical zone (sources explained in Appendix A)

3.6.2. Scope of the review

The main aims of reviewing the selected five precedents are to understand the climate modifications and the building strategies for warm climates with a special focus on ventilation design strategies in the moderate, hot-dry and hot-humid seasons. The strategies provide indications of how heat gain is controlled, such as, solar gain, conductive heat and internal gain control and provision of cooling, such as, air movement, NTV and thermal mass (as referred in Sections 2.6, 3.4 and 3.5).

Based on the availability of information, each case study building was firstly informed by its location, climatic context and building information. The environmental design elements were mainly focused on the following widely accepted criteria (Hyde, 2000, Wijewardane and Jayasinghe, 2008, Maxwell and Drew, 1964, Oakley, 1961):

- Configuration of the Inlet-outlet windows
- Location of the windows
- Shading devices for solar control
- Internal space layout and associated airflow pattern
- External walls and roof
- Internal floor, partition wall and ceiling

A description of these five studies can also be found in Appendix A**.**

3.6.3. Summary of the precedence study

Table 3-2 shows a summary of the five case study buildings and associated environmental design parameters (explained in Appendix A). From the study of precedents, it was found that the ventilation design and cooling strategies differ in accordance with the climatic seasons and diurnal variations. For instance, during hot dry season, the night ventilation has more impact than during the monsoon season as found in Torrent Research Building, East Gate Centre and Green Building Museum. Evaporative cooling was only found to work during hot dry season in the Torrent Research Building while the ambient RH is relatively low. Traditional handloom workers also have more personalised control over their comfort and ventilation.

Table 3-2 Summary of passive strategies and design parameters of the case study buildings

Precedents in native and international context						
Subject		**Case study 1**	**Case study 2**	**Case study 3**	**Case study 4**	**Case study 5**
Contextual information	*Name*	Traditional Handloom-workspaces	National Parliament Building	Torrent Research Building	East-gate Centre	Green Building Museum
	Location	Demra, Dhaka, Bangladesh	Dhaka, Bangladesh	Ahmedabad, India	Harare, Zimbabwe	Hangzhou, China
	Latitude, Longitude	23.729°N, 90.513°E	23.763°N, 90.379°E	23.102°N, 72.629°E	17.831°S, 31.052°E	30.473°N, 120.249°E
	Climate	Tropical, Aw	Tropical, Aw	tropical savannah, BSh	Subtropical highland, Cwb	Humid Subtropical, Cfa
	No. of stories	1	5	3	9	4
	Function	Non-residential (handmade garment production)	Non-residential (office spaces and assembly)	Non-residential (Office area and laboratory)	Non-residential (Office spaces and retail shops)	Non-residential (Office workspace)
Passive design strategies and parameters	*Ventilation*	Natural ventilation	Partially Natural ventilation	Passive Downdraft Evaporative Cooling	natural and forced ventilation	Hybrid Ventilation
	Application of NTV	Yes	Yes	Yes	Yes	Yes
	Thermal mass	Yes	Yes	Yes	Yes	Yes
	Inlet-outlet configuration	Vertical swing window	Side-swing windows and light-air shafts	Central inlet towers and shafts with motorised louvres	Low-level inlet from atrium and brick chimneys	Central atrium and shafts
	Solar control	Vertical swing device	Screen walls	Buffer walls	Extended stones elements	Motorised blinds and Low-e glazing
	Stack induced ventilation	No	No	Yes	Yes	Yes
	Segmented indoor spaces	No	Yes	Yes	Yes	Yes

NTV with thermal mass strategy is found to be the widely used approach in both traditional and contemporary precedents. Precedents also indicated the convenience of having a certain extent of the flexibility of window. For example, windows in traditional handloom workspaces of Bangladesh commonly have flexible control and maximum effective opening for ventilation which can be used even during the rainy season to allow physiological comfort for occupants. Integrated stack induced ventilation strategy was also found to be utilised within contemporary precedents. Segmented ventilation focusing on functional spaces and additional overhang on the windows were also found in some of the selected precedents as the heat control strategies.

In the next section (Section 3.7), these findings will be compared with the findings from other literature to formulate a number of suitable strategies and design parameters for RMG factories.

3.7. Potential Design Strategies and Parameters for RMG Factories

In addition to lessons learnt from the above precedent studies, a further literature review on environmental design strategies was conducted to identify the benefits of the following applied environmental design strategies. Some other basic parameters, such as building orientation, built form and roof types, are beyond the scope of these strategies.

3.7.1. Night-time ventilation (NTV) and thermal mass

Night-time ventilation and utilising thermal mass are found as the common strategies in all the majority of the case study building. In the tropical context, night-time outdoor AT can be cool enough to 'pre-cool' the indoor of the building for the next day, even in presence of a high outdoor temperature during the day time (Section 3.5.2) (Santamouris and Kolokotsa, 2013, Roche and Milne, 2004, Givoni, 1994). Nevertheless, the particular reduction of temperature of a built environment depends on the thermal mass, the temperature swing and the rate of night ventilation (Shaviv et al., 2001) through the indoor environment. In a hot-humid climatic context, the cooling effect of night time ventilation is larger and can reduce up to 2.5°C peak temperature and 2°C night-time temperature (Kubota et al., 2009). Since the thermal

mass combining the window opening frequency help to slow down the temperature response to internal and external heat gains (Rijal et al., 2007) (Section 3.5), adding more thermal mass with NTV can potentially reduce the running period of existing fans and save electrical energy. Therefore, the application of NTV strategy with thermal mass can be further investigated for improving the thermal performance of garment factories in different climatic seasons of Bangladesh.

3.7.2. Window design and control strategies

Study of both traditional and contemporary precedents demonstrated the significance of configuration of windows, including the flexible control, size, effective opening area and location within the built form, in stimulating indoor natural ventilation. Simultaneously, manoeuvre and control strategies of these windows were found to be important as well to protect the indoor environment from excessive heat loss and direct solar radiation. In reference to other previous research, such as the study conducted by Artmann et al. (2008), evidenced that increasing air flow rates with NTV strategy may reduce the hours with high AT. In this case, the air speed and direction can also be controlled by suitable window types. Amos-Abanyie et al. (2013) evinced the combined application of window size, NTV and thermal mass in reducing the peak indoor temperature and improving thermal comfort in a warm-humid context.

The research focusing air flow pattern by Heiselberg et al. (2011) in large spanned buildings endorsed the foremost role of the type of windows (e.g. top hung, bottom hung, side hung, etc.) since the cool outdoor air travels through the windows and the largest distance before it reaches the middle occupied zone. Beyond the reduction of direct solar radiation through shading devices, the physiological cooling effect of air movement can also be achieved by cross-ventilation and design of the window-opening faced within 45° of the prevailing wind direction (Szokolay, 2008). Even while the still condition of the outdoor air, dual windows may increase displacement ventilation with high air flow rate in the context of Bangladesh (Ahmed et al., 2006). However, the window openings should be positioned on the façade coupled with shading devices for improving thermal comfort (Barbosa et al., 2015) and should have certain control to avoid nuisance droughts caused by direct air flow (CIBSE, 2005), particularly for the buildings with fan forced ventilation.

Apart from controlling air flow pattern by various type of windows, Cui et al. (2013) supported the escalation of the 'effective opening size' which has also an impact on improving indoor thermal comfort and reducing the energy consumption. An increase of WWR can also improve the ventilation flow rate significantly which can be especially valuable in a warm-humid climatic context (Liping and Hien, 2007). In the urban context, providing more openings on facades and vegetation were mentioned as possible solutions by Ahmed and Roy (2007). Hence, the size and the effective area of the opening should be as high as possible without hampering the work desk. Segmented and stack induced ventilation

3.7.3. Segmented and stack induced ventilation

Use of courtyard and stack ventilation with shafts are another design strategies that are found within the case studies to provide additional cooling to the building. In the contemporary case studies, central atria are usually created sourcing the cool air and exhausting the indoor hot air through stack induced ventilators or shafts (Koch-nielsen, 2002). In different climatic context, several studies showed that the positive value of ΔT helps instigate the natural air flow through convective cooling and thus the stack ventilation uplift the thermal performance (Ernest and Ford, 2012, Liu et al., 2012, Koch-nielsen, 2002). If ΔT is high enough to induce the air flow, stack ventilation strategy is proven to be an appropriate passive design strategy in non-domestic buildings in a warm-humid context (Ismail and Rahman, 2012, Prajongsan and Sharples, 2012). ΔT and Z_n (Figure 3-6) are the two key aspects for the efficiency of this method (Aflaki et al., 2015).

Segmented spaces that maintain separate air flow (Section 3.4.3) is another common feature found in contemporary case studies. For example, individual spaces of Torrent Research Centre, East Gate Centre and Green building museum have their separate air inlets and outlets shafts to maintain the diversified ventilation rate as required. The internal functional layout is also synchronised with the air flow pattern to ensure optimum comfort for the users. Bay and Ong (2006) suggested cross ventilation in the fully humid tropical context. While cross ventilation is not possible in the buildings with large spans, adding ventilation shaft can reduce travel distance between inlet and outlet and enhance stack induced ventilation.

3.8. Summary

This chapter identifies the significant environmental strategies in the tropical climatic context through reviewing literature and five case study buildings in local and international context. The main intention of studying these buildings is to carefully observe the various environmental design strategies that are embodied in buildings by architects and adaptive behaviours that are practised by their occupants. Moreover, it was also an aim to identify a number of ventilation design parameters that generally enhance the thermal performance of the buildings in the tropical region.

Since environmental design strategies act as the indoor climate modifiers to ensure building and physiological cooling, it is important to understand the potential heat control and cooling strategies of a building. In the tropical climate of Bangladesh, direct solar radiation, conductive heat gain, internal heart gain, ventilation gains and infiltration gains are major aspects of heat control strategies. Moreover, sufficient provision of air movement, NTV strategy coupled with thermal mass, evaporative cooling and mechanical dehumidification are also major cooling strategies. These strategies are very generic following a number of scientific equations and rules of thumb.

From the review of precedents and literature, the hypothesis was made that the following environmental design strategies will be effective to improve the thermal environment of RMG factories' workspaces:

- Utilisation of NTV
- Use of thermal mass to complement NTV
- Configuration, size, effective area and location of the inlet and outlets
- Control strategies for comfort air flow and solar protection
- Exploration of stack induced ventilation shafts for passive ventilation
- Segmentation of spaces and functional layout to enhance ventilation.

Next chapter (Chapter 4) will focus on reviewing previous research design and methods to design the main research methodology.

CHAPTER 4. LITERATURE REVIEW: METHODS OF FIELD MONITORING, SURVEY AND SIMULATION

This chapter presents a literature review focusing on the methods of field monitoring, survey and simulation studies adopted in previous empirical research. It identifies the methods and strategies considered suitable for conducting this PhD research including the field investigations and simulation study.

CHAPTER 4. LITERATURE REVIEW: METHODS OF FIELD MONITORING, SURVEY AND SIMULATION

4.1. Introduction

Chapters 2 and 3 included a literature review focusing on the research context, thermal comfort, knowledge gap and applicable design strategies. This chapter provides literature reviews emphasising on research design, methodologies and methods that have been adopted in a number of previous empirical research studies with a focus similar to this. It indicates the key aspects that need to be considered while selecting the case studies, samples, data collection and analysis methods.

4.2. Chapter Aim and Scope

The main aims of this chapter are to review literature on applicable data collection methods for research focusing on thermal comfort, ventilation and performance of built environment and to recommend a range of applicable methods of field monitoring, survey and simulations for this PhD research. The outcome of this chapter will be a reference for formulating the research methodology in Chapter 5.

4.3. Research Design and Approaches

In order to achieve the main aim and objectives of a research project, formulating the overall research methodology, also referred as 'Research Design' (du Toit and Mouton, 2013), is the key stage. This process helps a researcher to connect the empirical data to the main research questions (Denzin and Lincoln, 2000). The term 'Research methodology' was defined by Blaikie (1993) as *'the analysis of how research should or does proceed'*. Within research design are included the procedures of collecting, analysing and interpreting the appropriate data, or in other words, choosing appropriate 'research methods' to conduct the whole study (Creswell, 2009, Bryman and Teevan, 2005, de Vaus, 2001). This will focus on the key aspects of choosing relevant research methods based on research objectives and conceptual frameworks.

4.3.1. Conceptual framework and methodology selection

Methodological study is the vital step of a doctoral research, where main systems of inquiry, e.g. post-positivist, naturalistic and emancipatory, are taken into consideration

(Groat and Wang, 2013, Sattrup, 2012). Conceptual framework is the boundary within which the research ideas and scope of the inquiry are shaped, focusing on the main research question. Based on the conceptual framework developed from a literature review (Baxter and Jack, 2008), the relationship between these ideas matures and completes with the progress of data analysis. The research data and analysis approach can be both qualitative and quantitative (Groat and Wang, 2013). Since this research focuses on improvement of thermal comfort in RMG workspaces, quantitative thermal comfort and associated design parameters should be in the centre of conceptual framework. To maintain the quality of the research, the research assessment criteria should be selected maintaining the internal and external validity, reliability and objectivity of the research (Groat and Wang, 2013). Internal and external validity indicates the scope of generalising the results of the research, while reliability and objectivity expresses the rigour of the quantifiable data collection.

4.3.2. Selecting research strategies and methods

The type of research, such as research related to 'the built environment', usually dictates the appropriate research methodologies and underpins the particular research and data collection method achieving the objective of the study (Opoku et al., 2016). For the research on the built environment, survey, experiment, modelling and simulation, mapping and visualisation, field study, case study, textual and narrative studies, intervention research, evaluation research, and meta-research are the key research approaches found in literature (du Toit and Mouton, 2013, Laryea and Leiringer, 2011). Table 4-1 shows the research strategies and their associations to research questions revealing that survey strategies are able to answer a wide range of research questions.

Table 4-1 Research strategies and characteristics (source: Yin, 2018, Amaratunga et al., 2002)

Research Strategy	Form of research question	Requires control over behavioural events?
Survey	Who, what, where, how many, how much	No
Case study	How, why	No
Experiment	How, why	Yes
Archival analysis	How, why	No
History	How, why	No

Gomm et al. (2000) demonstrated a schematic comparison of the three key research approaches: case study, experiment and survey. Their study showed that the case study approach is more flexible compared with other methodologies in terms of selecting number of cases, amount of features for each case, quantification of data and, above all, 'naturalistic generalisation' of research findings. Through an extensive literature review on research design in the field of built environment, du Toit and Mouton (2013) showed that 22.2%, 10.6%, 5.5%, 4.6% and 4.6% of the research followed case studies, surveys, field studies, experiments, and modelling approaches respectively. The overall research design also depends on the design of research methods or subtypes (Table 4-2).

Table 4-2 Index of designs to study the built environment (source: du Toit and Mouton, 2013, p.128)

Research Designs	**Research Design Subtypes**
Surveys	Cross-sectional surveys
	Longitudinal surveys
Experiment	Laboratory experiment
	Quasi-experiment (field experiment)
Modelling, Simulation, mapping and visualisation	Modelling and simulation
	Mapping and visualisation
Field studies	Ethnography/ participant observation
	Phenomenology
Case studies	Single/multiple case studies
	Comparative case studies
Textual and narrative studies	Content analysis
	Discourse
	Historiography and biography
Intervention research	Site/settlement analysis
	Plan/policy analysis and assessment
Evaluation research	Diagnostic
	Implementation evaluation and programme monitoring
	Outcome/impact evaluation
Meta-research	Literature reviews and synthesis
	Conceptual analysis
	Philosophical/logical argumentation

Proverbs and Gameson (2009) also referred the case study approach as more appropriate for built environment research. In addition, reliance on surveys is predominant for these studies (Laryea and Leiringer, 2011).

4.3.3. Conducting a pilot or feasibility study

Prior to conducting the principal investigations, it was worth conducting a trial study, also known as pilot study (Doody and Doody, 2015, Yin, 2018). The objectives of the pilot study are to evaluate the issues related to the initial research design and methods such as checking availability of a sample and how to recruit subjects, testing instruments, alternative ways of data collection and analysis procedures (Doody and Doody, 2015). Through the experience of the pilot study, the large scale principle field studies and analyses can be adjusted reflecting the practicality of the research timeframe and budget (Doody and Doody, 2015, Yin, 2018). Looked at another way, the pilot study can also be considered a feasibility study achieving a partial objective of the research and limiting the scope of data collection methods (Billé, 2010, Yin, 2018). Hence, a pilot study can be adopted for this research prior to principal investigations.

4.3.4. Methodologies adopted in previous studies

Table 4-3 provides a summary of the research methodologies, data collection methods and the type of analysis previously adopted by a number of empirical research studies of thermal environment. It can be observed that a quantitative research approach is followed by majority of these studies. However, qualitative approaches are also used to compliment the quantitative approach in some of the studies related to architectural design. Simulation study approaches were adopted in most cases and there is a significant lack of studies collecting empirical data from the field. In particular, there is a limited body of research on RMG factories with the majority either based on field surveys or simulation studies. For simulation study, data from the field and laboratory has only been used for validation purposes (explained in Section 4.6.2).

Table 4-3 Index of research designs followed in previous empirical studies on thermal performance

Research Focus	Reference	Research Design considerations			
		Main Methodology	Methodological approach	Data collection methods	Analysis type
Effect of two type of roofs on thermal performance	(Chowdhury et al., 2017c)	Modelling and simulations	Quantitative	- Validation with field and lab data - Simulation study	Comparative
Shading devices and glazing configurations in office buildings	(Lau et al., 2016)	Modelling and simulations	Quantitative	- Simulation study	Comparative
NV office buildings with double skin façades under Brazilian climates	(Barbosa and Ip, 2016)	Modelling and simulations	Qualitative and quantitative	- Simulation study	Comparative
Thermal performance of Building envelope of RMG factory	(Chowdhury et al., 2015)	Modelling and simulations	Quantitative	- Laboratory testing - Simulation study	Correlations
Indoor environment quality of Green Factories in Sri Lanka	(Ravindu et al., 2015)	Case studies	Quantitative	- Field monitoring (IEQ parameters) - Questionnaire survey	Comparative
Shading devices and thermal performance of offices	(Freewan, 2014)	Modelling and simulations	Quantitative	- Experiment - Simulation study	Comparative
Roofing design for tropical building	(Al-Obaidi et al., 2013)	Modelling and simulations	Quantitative	- Simulation study	Comparative
Indoor thermal condition of factories	(Khan et al., 2011)	Case studies	Quantitative	- Field monitoring	Comparative
Thermal performance analysis of glazed rooms	(Al-Tamimi and Fadzil, 2011)	Experimental	Quantitative	- Field monitoring (Environmental parameters) - Simulation study	Comparative
Effect of naturally ventilated (NV) cavity roof	(Susanti et al., 2011)	Modelling and simulations	Quantitative	- Numerical simulation study	Numeric and Comparative
Hybrid ventilation for building design in south China	(Ji et al., 2009)	Modelling and simulations	Quantitative	- Simulation study	Comparative
Effect of Louver ventilator on natural ventilation	(Kang and Lee, 2008)	Experimental	Quantitative	- Laboratory testing - Simulation study	Comparative
Thermal comfort of factory workers	(Wijewardane and Jayasinghe, 2008)	Case studies and field Survey	Quantitative	- Field survey (physical and subjective data)	Comparative
Energy efficient design approach	(Naz, 2008)	Modelling and simulation	Qualitative and quantitative	- Field monitoring - Simulation study	Comparative
Thermal Environmental Performance in Atria	(Abdullah, 2007)	Modelling and simulation	Quantitative	- Field monitoring - Simulation study	Comparative

Methods of data collection can be both qualitative and quantitative to gain the answers to research questions (Section 4.3.1). While there are limitations of generating answers by adopting both quantitative and qualitative methods, *Triangulation* provides opportunities to overcome these limitations by effectively combining methodologies of the study (Amaratunga et al., 2002). For validating results when using mixed methodologies in research focused on the built environment, triangulation techniques are more adoptable than the other techniques (Dainty, 2007).

4.4. Case Study Approach

4.4.1. Advantages of this approach

From Section 4.3.2, it is recognised that case study approach is a flexible methodology for detailed investigation. This approach also fits into multi-paradigm theory-building research (Dooley, 2002). The main advantage of case study approach is that it can combine and complement various research methods on a same platform to achieve the main goal of a research (Lynham, 2002, Yin, 2018). Moreover, this approach is contextual and provides opportunities to analyse both quantitative and qualitative data with more understanding of the real-life situations compared to survey based or experimental research (Zainal, 2007).

4.4.2. Designing a case study approach

Designing case studies includes selecting the case(s), collecting data, analysing the data and writing the findings (Proverbs and Gameson, 2009). As referred by Gomm et al. (2000), the key aspects of designing a 'case study approach' are:

- Number of case studies and impact of comparing them
- The extent of detailed information to be collected
- Type of data collected and the context of the case(s)
- Analysis procedure

Flyvbjerg (2006) emphasised the 'selection of cases' as it is the major part of the case study research. Since the case study approach required in-depth understanding, data can be collected from multiple sources through observations, surveys, interviews etc. (Creswell, 2013, Sarvimaki, 2018, Yin, 2018). In that case, triangulation is essential for

an integrative data analysis for ensuring the validity of research outcome (Sarvimaki, 2018).

Case studies can be categorised into exploratory, descriptive, explanatory, instrumental and purely case studies (Zainal, 2007, Baxter and Jack, 2008). Exploratory case studies tend to explore the research scene where no single set of outcomes is expected (Baxter and Jack, 2008). From Sections 1.3, 2.5, 2.6, 3.7 and 4.3.2, it was observed that this research sub-questions include both the building performance and factors related to human factors and a wide range of thermal data collection. Hence, considering the time limit of this doctoral research, this project adopted a case study approach with triangulations between monitoring, survey and simulation methods to answer the research questions.

4.5. Methods for Field Monitoring and Surveys

4.5.1. Objective and subjective data

For case study based research, data can be objective and subjective in cases where the research methods are chosen to be quantitative or qualitative (Guerra-Santin and Tweed, 2015). While considering research into the thermal performance of a building, Guerra-Santin and Tweed (2015) referred to the environmental data as objective where perception of the users have no influence on them. Moreover, the occupants' feedback can be considered as subjective data which vary based on personal preference and perceptions. Both types of data acquisition are necessary to achieve a comprehensive understanding of the indoor thermal environment.

Olivia and Christopher (2015) provided detailed guidelines on methods for measuring and evaluating the data upon which thermal comforts based when undertaking empirical research. In their study, it was indicated that detail field studies are required for different case study buildings if the research is considering improvement of the thermal performance of the selected buildings. Figure 4-1 reveals that outdoor temperature, indoor temperature and RH should be measured during any level of investigation.

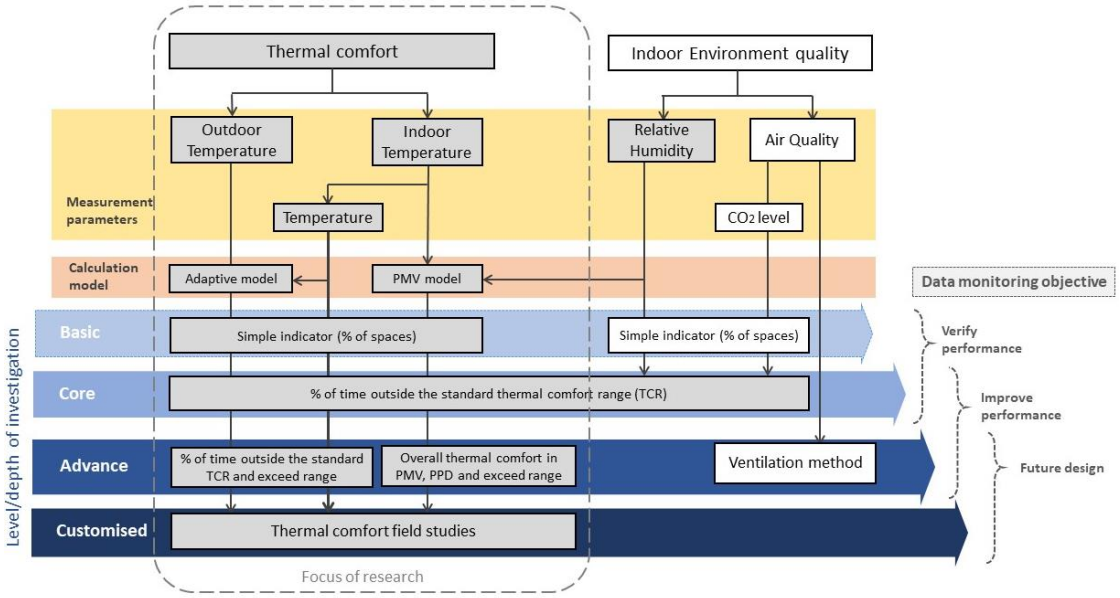


Figure 4-1: Data monitoring and thermal performance evaluation methods (source: Guerra-Santin and Tweed, 2015, Olivia and Christopher, 2015, newly drawn by the author)

According to a literature review by Dainty (2007), 71%, 8.4% and 11.2% of the research was found to adopt quantitative, qualitative and mixed methods respectively. Since both the built environment and factory workers are the focus of this study, both environmental or objective data and subjective responses from the workers are necessary to gain a comprehensive understanding of the thermal condition of RMG workspaces.

4.5.2. Duration of data collection

An extended duration of data collection and use of compliant tools help to ensure the validity, reliability and objectivity of a research (Groat and Wang, 2013). According to Guerra-Santin and Tweed (2015), the availability of resources, as well as the objective of the research, determine the duration of the data collection from a built environment, which can be long-term or short-term.

In case of *long-term thermal comfort survey,* seasonal measurement or longitudinal data acquisitions of indoor environment, such as AT, RH, are followed (Guerra-Santin and Tweed, 2015). Simultaneous physical data, such as AT, RH, OT and air speed, are also continuously monitored with the long-term subjective response. Occupants' relevant personal details, outdoor AT, sky condition, seasonal condition, users'

metabolic rate, Clo value and location should be included within the questionnaire (Guerra-Santin and Tweed, 2015).

On the other hand, a *short-term comfort survey* combines the use of comfort questionnaire survey and simultaneous spot measurement. As referred by Guerra-Santin and Tweed (2015), the following key aspects need to be ensured:

- Representative and most occupied space should be surveyed
- 10 days as the representative period of time for a season
- Both hot and cold seasons should be covered.

Nicol and Roaf (2005) and Guerra-Santin and Tweed (2015) emphasised the advantages as well as limitations of short-term survey methods. They revealed that assumptions about the participants can be avoided though these surveys. However, the comfort results are bounded by the particular situations of the subject. Hence, Guerra-Santin and Tweed (2015) suggested that short-term data acquisition can be conducted by monitoring in each season or dividing the long-term data per person. As seasonal differences have impact on adaptation of thermal comfort (Humphreys et al., 2007, Mishra and Ramgopal, 2013), it is also necessary to conduct surveys in various seasons of a tropical climate.

4.5.3. Stakeholders selection

While considering the thermal performance of a case study building or workspace, the subjective response should be collected from those target groups, also known as 'Stakeholders' who are affected by, or responsible for, the activities within the building (Mallory-Hill et al., 2012). Mallory-Hill et al. (2012) suggested that the stakeholders can be occupants, visitors, maintenance staff, property owners or managers, architects, engineers, and future users of a case study building or similar building types.

The objective of the research usually dictates the selection of stakeholders for a survey. Guerra-Santin and Tweed (2015) showed that client, users and building designers should be included as stakeholders for subjective measurement if the aims of the study are for verifying performance, improving performance, and future design of the building respectively. Since, this research focuses on improving the thermal

performance of the workspaces of RMG factories, the workers' feedback is mandatory, where clients' or building owners' feedback may complement data collected via worker survey.

4.5.4. Data collection methods

It is also expected that different data collection and assessment approaches will be combined in research related to building's performance in order to enhance understanding and have provision to crosscheck the results (Turpin-Brooks and Viccars, 2006). This is applicable for both physical and subjective measurements. Based on the level and objective of the investigation (Figure 4-1), the popular methods of data collection including their pros and cons are shown in Table 4-4.

Table 4-4 Data collection methods based on the nature and objective of the investigation (source: HEFCE, 2006, Turpin-Brooks and Viccars, 2006, Guerra-Santin and Tweed, 2015)

Data collection methods	Investigation aims, nature and timescale*	Advantages	Disadvantages
Walk-through survey	A	Simple and affordable	Subjective
Focus group discussion	A	Additional information than questionnaire, Cost effective	Need skilled facilitator
Questionnaire Survey	B, C	Comprehensive, Both quantitative and qualitative	Possibilities of missing out context and fine points
Individual Interviews	A, B, C	Appropriate from senior management	Time consuming and skills required
Plan analysis	A	Excellent Data source	Excessive information
Supplied data	A	Affordable	Rigour and interpreting issue
Monitored data	C	Quantitative and accurate	Cost and sampling methods

**Here, A: Verify performance, indicative (short period), B: Improve performance, investigative (one week to several months) and C: Future Design, diagnostic (several months to years)*

Interviews are usually arranged with certain groups of stakeholders, for instance, building owner, managers, designers, so that more detail information can be gathered with a provision of exchanging views (Mallory-Hill et al., 2012). Though a questionnaire survey can be conducted online or through email to get the perceptions and motivations of these particular stakeholders (Wong and Abe, 2014), personal interview is more useful to achieve unbiased answers. While deeper insights are required from

a survey, personal interviews, focus group discussion and observations are adopted in a research methodology mixing both quantitative and qualitative methods. Designing a questionnaire and interviews is a vital component of case study research where in-depth results are desired (Proverbs and Gameson, 2009).

4.5.5. Designing a valid thermal comfort survey

A thermal comfort survey that measures thermal comfort and thermal sensation of occupants, is one of the most significant parts of any Post Occupancy Evaluation (POE) study seeking to enhance the energy efficiency of tropical buildings (Göçer et al., 2015, Kwong et al., 2014). Three classes of thermal comfort survey, i.e. Class I, Class II and Class III, can be followed for data collection with the majority of research projects using the Class III method (Brager and de Dear, 1998, Gossauer and Wagner, 2007). Brager and de Dear (1998) described the Class I survey as a rigorous method where environmental data are measured at three heights above floor level simultaneously with the questionnaire survey (point scale), ASHRAE 55 and International Organization for Standardization (ISO) compliances are followed. A Class II survey includes measuring all the parameters related to PMV and PPD at one height simultaneously during the questionnaire survey. They referred to a Class III survey method as more simplified where AT and RH are measured and may not be simultaneously collected during questionnaire survey. Gossauer and Wagner (2007) suggested a rigorous comfort survey, particularly for NV buildings, due to the temporal variance of indoor climate in various seasons. Hence, for this research, the survey should follow Class I method to maintain the rigour of the study. The survey should consider the rigorous collection of both objective and subjective data, as shown in Table 4-5.

Table 4-5 Techniques of thermal comfort survey (source: Guerra-Santin and Tweed, 2015, p.205)

Thermal comfort data type	Techniques
Objective data: measurement of indoor and outdoor parameters	Spot measurements
	Longitudinal measurements
Subjective data: thermal comfort survey (occupant questionnaire)	Retrospective questionnaire
	Real time questionnaire
	Seasonal thermal comfort questionnaire

Questionnaire design is also important since it determines how the human perception on thermal comfort will be collected and quantified. Survey schedules can be designed two ways. In a *longitudinal survey*, occupants provide feedback on their thermal perception numerous times over a time-frame, while in *transverse survey*, many occupants participate in one evaluation (Humphreys et al., 2007). As referred in Section 2.5.1, the neutral point is counted as no sensation point on the ASHRAE seven point scale (Gossauer and Wagner, 2007) and thermal comfort is defined within 90% or 80% acceptable level (Figure 2-6). Moreover, McIntyre's and Nicol's scales (Section 2.5.1) are also useful to complement the results based of ASHRAE scale. In addition, Nicol (2004) emphasised the importance of collecting feedback on air movement and humidity during comfort field studies for a complete understanding of a thermal environment.

Reliability of the research outcome mainly depends on the specification of the instruments used to monitor the indoor environmental condition (Groat and Wang, 2013). Validating the efficiency of instruments is necessary to maintain the compliance of the study (Addy et al., 2014).

4.5.6. Sampling

Representativeness of the building and occupant sample is significant part of thermal comfort survey. Gossauer and Wagner (2007) suggested the following relevant aspects to be considered:

- Buildings with similar characteristics
- Workspaces with similar social-cultural background
- Sample size
- Gender
- Seasonal difference

Flyvbjerg (2006) stated that the sampling strategy can be random and information-oriented selection. Preferably, samples should be random to avoid biasness and large enough for generalisation. The main purposes of random and stratified sampling are to get a sample that is representative of the whole population and selecting special subgroups within the population for generalisation (Flyvbjerg, 2006). A previous study

also suggested that the balance of gender should be representative within the samples used for thermal comfort study as there are differences in thermal preference due to gender (Karjalainen, 2012).

4.5.7. Field monitoring and surveys in previous studies

Table 4-6 illustrates a summary of field monitoring and survey methods adopted by a number of previous empirical research studies in the field of thermal comfort and performance of NV buildings in the tropics. It reveals that AT, RH, GT and AV (i.e. air speed and direction) are the common environmental parameters that were monitored during the field studies. The monitoring of AT and RH (outdoor and indoor) were generally longer in duration and continuous in frequency. Thermal sensors, hygrometers and anemometers were used for both continuous and spot measurements. These physical parameters were used for not only measuring thermal and ventilation performance of a built environment, but also to complement the subjective responses from occupants. Additionally, use of 7-point measuring scale is commonly used in previous research as the subjective feedback on thermal comfort. Sample size used in the comfort surveys showed significant variations as well.

These reviews suggests that both environmental data monitoring and thermal comfort surveys should be conducted in all seasons for RMG factories in Bangladesh. The sample size should be maintained based on the representativeness of workers in the case study buildings and allowable timeframe of the research. Both outdoor and indoor environmental data should be also collected to support the validating simulation studies for this research (explained in Section 4.6.2)

Table 4-6 List of previously applied survey methods for evaluating thermal comfort of NV buildings

Research focus	Reference/ source	Duration and frequency	Physical measurement		Subjective data collection	
			Parameters	Instruments/ tools	Survey method (measuring scale)	Sample Size
Thermal comfort in three industrial buildings in Singapore	(Wong et al., 2016)	Two seasons (daily, morning and afternoon)	AT, AV, RH and GT (Class II protocol)	HOBO sensors and handheld Testo 445	Questionnaire (ASHRAE 7-point TSV and Bedford TCV)	388
Evaluating 42 urban and non-urban buildings	(Djamila, 2017, Djamila et al., 2014)	12 months (Monthly, hourly)	AT, RH, GT and AV	-	Questionnaire (ASHRAE 7-point TSV)	890
Adaptive thermal comfort for NV offices in India	(Indraganti et al., 2014)	14 months (winter, summer, two monsoons)	AT, RH, CO2, GT and AV	Hygrometer, anemometer and probe thermometer	Questionnaire (7-point TSV, 5 point TPV and TA)	2787 (18-68 years)
Thermal comfort at workspaces of 4 buildings	(Simons et al., 2014)	9.5 months (rainy and dry seasons)	AT, RH and AV (indoor and outdoor)	HOBO sensors and anemometer	Questionnaire (ASHRAE 7-point TSV)	195
Thermal comfort of RMG factory in Bangladesh	(Fatemi, 2012)	3 months (April – June)	AT, RH and AV	HOBO sensors and pocket weather meter	Questionnaire (7-point TSV and 7-point TCV)	240
Adaptive thermal comfort of hot humid climate, Brazil	(Cândido et al., 2011)	Aug- Sep: cool season, Feb-Mar: hot season	AT and RH (outdoor), AT, GT, AV and RH (indoor)	Microclimatic station	Questionnaire (TSV, PTV, TA, preference and AV acceptability)	1160 and 915
Thermal comfort of NV buildings in India	(Indraganti, 2010)	33 days May: summer, Jun-Jul: monsoon	AT, GT, RH and AV	Hygrometer, thermometer, vane anemometer	questionnaire (7-point TSV, 5-point TPV): Transverse and longitudinal	113
Thermal comfort study in 9 buildings in Malaysia	(Yau, 2008)	-	AT, RH, AV and MRT	Thermo-Hygro anemometer, ASHRAE thermal comfort tool	Questionnaire (5-point TSV)	141
Thermal comfort for factory workers in tropical climates	(Wijewardane and Jayasinghe, 2008)	Typical warm days	AT, RH and AV (Class III)	Thermometer, hygrometer and anemometer	Questionnaire (ASHRAE 7-point TSV)	430
Thermal comfort of NV houses in Indonesia	(Feriadi and Wong, 2004)	Within a year (dry and wet seasons)	AT, MRT, RH and AV (Class II)	Sensors and probes, hot wire anemometer	Questionnaire (7-point TSVs and McIntyre TPV)	263 and 262
Thermal comfort in classrooms in Singapore	(Wong and Khoo, 2003)	2 days (21 and 24 August)	AT and RH (out), AT, RH, AV and GT (indoor)	Climomaster, black globe thermometer	Questionnaire (7-point TSV and McIntyre TPV	506 (13-50 years)
Multi-storey workspaces in Indonesia	(Karyono, 2000)	12 months	AT, OT and RH	Hygrometer, Thermal comfort meter	Questionnaire (ASHRAE 7 scale TSV)	596 (19-53 years)
Indoor thermal comfort in Bangladesh	(Mallick, 1996)	Feb – Sep (hot-dry and hot-humid)	AT (indoor and outdoor), AV, RH and GT	-	Questionnaire (Bedford 7-point TCV)	400
Thermal comfort of NV offices in Thailand	(Busch, 1992)	1 week per season (hot and rainy)	AT, RH, GT and AV	Globe thermometer, anemometer	Questionnaire (7-point TSV, 7-point TCV, McIntyre TPV)	389
Thermal Comfort of Indian Subjects	(Sharma and Ali, 1986)	May-Jul: Lab test (half hourly)	AT, WBT, GT and AV	Hygrometer, Globe and Kata thermometer	Questionnaire (Bedford 7-point TCV)	18
Workplaces and homes in Singapore	(Ellis, 1953)	Several months (unspecified)	AT and WBT	Hygrometer, wet-bulb thermometer	Questionnaire (7-point scales)	> 134

4.6. Methods for Simulation Studies

For investigating the quantifiable effect of retrofitting exiting building design or future design on indoor thermal environment, collecting field data is necessary (Figure 4-1). However, due to limitations of given time-frame and budget of this research, it may not be viable to retrofit an existing RMG factory building and then monitor environmental data from the field. In this occasion, Addy et al. (2014) found that simulation helps by generating predicted results supporting future design and policy. Although the simulated results may not always perfectly match with the reality, the researcher needs to make sure to keep the deviations between predicted and real data to minimum.

4.6.1. Simulation tools

Aflaki et al. (2015) demonstrated that Dynamic Thermal (DT) simulations and CFD modelling are the common methods for analysing thermal performance and ventilation. A literature review, conducted by Wang and Zhai (2016), revealed that using a CFD approach, multi-zone approach, zonal approach and coupling of different models are the common simulation approaches for evaluating indoor ventilation. They also revealed that while adopting integrated simulations is challenging, it can provide effective results.

According to research conducted by Attia (2010), the IES-VE, Ecotect, Design Builder, Green Building Studio and Energy-10 simulation tools were found to be the popular tools for architects to conduct environmental assessment, while Design Builder, EnergyPlus, eQuest, DOE-2 and IES-VE tools were more appropriate for engineers. Based on the study of Crawley et al. (2008), Table 4-7 illustrates a number of simulation tools and their capabilities relevant to thermal performance studies.

Table 4-7 reveals that the IES-VE simulation software is capable of supporting all the analysis relevant to this research. Recently, IES-VE has also been validated to be reliable simulation and modelling tool coupling with CFD interface for thermal performance analysis and evidence based building design including many design and performance variables (Leng et al., 2012, Lim, 2012, Oduyemi and Okoroh, 2016, Loonen et al., 2016).

Table 4-7 List of selected simulation tools showing their capabilities (source: Crawley et al., 2008, p.667)

Software	Thermal performance and zone load analysis			Ventilation, air and multi-zone airflow		
	Specified dynamic design condition	Indoor convection and CFD	Internal Thermal mass	Natural ventilation	Hybrid ventilation	External condition and windows
IES-VE	√	√	√	√	√	√
Tas	√	√	√	√	√	-
Energy Plus	-	-	√	√	-	√
Energy-10	-	-	√	-	-	-
eQuest	-	-	√	-	-	-
DOE-2	-	-	√	-	-	-
Ecotect	-	-	√	-	-	-
TRNSYS	√	-	√	-	-	-
BSim	-	-	√	√	√	-
HEED		√	√	-	-	-

4.6.2. Validation of simulation model

The accuracy of simulated results of AT and RH depend on validation of weather data input, accurate input of construction details, wind direction details for air flow and the embodied heat of adjacent context (Leng et al., 2012). After ensuring these aspects, the simulated base model requires a validation. The validation process includes comparing the simulated environmental parameters, such as AT, RH and AV, with the measured data from the field or laboratory (Crawley et al., 2008, Chowdhury et al., 2017b, Strachan et al., 2016). From a literature review, the steps of validation can be stated as follows:

Step one: *Validation of weather data with field and/or meteorological data*

Step two: *Validation of simulation model by verifying the deviations between simulated data and monitored data from the field or laboratory*.

A literature review from Chen (2009) showed that CFD modelling was the most widespread method for evaluating and predicting ventilation performance within buildings. However, the main challenges of the steady-state CFD modelling for ventilation are the boundary conditions, turbulence modelling, numerical

approximation and the limitation is the need of computer with high specification (Li and Nielsen, 2011). Leng et al. (2012) demonstrated that IES-VE simulation tool could present nearly accurate results with deviations of not more than 10-12% if validations are done appropriately. The Literature recommends that deviations from the field data of up to 5% and 10% are acceptable for DT and CFD simulations respectively (Almhafdy et al., 2015, ASHRAE, 2013, Royapoor and Roskilly, 2015, Kang and Lee, 2008).

4.6.3. Simulation methods in previous studies

Table 4-8 provides an overview of simulation studies previously adopted by a number of research studies on workspace environment. Though validation of simulation models with real data were required, many of these research studies lack field or lab data to verify the simulation base models. The evaluations made using DT and CFD simulation tools mainly focused on AT, OT and AV to justify the thermal performance of the workspaces. The overall review suggests that the validation of the simulation study with the real data should not be avoided in any research regardless what simulation software was chosen to analyse the data. In this research, these aspects of the simulation studies will be applied to maintain the validity and reliability of the results.

Table 4-8 List of previously applied simulation methods for evaluating workspace environment

Research Focus	Source	Methods of the simulation studies		
		Validation	Assessment parameters	Simulation tool/ model
Effect of two type of roofs on thermal performance of RMG factory	(Chowdhury et al., 2017c)	Field data	AT, RH and WBGT	Energy plus and Open studio Plug-in
WBGT and PHS prediction for RMG workspaces	(Chowdhury et al., 2017b)	Field and meteorological data	AT, RH and AV	Energy plus with Open Studio Plug-in and Sketch-Up (DT simulation)
Shading devices and glazing configurations in office buildings	(Lau et al., 2016)	No	Energy consumption, cooling load	IES-VE
NV office buildings with double skin façades in Brazil	(Barbosa and Ip, 2016)	No	AT, OT and air speed,	IES-VE (DT simulation), Flovent (CFD modelling)
Thermal performance of building envelope of RMG factory	(Chowdhury et al., 2015)	Field and laboratory data	AT, ET, OT and MRT	Energy plus
NV building with double skin façade in tropical climate	(Barbosa et al., 2015)	No	AT, air flow rate and OT	IES-VE
Shading devices and thermal performance of workspaces in hot climatic region	(Freewan, 2014)	Field data	AT and thermal images	IES-VE
Roofing design for tropical building	(Al-Obaidi et al., 2013)	No	AT	IES-VE
Natural ventilation in a large factory	(Kang and Lee, 2008)	Scale-down experimental model and laboratory data	Flow rate and AV	CFD Wind tunnel test
Natural ventilation of a factory roof cavity	(Susanti et al., 2010)	No	AT and AV	Numeric calculation (Heat and force balances)
Energy Efficient Design Approach of factory	(Chowdhury and Alam, 2011)	No	AT	Ecotect
Computational analysis of thermal environment	(Jusoh et al., 2015)	Experimental chamber data (boundary conditions and heat sources)	AT, MRT, AV, pressure, PMV and PPD	CFD modelling
Thermal energy in industrial buildings	(Katunsky et al., 2013)	Field data	AT, Surface temperature,	ESP-r and BuildOpt-VIE (DT simulation)
Industrial building refurbishment	(Gourlis and Kovacic, 2016)	No	AT and hours with high AT	EnergyPlus (DT simulation)
Thermal performance analysis of glazed rooms	(Al-Tamimi and Fadzil, 2011)	Field data	AT and time in hours	Ecotect
Energy efficient design approach for RMG factory	(Naz, 2008)	No	AT and time in hours	Ecotect
Thermal environmental performance of Atria	(Abdullah, 2007)	Field data	AT and air flow	Tas (DT simulation), CFD modelling
Hybrid ventilation for building design in south China	(Ji et al., 2009)	No	AT, Resultant AT, air flow rate and cooling load	ANSYS CFX (CFD modelling), IES-VE (DT simulation)

4.7. Summary

Based on the literature review, this chapter initially provides an insight on the significance of developing a conceptual framework and selecting appropriate research methodology to answer the main research questions. Among a range of research approaches, case study, experiment and survey are found as the most common strategies for a research for evaluating built environment. Previous studies suggested selecting as empirical case study approach, as this approach provides more flexibilities in combining various data collection methods and in-depth analyses.

The number of case studies, the impact of comparing them, the extent of data, type of data, context of the cases and analysis procedure are the key aspects for designing a case study approach. A pilot study can be conducted to check the feasibility of the methods of principal investigation and fine tune the data collection strategies. For this research, exploratory type case studies may be more appropriate where triangulation between theoretical studies, field data and simulation results will provide valid results.

Since this doctoral research focuses on improving the thermal performance of RMG workspaces, both the objective (i.e. environmental data) and subjective data (i.e. perceptions from stakeholders) need to be collected, preferably through field studies. The duration of the data collection depends on research objectives, the given timeframe and the feasible budget. Among the short-term and long-term data collection methods, short-term data acquisition will be more viable for this research. The short-time data collection should be completed within the most occupied spaces, over a period of at least 10 days and at times in the year representing both hot and cold seasons.

For subjective feedback collection, the stakeholders can be the occupants, clients and designers of a built environment. A valid design and standard protocol of the feedback survey, including questionnaire surveys and interviews, should be maintained. The literature suggests to maintain the highest standard, i.e. 'Class I' standard, in thermal comfort survey for a valid and reliable set of data. Application of both ASHRAE 7-point scales and McIntyre's or Nicol's scales to gather feedback on AT, RH and AV is expected during the comfort survey. A calculation tool for predicting PPD and PMV may help to

compare user responses with the field results. Moreover, while selecting samples for the comfort survey, the samples should be large enough representing all genders, buildings with similar characteristics and climatic contexts. A review of a number of previous empirical research studies also suggested following the above data collection methods, as these methods were already validated through these empirical studies.

Since this research considers improving the thermal environment of existing workspaces, a simulation study may be required. For evaluating thermal environments, both DT and CFD simulations are conducted by using a range of simulation software. IES-VE software is useful in this regard. It was proven to provide more accurate results. The literature suggests developing a base model and validating both weather data and simulated results with the real field data before conducting the parametric studies.

This literature review on overall methodology, methods of field monitoring, surveys and simulations will be the underpinning reference for designing the research methodology in the next chapter (Chapter 5).

CHAPTER 5. RESEARCH METHODOLOGY

This chapter presents the detailed account of the method adopted for this research. The case study buildings are also introduced in this chapter. The rationales and descriptions of all the methods implemented within this research are also presented.

CHAPTER 5. RESEARCH METHODOLOGY

5.1. Introduction

Based on the findings from the previous chapters (Chapters 1-4), this chapter provides the overall research strategy selected for this doctoral research. It presents the objectives and methods adopted to conduct the pilot study, field and simulation studies. It also introduces the selected case study buildings for investigations.

5.2. Chapter Aim and Scope

The aim of this chapter is to provide an insight of overall methodology of this research so that it can be used as a reference and provide the results in the next chapters (Chapters 6 - 11). This chapter is limited to present the rationale and initial information on the selected methods of the research. Further information of the research methods, such as, detail profile of the case study buildings, analysis and validation procedure of simulation, may be provided in Chapters 6 - 11.

5.3. Overall Research Methodology

Base on the literature reviews presented in Chapters 1-2, the research framework was developed with five research objectives (Section 1.3). Appropriateness of the selecting research strategy for achieving these objectives were evaluated against the literature review of Chapter 4, the given timeframe and budget. Empirical case study approach was chosen for this research considering its flexibility of combining various research methods and getting in-depth contextual information (Section 4.4). Through this approach, triangulation between theoretical studies (i.e. literature review), field studies and simulation study was maintained for valid results (Figure 5-1). However, it was a challenge for the researcher to get consent for conducting long term surveys in RMG factories due to both ethical and commercial issues, such as protecting privacy of workers', managers', owners' information, maintaining privacy of the RMG factory company's profile, minimising disruptions to workers' workflow, etc. (reference letters shown in Appendix B). Therefore, researcher had to be flexible in designing the research methodology and had to keep alternative methodology in mind. Table 5-1 shows the chosen research strategies and methods against the research objectives.

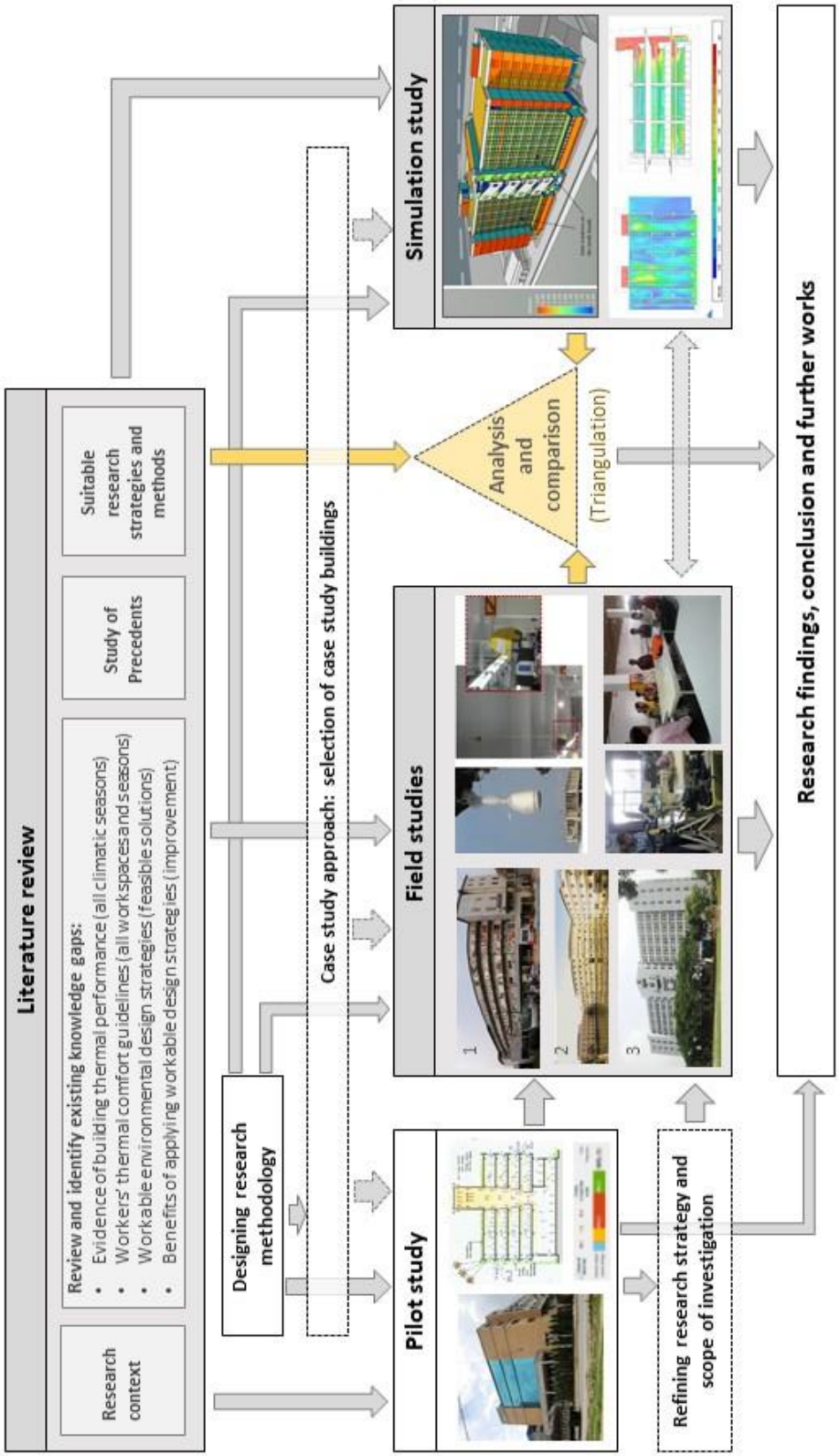


Figure 5-1: Flow diagram of overall research methodology

Table 5-1 Research strategies against the research objectives

Research objectives*	Focus of the investigation	Number of case studies	Research Strategy	Main methods
Objective 1	Environmental design parameters and thermal comfort aspects (Knowledge gap)	Five precedents	Theoretical studies	Literature review: - Established principles - Codes and building regulations - Previous empirical research - Precedents in the Tropics
Objective 2	Feasibility of applying passive design strategies in existing RMG factory (scope of study)	One	Pilot study	- Objective data: field measured data study - Subjective data: online structured questionnaire survey - Numeric calculation
Objective 3	Common parameters affecting thermal environment of RMG workspaces	Three	Field studies	Objective data: - Continuous data monitoring - On-site spot measurement - Field observations
Objective 4	Design Targets for workers' thermal comfort			Subjective data: - Transverse questionnaire survey - Focus group discussions - Semi-structured interview
	Workable design strategies for improving their thermal environment			
Objective 5	Environmental benefits of applying the workable design strategies	One	Simulation study	- DT and CFD simulation modelling - Validation with field data - Numeric calculation

**As presented in Section 1.3.*

Next sections will provide further details on case study buildings and methods adopted for the pilot study, field studies and simulation studies.

5.4. Methodology of the Pilot Study

5.4.1. Aim and scope of study

A pilot study was conducted prior to principal investigations, i.e. field studies and simulation studies, aiming to serve dual purposes. Firstly, it was aimed to achieve the research objective 2 (Section 1.3) and to test the feasibility of applying environmental design strategies in existing RMG factoring (the hypothesis of Section 3.8) to improve the present condition. Secondly, it aimed to partially test the methodologies and limit

the scope of studies (explained in Section 6.9). The pilot study includes climatic and field data analyses, theoretical calculation and online questionnaire study. Figure 5-2 shows the summary of the major steps of the pilot study and relevant methods.

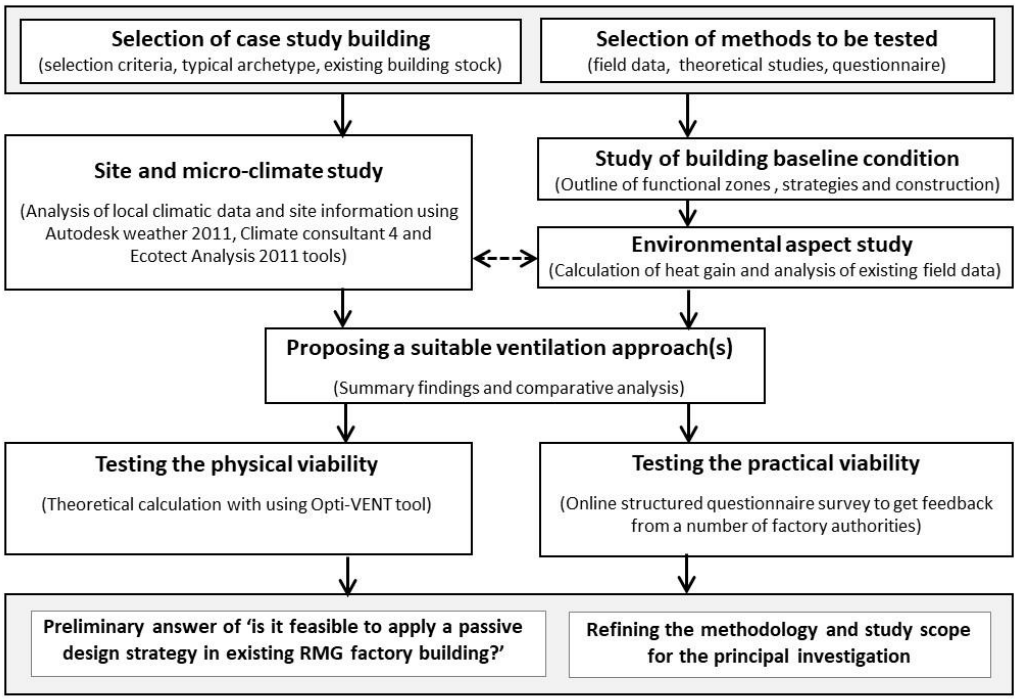


Figure 5-2: Summary of major steps of the pilot study

5.4.2. Selection of case a study building

As noted from the official website and database of the Bangladesh Garment Manufacturers and Exporters Association (BGMEA) in May 2014, there was a total of 5708 enlisted member garment factories in Bangladesh. As referred in Section 1.2, accords and alliance enlisted RMG factories were already in consideration for further refurbishment. Hence these enlisted factories were considered as the main reference to select the a RMG factory for a pilot study. Of these, 74.7%, 17.9% and 10.8% of factories are located in the Dhaka region (including Dhaka city, Savar and Gazipur), Narayanganj and Chittagong respectively (Foundation, 2013, Safety, 2013). 80% of these factories were also distinguished as the multi-storied building. As referred to previous studies, the key archetype of multi-storied garment factories is rectangular or 'shoe box' (Naz, 2008, Hossain, 2011, Fatemi, 2012). Therefore, it was reasonable to select a multi-storey RMG factory building within the Dhaka region assuming to represent a partial building stock and establish replicable outcome. However, it may

not represent the whole building stock due to variables such as site size and surrounding context, building orientations, number of building storey, planning etc.

According to the selection criteria used in a previous research by Hossain (2011), such as multi storey construction, regular rectangular form on a plan, the presence of extract ventilation fans and at least 500 number of workers work in the factory, a number of case study buildings were shortlisted (Figure 5-3). Considering the availability of previous empirical data set from the research by Hossain (2011), a multi-storied building with in the Dhaka region was selected for pilot study (Figure 5-4).

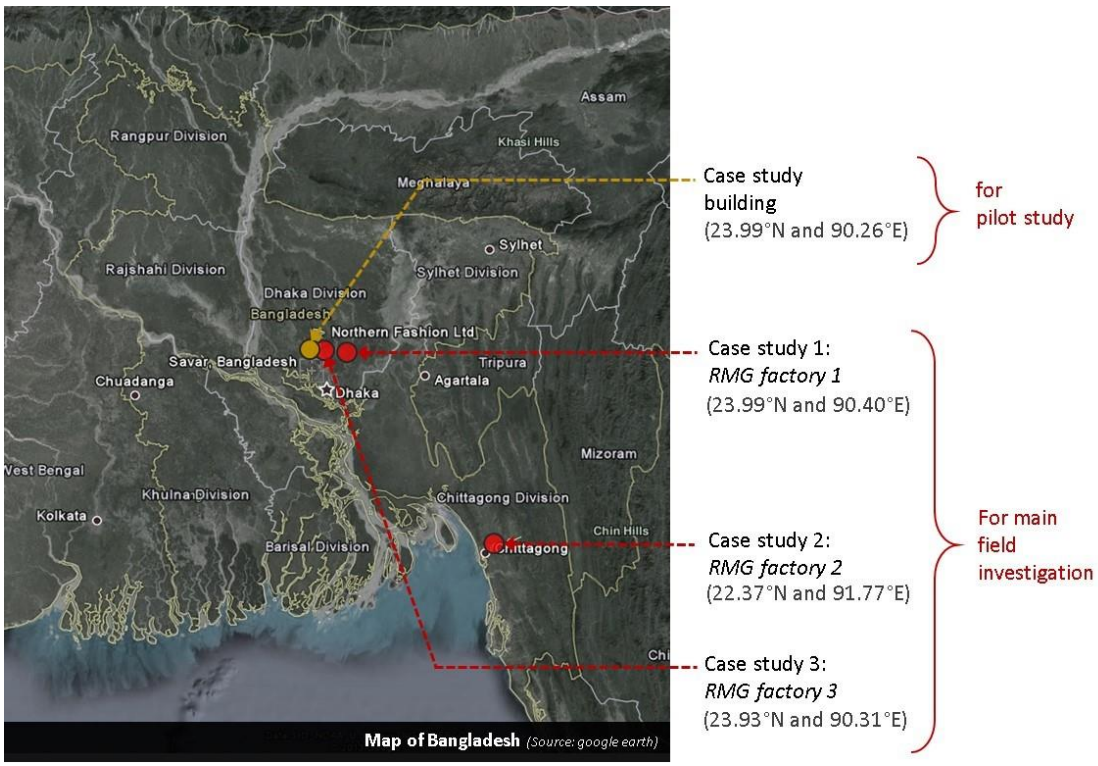


Figure 5-3: Location of the case study buildings for pilot study and main field studies in Bangladesh

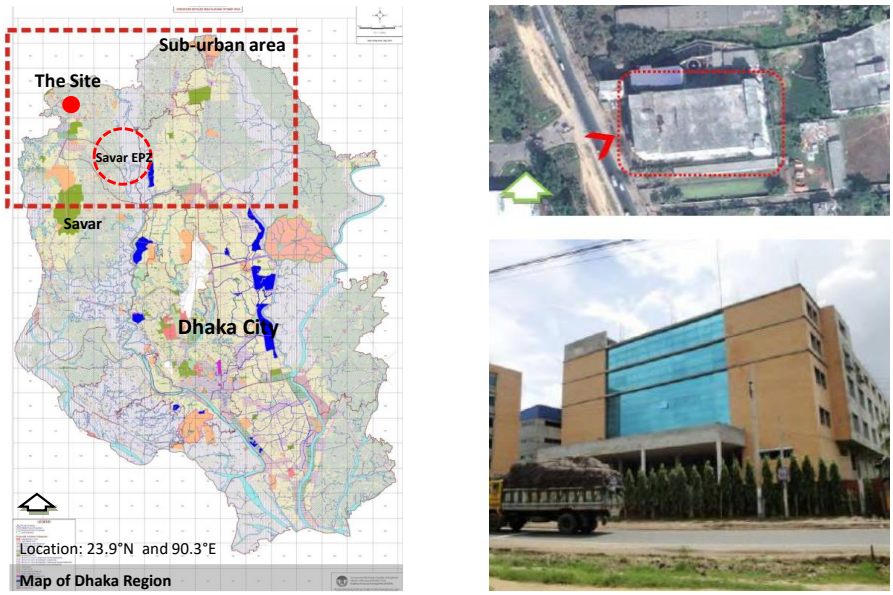


Figure 5-4: Selected case study building for pilot study within Dhaka region (source: Google Maps and map from the Dhaka City Corporation 2008)

The selected building has 6 floors including a mezzanine floor and is located in a semi-urban context near BEPZ (Figure 5-4). The typical floor width, ceiling height and floor area are 35.4m, 3.81m and 2250m^2 respectively. The building has the main openable windows on the north and south façades (explained in Sections 6.4 and 6.5).

5.4.3. Site and micro-climate analysis method

A qualitative and quantitative analysis of the building-site and micro-climate was undertaken to identify passive ventilation strategies suited to the climatic seasons encountered in Bangladesh. Figure 5-5 illustrates the main steps of the analysis.

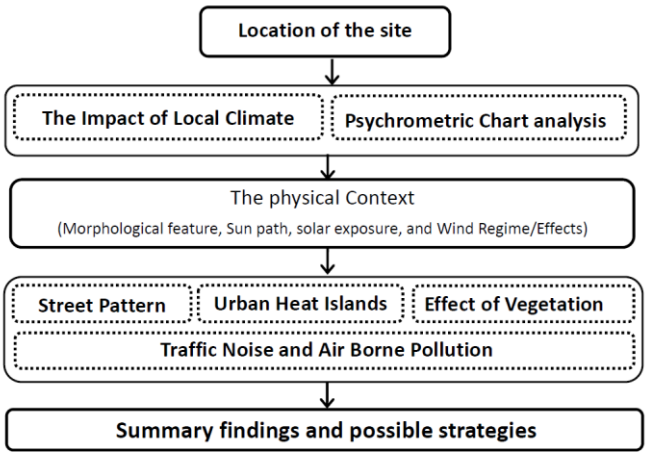


Figure 5-5: Major steps of site and microclimate analysis (after Ford et al. 2010)

The meteorological data for Dhaka, 26km away from the selected site, and weather file of the Dhaka region were used in computer tools such as 'Autodesk weather tool-2011' and 'Climate consultant-4' to explore climatic classification and applicability. The meteorological data were assumed as the micro-climate of the site. For the psychrometric chart analyses, initially assumed 'thermal comfort ranges', as outlined in Section 2.5.2, are followed. To support the site analyses, modelling and simulations were undertaken using 'Ecotect Analysis-2011' with a focus on shadows and solar radiation studies. The other analyses were undertaken using field data collected previously by the author in 2011, available drawings and Google Maps.

5.4.4. Building information and environmental data

The building information and thermal performance data were collected from author's previous research in 2011. A HOBO 'data logger' was used with the sensors measuring continuous indoor AT, RH and AV. The data logger was placed in the centre of the 1st floor at 2.1 m height from floor level (Figure 5-6, Appendix C-1).

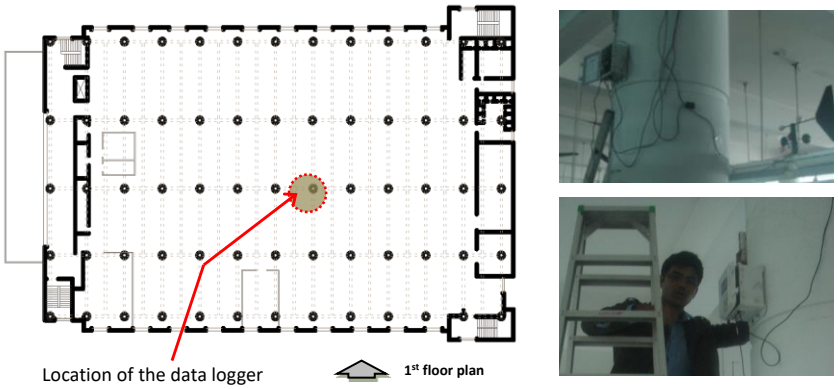


Figure 5-6: Location of the data logger in the selected building (source: Hossain 2011)

Other relevant information relating to the building, such as numbers of workers, activity types, the quantities of equipment with power ratings, architectural drawings were acquired from the author's previous M.Arch research project (Hossain, 2011) and updated with the further investigation in 2014.

5.4.5. Theoretical calculation method

A 'Microsoft Excel'-based calculation tool entitled 'Opti-vent ventilation', developed by Brian Ford & Associates, was used to calculate the ventilation flow rates and inlet opening areas required to remove the unwanted heat. Basic airflow and air cooling

equations are used in this tool following the CIBSE guides (CIBSE, 2006, p.4-10, CIBSE, 2005, p.45). In addition to fundamental principles of ventilation discussed in Sections 3.4 and 3.5, the following formulas and assumptions were considered during theoretical calculation:

Assuming the outside air is cooler than the indoor the indoor heat absorbed by the ventilation flow can be expressed by Equation 5-1.

$$Q_v = \frac{1}{3} nV(t_i - t_o)$$

Equation 5-1

Where, Q_v is the heat absorbed by the ventilation air (W), V is the volume of the zone (m^3), t_i and t_o are the indoor and outdoor air temperatures respectively and n is the air change rate. Hence, the ventilation flow rate required for cooling can also be derived by the Equation 5-2.

$$q_c = \frac{3Q_v}{3600(ti - to)}$$

Equation 5-2

Where, q_c is the air flow rate required for cooling (m^3/s). For stack driven ventilation, the air flow rate produced by the stack can be predicted from Equation 5-3:

$$q_s = 0.6A\sqrt{(2\Delta p}/\rho_i)$$

Equation 5-3

Here, q_s is the stack air flow rate (m^3/s), A is the effective inlet or outlet area (m^2), ρ_i is the density of the air inside the building (kg/m^3) and Δp is the pressure difference between the bottom and top stack with fixed discharge coefficient. The following formula (Equation 5-4) was used to calculate Δp:

$$\Delta p = \rho_i g H \left(\frac{T_i + 273}{T_o + 273} - 1\right)$$

Equation 5-4

Here, g is the acceleration due to gravity ($10m/s^2$), H is the Stack height measured between the centre of the inlet and the centre of outlet (m), T_i is the indoor

temperature (°C) often taken as the upper adaptive comfort band and T_o is the outdoor temperature (°C) based on the acceptable failure rate of the ventilation system.

To contextualise this tool for its application to the selected site in Dhaka, key input data, such as external solar gain (W/m^2), were replaced by the solar radiation data obtained specifically for this site from the 'Ecotect analysis 2011'. Heat gains to come from all equipment were estimated from their specification and energy efficiency data (Engineering ToolBox, 2004). Gains to the building to come from direct and indirect solar transmission were assumed (Table 5-2). The direct solar gains occurs via the windows, which were assumed 97.02m^2 of glazing area in the first floor have a transmittance of 0.75 and indirect solar gains were assumed to occur via opaque parts of the envelope, such as roof, which was assumed to have an absorption of 0.65 and U-value of 1.15 $W/m^2.K$ (Table 5-2). Direct and diffused solar radiation data were obtained from the 'EnergyPlus' weather file for Dhaka.

Table 5-2: Internal and external heat gain data for Opti-vent

Floors/ zone	**Internal heat gain parameters**				**External heat gain parameters**				
					Roof Surface absorbance: 0.65, Roof U-Value:1.15 $W/m^2.K$ Roof Ext. Surf. Conductance: 8.5 $W/m^2.K$				
	Equipment gain (W/m^2)	Lighting gain (W/m^2)	Total number of occupants at work (People)	Gain from Occupants (W/m^2)	Solar Rad: Vertical Surface (W/m^2)	Solar Rad: Horizontal Surface (W/m^2)	Vertical Glazing area (m^2)	Transmit-tance factor Vertical Glazing	Shading proportion factor Vertical Glazing (%)
Ground floor + mezzanine floor	35.7	5.7	50	3.7	350	550	94	0.75	10
1st floor	22.2	25.2	310	18.2	350	550	97.02	0.75	10
2nd floor	5.6	10.4	250	15.5	350	550	97.02	0.75	10
3rd floor	22.2	24.9	300	17.7	350	550	97.02	0.75	10
4th floor (Top floor)	22.2	10.0	320	19.3	350	550	97.02	0.75	10

Thermal comfort targets for each climatic season were set based on Section 2.5.2. Cooling load and required ventilation flow rate were calculated accordingly with this tool and associated formulas. The target design flow rates were assumed to be 1-2 ACH for fresh air and 12-15 ACH for comfort cooling (N. Baker, 2013).

5.4.6. Online questionnaire survey method

This pilot study also made use of a questionnaire study administered to the owners, managing directors and managers of the multi-storied RMG factories in Bangladesh. The main objective was to understand how receptive of these stakeholders would be to design strategies proposed for improving workers' thermal comfort. Initially, a number of multi-storied RMG factories in Bangladesh from the BGMEA website and Accord list were selected. The selection process was 'stratified random' where all the buildings must be multi-storied and within the representative building stock. A document related to ethical process can be found in Appendix B-4. An online questionnaire survey was completed using a freely available online application: 'Adobe Forms central'. Invitations to complete the survey were sent by email to 40 factory authorities and feedback was received from 18 respondents. Table 5-3 shows the objectives of the questions asked through online survey.

Table 5-3: Objectives of the 11 questions of the survey

Question no.	Objective of the questions
01 - 05	To collect stakeholders' feedback relating to factory base conditions
06	To understand stakeholders' perception about natural and passive ventilation in improving workspace environment
07 - 08	To measure stakeholders' interest in implementing proposed design strategies through undertaking refurbishments
09 - 11	To get an idea of stakeholders' view on acceptable budget, payback plan in relation to implementing design strategies and their opinion on possible constraints

Within the questionnaire, 11 structured questions (Appendix D) were framed to understand respondents' perception about natural ventilation and electrical energy consumption in their factories, to infer their interest in undertaking refurbishments and to identify possible constraints (Table 5-3).

5.4.7. Limitations within this methodology

Since the pilot study was completed without a field visit, due to getting limited consent from the factory, all the methods of study could not be modelled and tested. For instance, questionnaire survey and focus group discussion methods for collecting

subjective data on occupants' comfort and adaptation strategies could not be undertaken and no simulation study was conducted in this stage due to lack of valid data from the field.

5.5. Methodology of the Main Field Studies

5.5.1. Aim and scope of study

The field studies were aimed to made use of site and micro-climate study, environmental data collection and subjective response collection from occupants and building owners and meet the research objectives 3 and 4 (Section 1.3). Moreover, the data will also be used to validate the simulation study (Section 5.6. Figure 5-7 shows a summary of the major steps of studies and relevant methods used in the studies.

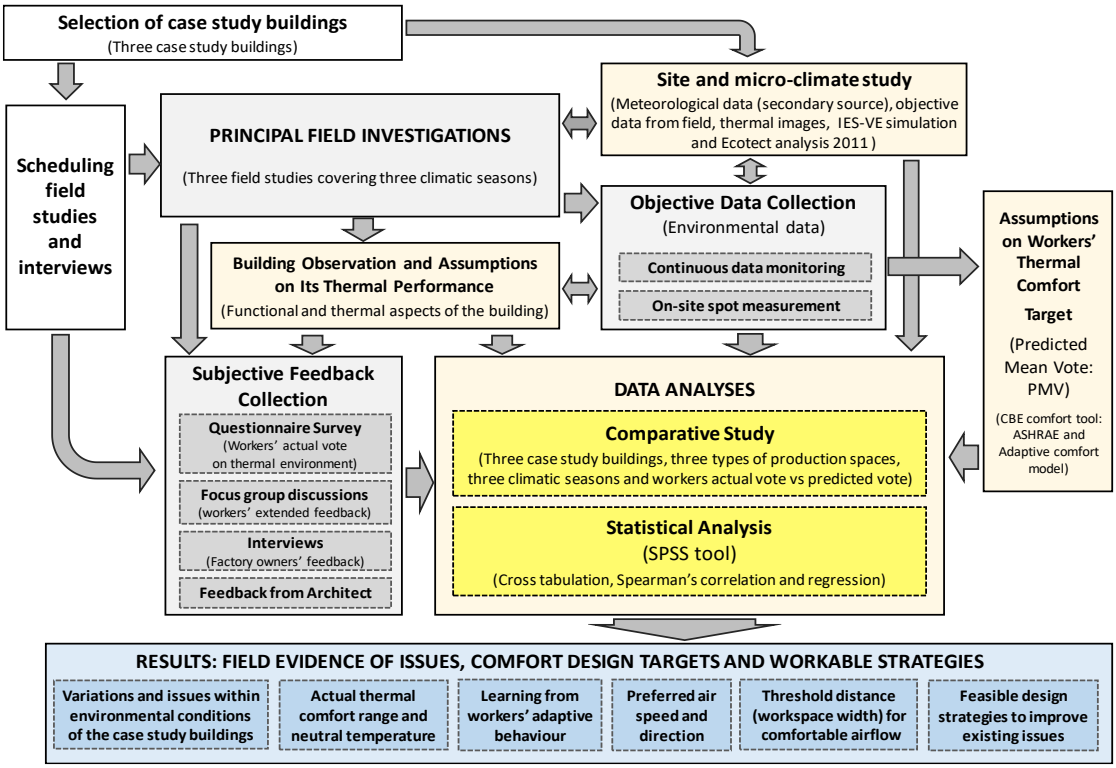


Figure 5-7: Summary of major steps and methods used in this chapter

5.5.2. Selection of case study buildings

The selection criteria were same as stated in Section 5.4.2. However, an up-to-date building stock of 6000 RMG buildings, including Chittagong region was used for the selection. Seven multi-storied building were initially shortlisted, and consent were secured through a number of steps including a recommendation letter from BGMEA (letters attached in Appendix B). However, based on further approval from the owners

of the RMG factories, three multi storey case study buildings were selected for principal investigation. Figure 5-3 shows the location of three multi-storey case study buildings that were selected in the Dhaka and Chittagong regions of Bangladesh. The images of the buildings were presented in Figure 5-8.



Case study building-1: *RMG factory 1*



Case study building-2: *RMG factory 2*



Case study building-3: *RMG factory 3*

Figure 5-8: Selected three case study buildings for main field studies

In order to maintain the privacy of the RMG factories, the case study buildings' original names are not presented in this thesis. Case study building-1 (*RMG factory 1*) and case study building-3 (*RMG factory 3*) are located in the Dhaka region. Case study building-2 (*RMG factory 2*) is located in the Chittagong region, 250km to the south-east of Dhaka. Figure 5-9 provides an insight of the three case study buildings with their building shape, workspace width, WFR and average number of workers per floor.

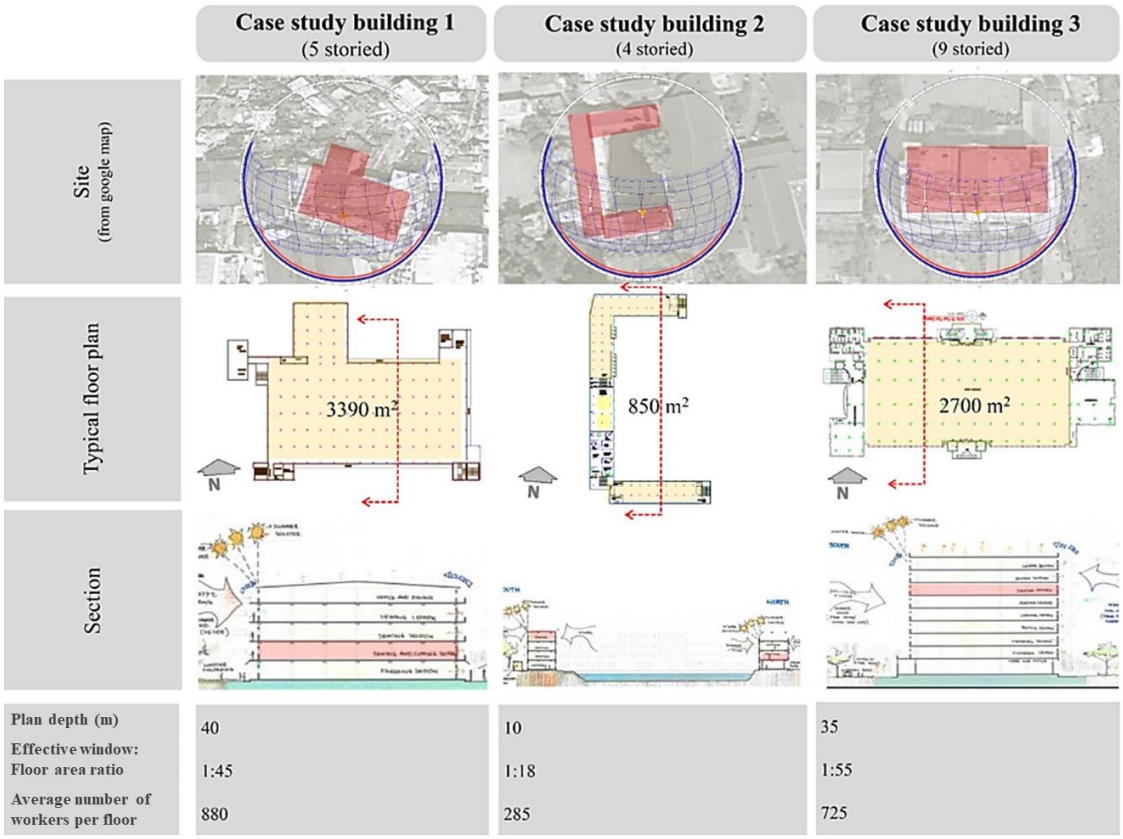


Figure 5-9: Site, typical floor plans, sections and information of three case study buildings

The detail of regional context, site and building information of these case study building are provided in Chapters 7, 8 and 9.

5.5.3. Schedule of field studies and interviews

Three main field studies were conducted, one during each of the climatic seasons in the year of 2015. The data collected therefore are assumed to provide a representative picture of full year. Table 5-4 shows the detailed schedule of the field studies in three case study buildings. Access to the buildings was limited however permission was secured for around 7-10 days of data collection including at least one weekend or official closure day, as the short-term survey method (Section 4.5.2). However, in some

cases, the standard duration could not be followed. Interviews with building owners and managing directors were also arranged in August 2015, as shown in Table 5-4.

Table 5-4: Schedule of field data collection for three case study buildings in the year of 2015

Field study no.	Main Seasons	Scheduled field visits for all three case study buildings	Case study building	Scheduled field study for field studies in *RMG factory 1*				
				Environmental data collection		Subjective Response collection		
				Continuous data monitoring*	Onsite spot measurement	questionnaire interviews with workers	Focus group discussions with workers	Interview with the factory owners
		Dates (duration)		Dates (duration)	Dates (duration**)	Dates (duration**)	Dates (duration)	Dates (duration)
One	Cool-dry (Dec-Feb)	4 January - 5 February (33 days)	*RMG factory 1*	4 - 13 January (10 days)	4 - 13 January (9 working days)	4 - 13 January (9 working days)	7 January (50 minutes per group)	-
			RMG factory 2	15- 24 January (10 days)	15- 24 January (8 working days)	15- 24 January (8 working days)	20 January (50 minutes per group)	-
			RMG factory 3	26 January – 5 February (11 days)	26 January – 5 February (10 working days)	26 January – 5 February (10 working days)	4 February (50 minutes per group)	-
Two	Hot-dry (Mar-May)	4 April - 5 May (32 days)	*RMG factory 1*	4-13 Apr (10 days)	4-13 April (9 working days)	4-13 April (9 working days)	-	-
			RMG factory 2	15-27 April (13 days)	15-27 April (11 working days)	15-27 April (11 working days	-	-
			RMG factory 3	23 April – 5 May (13 days)	23 April – 5 May (11 working days)	23 April – 5 May (11 working days)	-	-
Three	Warm-humid (Jan-Nov)	5 August – 2 September (29 days)	*RMG factory 1*	5-12 Aug (08 days)	5-12 August (7 working days)	5-12 August (7 working days)	-	19 August 2015 (50 minutes)
			RMG factory 2	13-19 August (7 days)	13-19 August (6 working days)	13-19 August (6 working days)	-	17 August 2015 (50 minutes)
			RMG factory 3	21 August – 1 September (12 days)	21 August – 1 September (11 working days)	21 August – 1 September (11 working days)	-	(25 August 2015 (50 minutes)

**Main data monitoring schedule. However, additional field experiments were conducted outside this schedule.*
***Working days are usually from Saturday to Thursday. Working hours are 08:00-20:00 (RMG factory 1) and 08:00-19:00 (RMG factory 2 and RMG factory 3) with an hour of lunch break between 13:00-14:00.*

5.5.4. Site and micro-climate study method

In cases of *RMG factory 1* and *RMG factory 3*, the meteorological data (year 2015) for Dhaka, recorded 25km and 12km away from the selected sites respectively, and up-to-

date weather file of the Dhaka along with computer aided tools such as 'Autodesk weather tool-2011' have been utilised for initial evaluation of the sites. Similarly for *RMG factory 2*, the meteorological data (year 2015) of Chittagong, recorded in 5km away from the selected site, and up-to-date weather file of the Chittagong were used. Modelling and simulations have been accompanied with the 'IES-VE 2017' and 'Ecotect Analysis-2011' tools for analysing shadows and incident solar radiations. The other analyses were completed based on the environmental data collected during field studies, e.g. outdoor AT, RH, AV, ST and thermal images (explained in Section 5.5.6).

5.5.5. Building observation and Performance assumptions

Architectural drawings including furniture, equipment and floor layouts are collected from the case study buildings' administrative office and verified with field measurements. To estimate the internal heat gain and electrical energy demand for production floors, monthly bills, equipment's specifications and official documents were collected from the administrative office of the building. A number of field observations, such as thermal imaging, air speed measuring, were also made to crosscheck the potential heat gain and efficiency of existing equipment, fans and lights and their running hours against the available documents and reports. Main construction elements, such as external walls, ceilings, floor slabs, etc. were also observed during field studies and estimates of their thermal properties were made by the author with the help of data from 'IES-VE 2017' simulation tool. Base one the preliminary observations, hypotheses or assumptions were made on the thermal parameters that may affecting the thermal performance of building. These assumptions were tested through studying the objective and subjective data (Sections 5.5.6 and 5.5.7)

5.5.6. Objective data collection

Objective data collection was undertaken through physical measurements at all case study buildings. Continuous data logging and spot measurement methods were used collect the environmental data at both indoor and outdoor areas following ISO 7726 (1998) standards.

5.5.6.1. Continuous data logging

During field studies at *RMG factory 1, c*ontinuous outdoor data logging was undertaken at three different positions (i.e. near to the ground floor level, 2nd or 3rd floor level and at the roof level). In particular, outdoor AT and RH were continuously measured using Tinytag data logging sensors (types TGU-4500 and TV-4505) (Appendix C-2) 8m above the ground floor level on the south side of the building and 3m above the roof level. Moreover, the external probes of the data loggers were also used on the 1st floor to compare between indoor and outdoor environment (as shown in Figure 5-10).

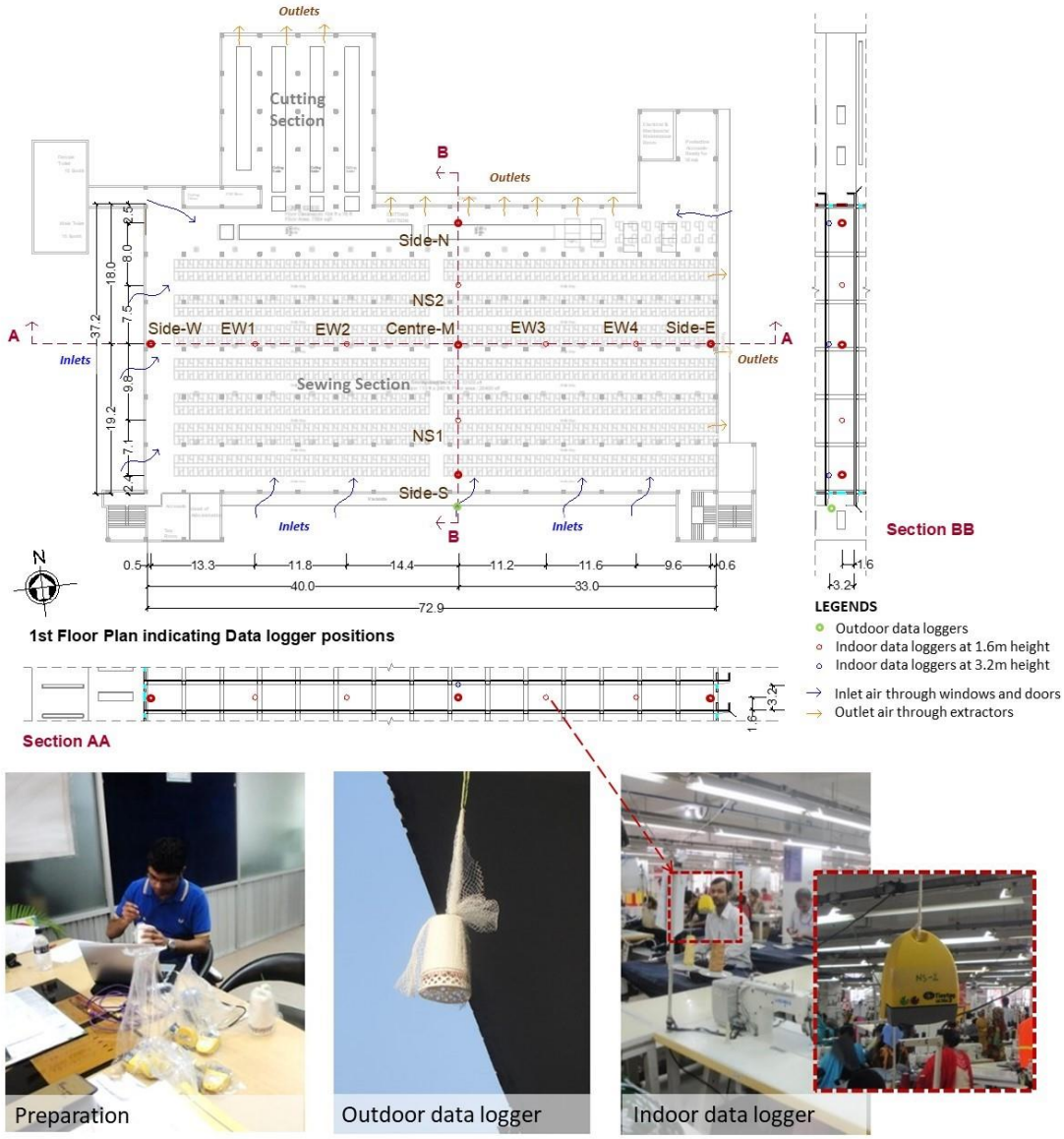


Figure 5-10: Location of data logger sensors on 1st floor of *RMG factory 1* to monitor horizontal and vertical distribution of AT and RH

To collect continuous indoor AT and RH data at *RMG factory 1*, data loggers were used placing approximately at 1.6 m and 3.2 m level above the floor level (Figure 5-10) in one of the production floors. Data were continuously monitored in every 30 minutes for a minimum 7 days covering at least a weekend or an official closure day to compare the thermal performance with and without internal heat gains. One set of sensors were located along a line running between the ventilation inlets and outlets, as indicated in Figure 5-10 and a second set were located along a line perpendicular to this. These locations were selected in order to obtain a picture of AT variation across the production space. An additional data logger was also placed in the cutting section (extended north-west wing) on the first floor to measure AT and RH of cutting section. There were another set of data logger sensors placed in each floor of the building and production space for comparative study.

For *RMG factory 2*, same methods and assumptions were followed. However, the outdoor data loggers were placed at 3m above the roof level only due to security issue at the site. Figure 5-11 shows the location of both indoor and outdoor data logger sensors in *RMG factory 2*. Since the building archetype is C-shaped, the blocks of the buildings were divided into South-wing, North-wing and West-wing (Figure 5-11).

For *RMG factory 3, s*ame methods and assumptions were followed. The Outdoor data loggers were placed at the 1st floor and 8th floor level. Figure 5-12 shows the location of the data logger sensors in *RMG factory 3*. Since the building is nine storied, the indoor data loggers were positioned on the ground, 1st, 4th and 8th floors representing the storage, FS, SS and CS respectively.

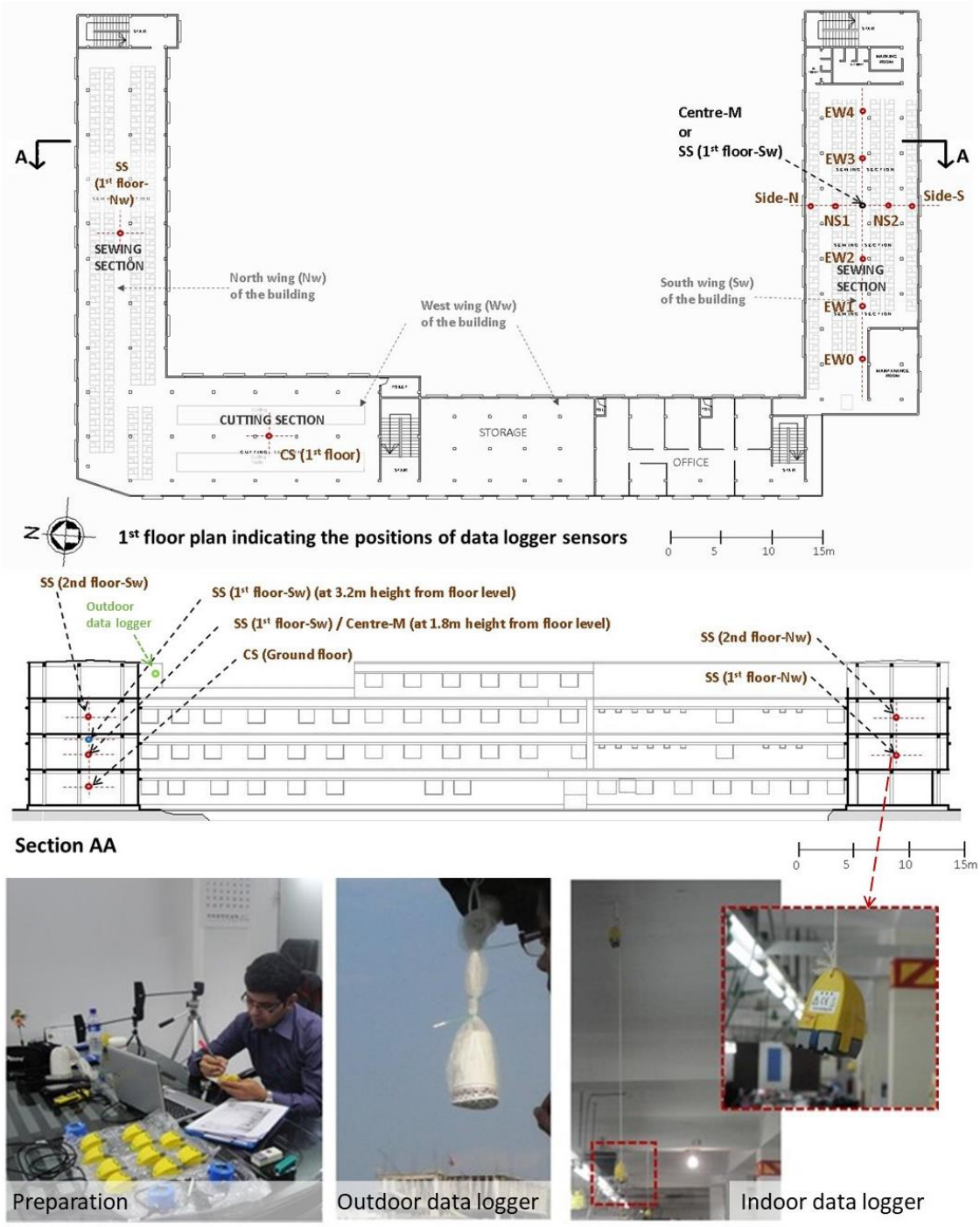


Figure 5-11: Location of data loggers on various floors of *RMG factory 2* to monitor horizontal and vertical distribution of AT and RH

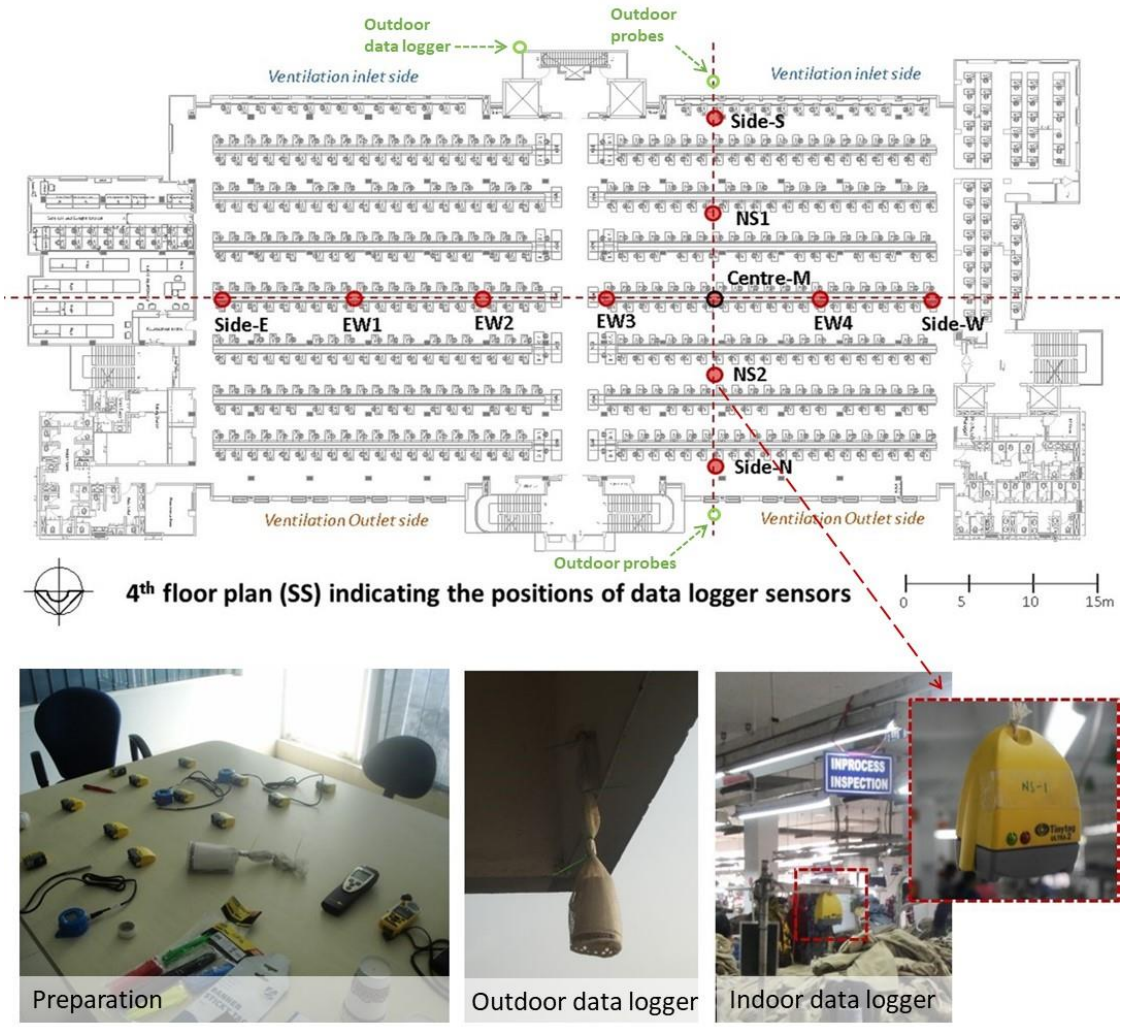


Figure 5-12: Location of data logger sensors on the 4th floor of *RMG factory 3* to monitor AT and RH

5.5.6.2. Spot measurements

In all case study buildings, regular spot measurements were undertaken to record indoor thermal and ventilation conditions. Different production sections, such as the CS, SS and FS are located on different floors of these multi-storey RMG factories. As they have different occupant density and internal heat gains, separate surveys were made of each floor (Figure 5-13). The spot measurements included AT, RH, ST, AVFR, GT, AV, additionally carbon dioxide (CO_2) and carbon monoxide (CO). These were made using hand held instruments including a FLIR Thermal Imaging Camera (Modelno-E60), Infrared Thermometer (Raytek mini-temp MT4), vane anemometer (Testo 417), heat stress tracker (Kestrel 4600) with portable Vane Mount (Model: KVANE–0791) and CO/CO_2 monitoring device (Testo 315-3). A laser distance measuring instrument (Stanley TLM-165) was used to locate the measured spots (Appendix C-2).



RMG Factory 1



RMG Factory 2



RMG Factory 3

Figure 5-13: Spot measurement procedures within all case study buildings

To ensure the accuracy of the spot measurement at workstations during workers' comfort survey, both 'CLASS I' and 'CLASS II' protocols were maintained (Section 4.5.5). The hand-held instruments were placed close to the workers' personal working area at 0.1m, 0.6m and 1.1m heights from floor levels, similar to a standard practice titled 'Cart Mk II' used for indoor climatic data acquisition (de Dear and Fountain, 1994, Brager and de Dear, 1998) with the help of different height of tripods (Figure 5-13). From these an average reading was taken for analysis providing a measure of thermal experience of the worker within their workstation volume (assumed as 1.5m×1.5m×1.5m). The air speed was also measured at three vertical levels as well as in different directions (North-south, East-west and Up-down), during the hot-dry and warm-humid seasons while all the ceiling fans were switched on. The Testo-417 was used to monitor and calculate the average air volume flow rate (AVFR) (in m^3/s) in the

production floors (Figure 5-13). Surface temperature profiles of the building envelope (indoor and outdoor), various equipment inside the production spaces (i.e. sewing machines, irons, lights, fans, fusing machines etc.) were measured with the help of the Infrared thermometer and thermal imaging camera during the survey.

5.5.7. Subjective feedback collection

5.5.7.1. Stakeholders

Following the guidelines referred in Section 4.5.3, the workers, managing directors, owners and architect of case study buildings were considers as the stakeholders for subjective data collections. The details of the selected stakeholders and subjective data collection methods are provided within the Sections 5.5.7.2 - 5.5.7.5.

5.5.7.2. Questionnaire and sampling for comfort survey

A questionnaire survey was used to collect qualitative and quantitative data from the workers about their thermal comfort perceptions at their workstations for the different climatic seasons and to understand any adaptive behaviours they practice. *'Transverse survey'* (i.e. snapshot survey) method was applied and questionnaire was designed accordingly (as suggested in Section 4.5.5). Spot measurements were also undertaken simultaneously maintaining both CLASS I and CLASS II protocols (as stated in Sections 4.5.5 and 5.5.6.2).

The whole set of the 'structured questionnaire' were also developed with minor adjustments based on a preliminary study. Since the workers were not allowed to leave their work desk while answering the questions and majority of them were not be educated enough to read the questionnaire; the individual questionnaire was filled in by the researcher though interviewing the workers at their work desks with assistants provided by the factory authority (Figure 5-14). To ensure their clear understanding of all procedures, questions were presented in 'Bengali' which was their native language (translated) and the questionnaire interviews were held in 'Bengali' language as well. During this comfort survey, subjective thermal responses of workers were assessed in their actual indoor environments. Responses of three environmental variables and relevant to indoor ventilation were investigated under three separate sections with a minor repetition of similar answers to crosscheck among the answers. The questions

directly related to their comfort (i.e. sensation, comfort-perception and preference) and adaptive behaviour were asked among all the subjects during the spot measurements. The 'workers' personal information' in the questionnaire was also collected from their ID card, personal information sheet attached to the workstation and individual workers' response. The detail of the questionnaire and spot measurement forms were included in Appendix E-1.



RMG Factory 1



RMG Factory 2



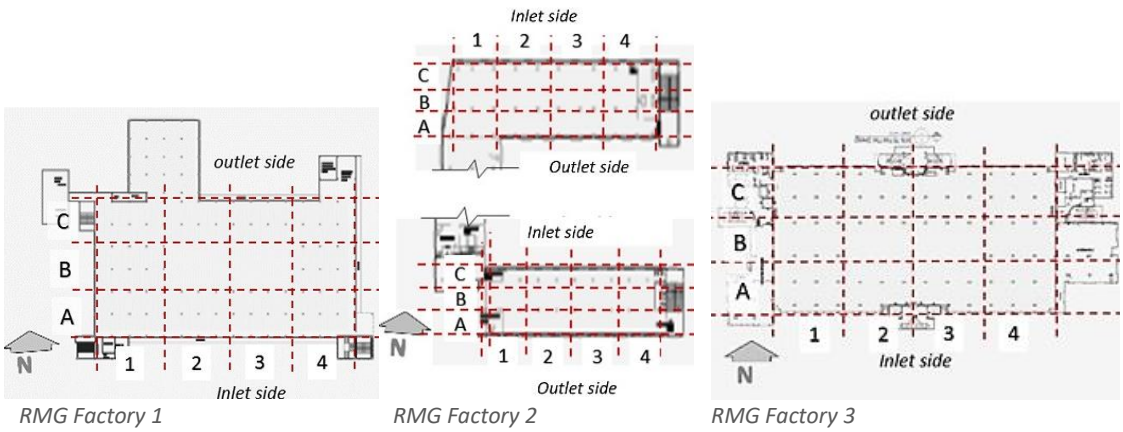
RMG Factory 3

Figure 5-14: Questionnaire survey among workers with the simultaneous spot measurements

A 'Personal comfort questionnaire' was developed following the established comfort models as stated in Sections 2.5.1 and 4.5.5. Particularly, based on the literature review on developing thermal comfort standards (Peretti and Schiavon, 2011), 'ASHRAE 55' comfort model was chosen to collect the 'Thermal Sensation Vote' (TSV) through a 7-scale questionnaire study (Wilson and Corlett, 2005, p.556). For measuring votes of

thermal sensation, humidity and airflow '-3 to +3 scales' (for examples 'cold, cool, slightly cool, neutral, slightly warm, warm and hot' for TSV) suggested by ASHRAE 55-2013 were used. An additional vote using the Bedford scale (Wong et al., 2003) was also collected on the existing 'indoor air quality' which was described to the subjects as 'freshness of air'. Four additional customised questions exploring general comfort using scales of 'comfortable' or 'uncomfortable' were also added by the researcher to generate data for comparison with the TSV. The 'McIntyre' preference scale (Fountain et al., 1996) was also adopted in three questions for this research.

Due to the frequent turnover of staff in the factory, it was not feasible to choose the same group of subjects for the comfort study in each field study. Hence sample size varied for each season (i.e. each scheduled field study) based on the limited working hours of survey allowed inside the factories and availability of assistance from the factory. However, the location of the workstation was kept similar in all three field study visits to maintain some consistency of the data set. In each field study, the subjects were selected ensuring the equal percentage of subjects in each demarcated zone shown in Figure 5-15. The 12 demarcated zones are numbered A1 to C4 and the location of workstations in respect to inlets and outlet windows were documented within a production floor. A standard approved ethical procedure using relevant documents (i.e. invitation letter, information sheets, and consent forms with subject's signature) were used to administer the surveys (Appendix B-5).



RMG Factory 1 *RMG Factory 2* *RMG Factory 3*

Figure 5-15: Defined zones within the building floor indicating distribution of subjects surveyed in each field study

Table 5-5 provides the profile of the participants under this comfort study. The typical number of workers per production floor in the case studies *RMG Factory 1*, *RMG Factory 2* and *RMG Factory 3* were 880, 285 and 725 respectively (Figure 5-9). Personal information, on-site spot measurements and observations were carried out with a total of 908 RMG factory workers at their work desks in different seasons. 291 subjects (32%) were male workers while 617 (68%) subjects were female. The higher percentage of female respondents represent a higher number of female subjects reflecting the higher population of female in these production sections. The comfort survey was conducted with approximately 98% response rate.

Table 5-5: Profile of the subjects in terms of three field studies and case study buildings

Case study building	Field visit no.	Season	Subject (Nos.)	Sex	Nos. (%) of subjects	Mean age (years)	Mean weight (kg)	Mean height (m)	Mean Clo value
RMG factory 1	One	Cool-dry	80	M	28 (35%)	26	59	1.7	0.67
				F	52 (65%)	25	53	1.5	0.50
	Two	Hot-dry	115	M	49 (43%)	26	60	1.7	0.60
				F	66 (57%)	25	53	1.5	0.51
	Three	Warm-humid	61	M	27 (44%)	28	69	1.7	0.53
				F	34 (56%)	26	58	1.5	0.52
	Total (three seasons)		**256**	**M**	**104 (41%)**	-	-	-	-
				F	**152 (59%)**	-	-	-	-
RMG factory 2	One	Cool-dry	150	M	26 (17%)	25	56	1.7	0.66
				F	124 (83%)	25	49	1.5	0.53
	Two	Hot-dry	100	M	15 (15%)	24	61	1.7	0.62
				F	85 (85%)	24	53	1.5	0.51
	Three	Warm-humid	66	M	17 (26%)	26	67	1.7	0.50
				F	49 (74%)	26	60	1.5	0.51
	Total (three seasons)		**316**	**M**	**58 (18%)**	-	-	-	-
				F	**258 (82%)**	-	-	-	-
RMG factory 3	One	Cool-dry	154	M	52 (34%)	26	56	1.7	0.71
				F	102 (66%)	24	49	1.5	0.50
	Two	Hot-dry	112	M	52 (46%)	28	62	1.7	0.62
				F	60 (54%)	27	54	1.5	0.55
	Three	Warm-humid	70	M	25 (36%)	27	68	1.7	0.50
				F	45 (64%)	26	56	1.5	0.50
	Total (three seasons)		**336**	**M**	**129 (38%)**	-	-	-	-
				F	**207 (62%)**	-	-	-	-
Total (three field visits and three case study buildings)			**908**	**M**	**291 (32%)**	**25.7**	**55.4**	**1.56**	**0.54**
				F	**617 (68%)**				

Here, M=Male, F=Female

All the participants were within the age group of 19-55 years, where mean age recorded was 25.7 years (SD = 4.72 years) with the higher frequency of 25 years. Their weight varied from 40kg to 89kg with a mean weight of 55.36Kg (SD = 7.47kg). Their heights were also within the range of 1.24- 1.78m where average mean height was 1.56m (SD = 0.092m). 23.3 months and 17.8 months were the mean work experiences of the male and female subjects respectively. This ensures that the workers had enough time to be acclimatised with local climate and indoor environment.

All Clo and Met values were calculated based on the collected information on 'clothing type' and 'activity level before and during the survey' (Appendix E-1). The clothing of the workers varied due to not only the gender variations (i.e. male or female) but also seasonal distinctions. The Clothing insulation (Clo) values of all the subjects were estimated using the standard lists and summation formula (ASHRAE, 2009, Berthold et al., 2007, Indraganti, 2010, CIBSE, 2013). From the pilot study, the common clothing types (both for male and female) were pre-categorised and calculated based on the Clo values, such as, short sleeve T-shirt (SST) with trousers = 0.5, full sleeve short T-shirt (FSST) with trousers = 0.8, cotton 'Salwar Kameez' (CSK) = 0.5, Sharee = 0.57, CSK with 'head scurf' = 0.67, any clothing with sweater = 1.0 etc. The Clo values of the all studied participants varied from 0.50 to 0.97 where the mean value was 0.54 (SD = 0.11). Met values (metabolic rate) were calculated ranging 1.0-1.8. Here the Met values of the subjects in active cutting, stamping (while standing), Ironing (while standing), sewing, finishing (sewing buttons) and any activity in pause (resting on a seat) were estimated as 1.8, 1.7, 1.7, 1.4, 1.4 and 1.0 respectively (CIBSE, 2013, ASHRAE, 2013, ASHRAE, 2009) (Section 2.5.2). It was determined after the study that 69.3%, 9.1%, 8.3%, 7.8% and 5.5% of the studied subjects had the Met values of 1.4, 1.7, 1.2, 1.8 and 1 respectively.

5.5.7.3. Focus group discussions

Total six focus group discussions were conducted to gather detailed feedback from workers in an informal manner (Figure 5-16). The discussions explored their thermal perception at their existing workstations during the different climatic seasons, their adaptive comfort strategies, and on how their existing workspace environment might be improved. 8–9 participants participated in each focus group discussion. The

structure of the discussion, sampling and group size were designed according to the published guides provided by University of Westminster, UK and BRE building performance guide for post-occupancy evaluations (Mishra and Ramgopal, 2015, Field and Hole, 2006, HEFCE, 2006, Jaunzens et al., 2003) and as referred in Section 4.5.4. Standard ethical procedures were followed (letter attached in Appendix B-5).



Here, ***focus group one:*** *workstations located close to windows or outlet fans,* ***focus group two:*** *workstations remote from windows*

Figure 5-16: Discussions with six focus groups in three case study buildings

Table 5-6 provides details of the participant from two focus groups. One group consisted of workers whose workstations were located close to the windows or outlet fans, while the other group consisted of workers whose workstations were remote from windows, usually close to the middle of the production floor. All the participants in the groups had at least two years of work experience and it was presumed that their

feedback would reflect their personal thermal experience during various seasons of previous 2 years in this factory.

Table 5-6: Details of the participants from the six focus groups within three case study buildings

Group	Participant no.	*RMG factory 1*					*RMG factory 2*					*RMG factory 3*				
		Sex**	Age (years)	Height (m)	Weight (Kg)	Workspace type***	Sex**	Age (years)	Height (m)	Weight (Kg)	Workspace type***	Sex**	Age (years)	Height (m)	Weight (Kg)	Workspace type***
Focus group one*	1	M	25	1.68	59	FS	M	26	1.68	65	SS	F	26	1.52	49	SS
	2	M	24	1.68	65	SS	M	21	1.50	45	SS	F	23	1.55	45	FS
	3	M	25	1.75	62	FS	M	21	1.70	60	CS	F	30	1.52	52	FS
	4	F	24	1.42	45	SS	M	25	1.68	58	SS	F	20	1.50	52	CS
	5	F	30	1.45	55	SS	M	20	1.68	59	FS	F	35	1.55	56	SS
	6	F	25	1.52	50	SS	F	27	1.65	57	SS	F	20	1.54	49	SS
	7	M	55	1.75	65	CS	F	38	1.55	49	SS	M	23	1.72	62	FS
	8	M	28	1.68	65	CS	F	19	1.50	49	SS	M	24	1.68	58	CS
	9	M	23	1.70	60	CS	-	-	-	-	-	-	-	-	-	-
Focus group two*	1	M	25	1.70	60	SS	M	38	1.60	56	FS	M	38	1.65	52	CS
	2	M	22	1.68	60	SS	M	23	1.68	59	SS	F	22	1.52	51	FS
	3	F	25	1.52	60	FS	M	25	1.58	55	SS	M	22	1.52	42	FS
	4	F	28	1.52	52	SS	M	22	1.65	53	CS	M	26	1.73	63	FS
	5	F	26	1.45	50	SS	F	24	1.50	55	SS	F	36	1.52	40	SS
	6	F	26	1.47	50	SS	F	20	1.50	49	SS	F	28	1.50	40	SS
	7	F	43	1.52	56	CS	F	21	1.45	40	SS	M	35	1.73	65	CS
	8	M	20	1.63	55	FS	F	35	1.52	51	SS	M	37	1.52	54	CS

Focus group one: *workstations located close to windows or outlet fans,* **Focus group two:** *workstations remote from windows; **M=Male, F=Female; ***CS: Cutting Section, SS: Sewing Section and FS: Finishing Section*

Appendix E-2 provides the 'questionnaire form' used to record the focus group discussions. The outcome of the focus group discussions was crosschecked with the questionnaire study results to help identify measures of improvement.

5.5.7.4. Interview with the factory owner and directors

Total three interviews were arranged and undertaken with the building owners with the presence of managing directors of three case study buildings. The main aim of the interviews was to gather their perception of the existing thermal conditions in the RMG production spaces, discuss the scope for improvements and understand the viability of introducing a list of design changes into their existing RMG factory buildings. The list focused on design proposals that might help improve their factories' existing indoor environment and thermal comfort conditions.

Approved ethical procedures were followed in this study (letter attached in Appendix B-6. Appendix E-3 includes the five main agenda of each interview with semi-structured questions that were posed to the participants during the interviews. The questions were designed to seek their feedback on the RMG working environment, views on the value of improving the present conditions and whether these is value in implementing the proposed design interventions in their existing as well as new RMG buildings.

5.5.7.5. Feedback from building designers

It was originally planned to arrange and conduct an interview with the architects of all case study buildings for better understanding the design intention and environmental design considerations for workers' thermal comfort at the design stage. However, no formal interview could be arranged since *RMG factory 1* and *RMG Factory 2* were not purpose-built and no valid name of the architect of these factories was found. In contrast, *RMG factory* 3 was purpose built and an informal interview with the architect was arranged in January 2015. However, no further formal interview was undertaken due to protect personal data and unavailability issue within a given timeframe.

5.5.8. Preliminary assumptions and analysis methods

5.5.8.1. Predictions and preliminary assessment

The analyses of the field data gathered were limited to preliminary quantitative assessment of the workers' thermal comfort. Only the spot measurement data were evaluated being used as a comparator against predicted and assumed thermal comfort targets (Section 4.5.5). The quantitative data on workers' actual thermal perception

were assessed using descriptive statistics, such as histograms or frequency of subjective response.

To visualise spot measured data on a psychrometric chart and obtain a preliminarily prediction of the thermal comfort vote, the 'CBE Thermal Comfort Tool' was used. This is a web-based application (Tyler et al., 2013) that compliances with the ASHRAE-55 2013 standard (Schiavon et al., 2014). It is able to predict the comfort zones by providing PMV, PPD, TSV, SET (based on P.O. Fanger's PMV model) and OT ranges for both 80% and 90% acceptability status (based on adaptive method). By utilising an additional feature of this tool, all the onsite spot measurements and respondent's physiological data (i.e. AT, MRT, AV, RH, Met and Clo) were uploaded and plotted on the ASHRAE psychrometric chart (e.g. AT vs Humidity ratio) to visualise the predicted thermal comfort scenario for the different climatic seasons in respect to ASHRAE-55 standard. However, the main limitations of this system was it may not represent the actual votes considering the occupants capacity of adaptation with the climate and thermal environment. Hence results achieved from this tool were only used for comparing with and validating the actual comfort votes during field studies.

Mean values of OT, WBGT and MRT were also calculated and included in a summary data base of spot measurements to assess workers' thermal performance at their workstations. The calculation methods are explained below.

Operative temperature (T_{op}) combines the mean radiant temperature (T_{mrt}) and T_a and has been widely used in previous research studies combining the factors of behavioural and physiological adaptations (Schweiker and Wagner, 2015). To predict the comfortable OT range, the adaptive method was applied (Section 2.5.1.2) and using as an input was prevailing mean outdoor AT data to determine its' applicability compared to PMV method (Luo et al., 2015, Yau and Chew, 2012). Data were used for those workers with a Met value ranging 1.0-1.3, who have full provision to operate the nearby windows or fans as well as have freedom to change their clothing within the Clo values 0.5-1.0 (Schiavon et al., 2014). To assess the heat stress of the workers, WBGT was used which combines the effects of AT, RH, MRT and air speed in a single value (Bernard and Hanna, 1998, Parsons, 2006, Chowdhury et al., 2017b). For indoor

workspaces exposed to negligible levels of solar radiation, WBGT was calculated using the following formula (Moran et al., 2001):

$$T_{wbgt=} 0.7T_w + 0.3T_g$$

Equation 5-5

Which is valid for observations made when AV lies between 0.25 and 3 m/s and wet-bulb temperature, $T_w = T_{nwb}$, $T_g = T_a$

The mean radiant temperature (T_{mrt}) at workstations was derived from the measured globe temperature based on the following formula and utilising the 'CBE Thermal Comfort Tool' (ISO, 1998, Schiavon et al., 2014, p.333):

$$T_{mrt} = [(T_g + 273)^4 + 2.5 \times 10^8 . v^{0.6}(T_g - T_a)]^{1/4} - 273$$

Equation 5-6

Where T_{mrt} is mean radiant temperature (°C), T_g is the globe temperature for a standard globe (diameter of the globe = 0.15m**, the emissivity of the globe= 0.95) (°C), T_a is air temperature (°C) and v is air speed (m/s). The globe thermometer used in this study (diameter: 0.025m), was manufactured and calibrated to provide the same result as that obtained from a standard globe. As a part of quantifying the combined effect of T_{mrt} and T_a, T_{op} was calculated based on the Equation 5-7 (Tymkow et al., 2013), where T_{mrt}, T_a and v are the same as Equation 5-6:

$$T_{op} = \frac{T_{mrt} + (T_a \times \sqrt{10v})}{1 + \sqrt{10v}}$$

Equation 5-7

When the air speed (v) tends to below 0.2 m/s, $T_{mrt} = T_g$. Hence, it was assumed,

$$T_{op} = (T_{mrt} + T_a)/2 \text{ and/or } T_{op} = (T_g + T_a)/2$$

Equation 5-8

5.5.8.2. Comparative study and statistical analysis

Comparisons among the case study buildings and seasons were made through identifying the similarities and deviations of continuously recorded data and spot measured data at the workstations. 'IBM SPSS Statistics' (version 24) tool was used for the data management and analysis. For comparative study, descriptive statistics of the

field measured data were used to identify the notable similarities and difference among the indoor thermal condition of the workspaces (i.e. CS, SS and FS) in three case study buildings and climatic seasons. Spearman's rank-order correlation and regression models among workers' various comfort votes (i.e. votes in ASHRAE, McIntyre scale) and onsite spot measured data were executed to reveal the neutral temperature and comfortable temperature ranges for the workers in three production workspaces and seasons.

To determine the expected air speed ranges for the workers to work comfortably their specific production floors, analysis was bounded to warm humid season only. Spearman's rank-order correlation (Field, 2013) were executed to identify the relationship between the direction of air and workers' response to air velocity they experience. In addition, correlations and Spearman's rank-order correlation regression model between the distance of inlet windows from the participants and workers' thermal comfort were carried to determine how workers' positions within in a building floor impact their thermal condition. It also led to recommend the threshold distance between inlets and workstations and ideal building width elevating the air velocity.

5.5.9. Limitations within this methodology

The limitations of selecting three case studies and overall field study methodologies can be emphasised as follows:

- The case study building may not be representative of the whole RMG building stock of Bangladesh
- Only snapshot comfort survey was undertaken due to given timeframe and access to the buildings.
- Sample size for comfort survey was varied in each season.
- Three semi-structured interviews with the building owners and managing directors of the case study buildings were undertaken. Hence, the findings may not be applicable for other RMG factories.
- There was no formal interview with the architect of the buildings was arranged.

5.6. Methodology of the Simulation Study

5.6.1. Aim and scope of study

The main aim of the simulation study is to achieve the objective 5 of this research (Section 1.3). Considering the given scope and time-frame of the research, it was not feasible to physically explore the benefits of the workable strategies in a real site or RMG factory buildings in Bangladesh. As a previously established method of evaluating and optimising the environmental performance of an existing building, a detail parametric study method was developed by the author utilising a suitable computer-based simulation tool (Section 4.6). Figure 5-17 illustrates the summary of the major steps and relevant methods used for the simulation study.

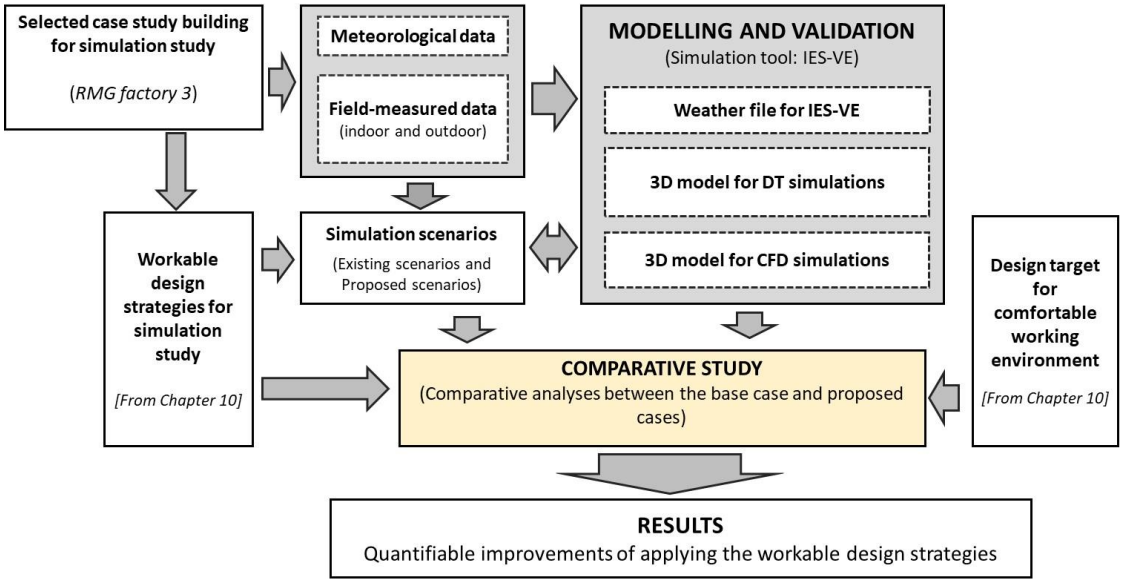


Figure 5-17: Summary of major steps and methods used in this chapter

5.6.2. Selection of a case study building

Case study building-3 (*RMG factory 3*) was adopted as the subject of the simulation study. Since this is the only purpose-built factory among the three case study buildings and the ventilation air flow pattern can be predicted more accurately with a simplified model due to having no ceiling fans, *RMG factory 3* is chosen. It is a RMG factory building with a deep plan that is regular in shape with its long axes north-south oriented. Where case study building-3 departs from the norm is in relation to its immediate surrounding structures which are all one-storied, whereas those of other two selected case study buildings are one to six stories tall (Sections 5.5.2 and 7.4).

5.6.3. Simulation tool, modelling and input parameters

A licenced simulation software package named 'Integrated Environmental Solutions-Virtual Environment (IES-VE) version-2017' was used to perform an air flow ventilation and thermal analyses of the case study building. It was selected after considering the capabilities and limitations of other available simulation tools, as stated in Section 4.6.1. The 3D modelling of the building with its surrounding contexts was completed within IES-VE using 'ModelIT' tool, based on the official architectural drawings and field data. These were also used to specify construction materials and occupancy patterns. A validated IES-VE simulation model of the case study building-3 with the immediate site context and the geometry were shown in Figure 5-18.

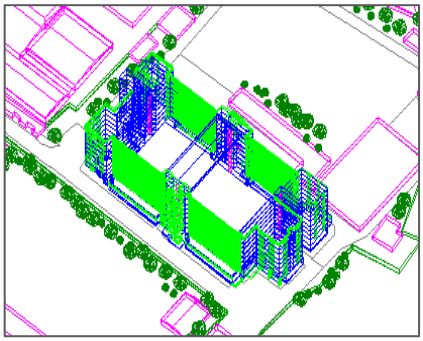
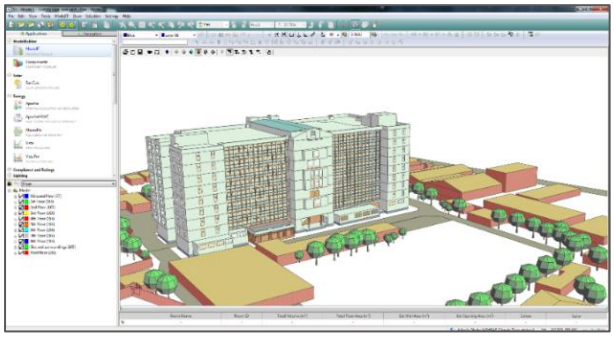
(a)  (b) 

Figure 5-18: 3D model showing (a) Wireframe, (b) shaded view (source: author)

The analyses were completed by using IES-VE's Dynamic Thermal (DT) Simulation tool 'Apache', ventilation design tool 'MacroFlo' and Computational Fluid Dynamics (CFD) simulation tool 'Microflo'. Table 5-7 shows the input parameters that were considered for modelling prior to validation and analysis. The parameters were assumed and in some cases calculated based on the data from the field studies and described in Section 11.4 . DT simulation was mainly used to measure the long-term thermal performance of the CS, SS and FS.

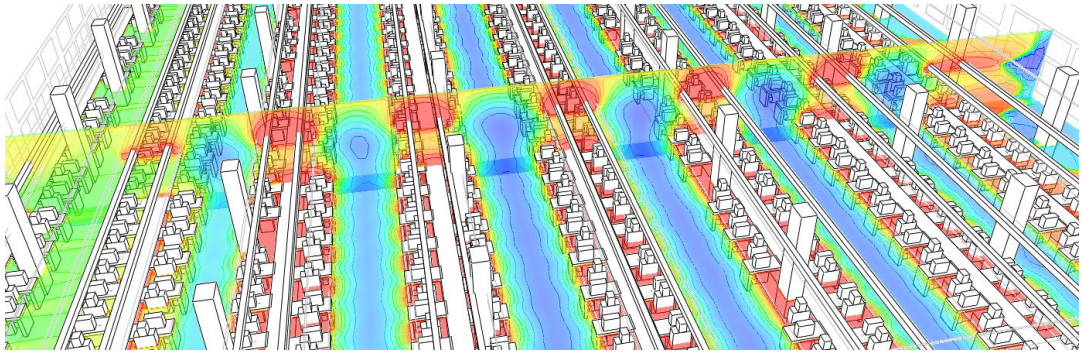
To visualise the effect of changing the window design on indoor temperature and air distribution in the SS, a number of simulation scenarios were explored further using 'Microflo' – the CFD analysis tool within IES-VE. Due to limitations in the available physical memory of the computer used in this analysis, the production space was assumed to be symmetrical and only half was modelled.

Table 5-7: Main input parameters considered for simulation modelling

Aspect of the simulation model	Input parameters
Common parameters	Weather data, calendar and working hours
Thermal aspects: fixed parameters	Room conditions, systems, internal gains, air exchanges
Constructions: fixed parameters	Roof, internal ceiling/floor, external walls, glazing and frame types, door, local shade
Ventilation (MacroFlo): fixed parameter	Opening type, door, degree of opening (modulating profile)
Air flow (Microflo): fixed parameters	Boundary conditions, surface heat transfer, iterations turbulence model, discretisation, flow rates, stand-alone schedule

The boundary condition was directly exported within IES-VE, after validating through Apache simulations and utilising 'MacroFlo'. The components such as workstations, workers, fluorescent lights etc. inside the workspaces were initially modelled as attached box components, as shown in Figure 5-19(a). However, due to limited physical memory, second round of simplified model were completed and presented as boxes of approximately the same volume, as indicated in Figure 5-19(b).

(a)



(b)

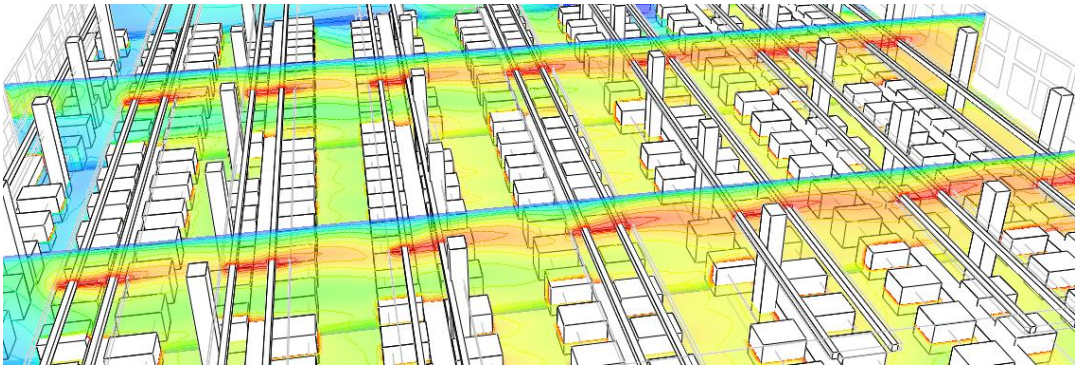


Figure 5-19: (a) first and (b) second round of simplifying components for CFD simulation modelling

The associate thermal parameters of the components, such as, surface temperature and heat source, were assigned according to field studies shown in. Each of the extract fans on the north facade was capable of generating 12m^3/s air flow rates and was located in the CFD model as found in the field study (Section 9.4).

5.6.4. Validation process

As the first step, the weather data was validated against the outdoor climate data collected from the field studies. The average meteorological data for the years 2015, 2014 and 2013 for the Dhaka region were considered and were compared against the field data. Then the climate data was converted into an '.epw' formatted 'weather file'. The second step was to validate the DT and CFD models. For DT model validation, descriptive statistics of the field measured and simulated data, such as AT and RH, for the warm season were calculated and the deviations among them were compared. The CFD model was also compare with air speed data collected from field study. Moreover, the simulated air volume flow rate through individual openings, as well as the total volume of the SS for the existing scenario was cross-checked with the field data. The total validation process was undertaken following the previously established methods, as stated in Section 4.6.2.

5.6.5. Simulation Scenarios

Following the recommended procedures set at by Nguyen et al. (2014), main 'Simulation Scenarios' were selected wherein each one variable was modified while keeping the other existing parameters, such as thermal and construction variables, constant. A comparative analysis was made of the results from DT simulations for cutting, sewing and ironing sections changing different climatic seasons. A more detail study of ventilation was made possible through the use of CFD simulations (Chen, 2009), with a focus on improvement of air movement within the sewing section located on the 4th floor of the building.

Simulation scenarios were grouped into two main categories. They are as follows.

Workable strategies type-1*: The most feasible and immediately applicable strategies in existing RMG factory buildings.*

Workable strategies type-2: *The strategies that are less feasible to implement in existing case study buildings but potentially more applicable to new RMG factory buildings.*

A detailed description of the simulation scenarios is provided in Section 11.6.

5.6.6. Design targets and improvement assessment criteria

'Percentage of the working hours within comfort zone' was used as a main criterion for assessing the thermal performance of simulated scenarios and measuring the improvement. In addition, the simulated models were evaluated in terms of workers' preference criteria reflecting a number of parameters such as preferred temperature (i.e. threshold values for thermal comfort), RH, preferred air velocity and directions of air flow. Distance between inlet and outlet was also taken into consideration based on the results shown in Chapter 10.

5.6.7. Limitations within this methodology

The limitations of simulation study method can be emphasised as follows:

- Only one case study building was selected for simulation study which may not be representative of the multi-storey RMG building stock of Bangladesh.
- The weather data set was created based on meteorological data of recent three years and may not represent future high temperature due to global warming.
- Accuracy of CFD models is limited to given time and available resources.
- As all of its production areas are located above ground level, the wind shielding offered by adjacent buildings can be ignored (Ramponi and Angelotti, 2014). As a result, the findings from this simulation study will not be fully applicable to other RMG factories with different plans, orientations and internal fan layouts. The greatest discrepancy is likely to relate to its unusual urban contexts.

5.7. Summary

This chapter provided an overview of the research methodology adopted to undertake this whole research. Based on the literature review, a number of research objective were set and an empirical case study approach was followed allowing triangulation

among theoretical studies, field studies and a simulation study to achieve the research objectives.

Prior to principal investigation, a pilot study was also accomplished through a site and micro-climate analysis, theoretical calculations within a case study building and online questionnaire surveys among RMG factory owners (18 subjects) to understand the applicability of one of the passive design approaches in existing multi-storey RMG factories. This initial study helped not only to limit the scope of comprehensive field investigations, but also to achieve the second objective of the research.

The principle research involved in studying and incorporating multiple sources of field evidence collected from three case study buildings, i.e. *RMG factory 1*, *RMG factory 2*, *and RMG factory 3*, in the real site and context of Bangladesh. Three field studies were scheduled to collect both objective and subjective data representing three main climatic seasons of Bangladesh. Based on the measured data and field observations, a site and micro-climate analysis was also conducted. The objective data included the physical measurements, both continuous monitoring and spot measurements, of indoor and outdoor climatic conditions. Subjective data was collected from the stakeholders that included workers, building owners, managing directors and the designer of the case study buildings. For comfort survey, snapshot questionnaire survey approach was adopted collecting TSV, TCV and PT in addition to feedback on air velocities and directions. The total sample size was 908 where the number of subjects were varied from 61 to 154 per season in each case study buildings. Six focus group discussions were conducted to gain extended feedback from workers on their perception of indoor thermal environment during different seasons, their adaptive measures and possible solutions. Three semi-structured interviews and an informal discussion were conducted with the building owners and the designer of case study building-3 to identify the workable design strategies improving the existing thermal conditions of workspaces. Comparative study and statistical analyses were undertaken to find quantifiable thermal comfort ranges and associate design targets.

Simulation study was undertaken within the *RMG factory 3* by utilising DT and CFD interface of IES-VE simulation tool. In addition to crosschecking the weather data with meteorological and field data, both DT and CFD models were validated with field

measurements. While assessment of the simulated models of the existing and proposed scenarios were based on comfortable working hours and other environmental parameters, the retrofitting scenarios were categorised into two groups based on the viability of immediate implementation within existing building.

The next chapter will include a pilot study on an existing garment factory building testing the viability of the passive design strategies and will guide further analyses of the research.

CHAPTER 6. PILOT STUDY: FEASIBILITY OF PASSIVE STRATEGIES IN RMG FACTORIES

This chapter presents a feasibility study at the pilot study stage to test the applicability of the passive design strategies within existing garment factory buildings. Results from a theoretical analysis and an online questionnaire survey guide further analyses of this research and indicate the extended scope of main field studies.

CHAPTER 6. A PILOT STUDY: FEASIBILITY OF PASSIVE STRATEGIES IN RMG FACTORIES

6.1. Introduction

Chapter 3 reviewed and suggested a range of environmental design strategies and ventilation approaches that may potentially improve the thermal performance of workspaces in tropical climate. This chapter presents a pilot study along with a feasibility study undertaken to understand whether one of the ventilation strategies would be viable in existing multi-storied RMG factories in the context of Bangladesh.

6.2. Chapter Aim and Scope

Apart from testing the viability of the main research methodology, the aim of this chapter is to achieve the second research objective (Section 1.3). Hence, this chapter covers a pilot study conducted in an existing RMG factory building to identify a suitable passive ventilation approach and test the physical viability of the approach. Moreover, feedback was also collected from a number of factory authorities to understand their perception about implementing a refurbishment in their buildings designed to improve the existing environmental condition as defined by workers' thermal comfort.

6.3. Rationale of the Feasibility Study

Based on reviewing a number of literature and architectural precedents, Chapter 3 described a number of ventilation strategies, such as stack ventilation with shafts, night-time ventilation and cross ventilation, applicable to indoor workspaces in the Tropics. However, in the context of RMG factories, the deep-plan design of the multi-storeyed buildings severely limit the natural cross ventilation. In order to employ a passive solution in existing buildings, the new feasible solutions are to alter the fabric of the building, to add shafts or atria, to optimise space utilisation and to install control systems (Lush and Meikle, 1988). Since no research has demonstrated passive design solutions for RMG factories, the approaches suggested by Lush and Meikle (1988) require a feasibility study to understand their applicability in RMG sector. Therefore, the second objective of the research was formulated to assess the feasibility of passive design strategies in existing multi-storey RMG factories of Bangladesh.

As referred in Section 5.4 of Chapter 5, this research made use of a pilot study stage to test partially the methodology of the research before the principal investigation. Therefore, this pilot study stage was designed with duel purposes not only to guide the scope of a field studies' methodology but also to test the feasibility of passive design strategies in RMG factories.

6.4. Site and Micro-climate Analysis

6.4.1. Impact of local climate

The climatic condition is described in Section 2.4. The diurnal variations, as shown in Figure 2-4 is suggesting the potential opportunities to use night ventilation to improve comfort, (Kolokotroni and Santamouris, 2007, Ford, 2010).

6.4.2. Psychrometric chart analysis

Figure 6-1 plots the climatic data on psychrometric chart and reveals that comfort target, as assumed in Section 2.5.2, can be achieved for around 9.4% of hours, including both working hours and out of working hours of a day, within a year by only natural ventilation cooling. The data outside the comfort zone should be addressed by careful design of the building envelope to control heat gain. However, the comfort range may vary considering the occupant's adaptive capacity with varied seasons. Furthermore, fan forced ventilation can complement with natural ventilation to further elevate the comfort condition of the workers. Therefore, incorporating passive ventilation may potentially improve comfort for the workers for a higher percentage of hours in a year. However, field measured micro-climate data are required for further assumptions.

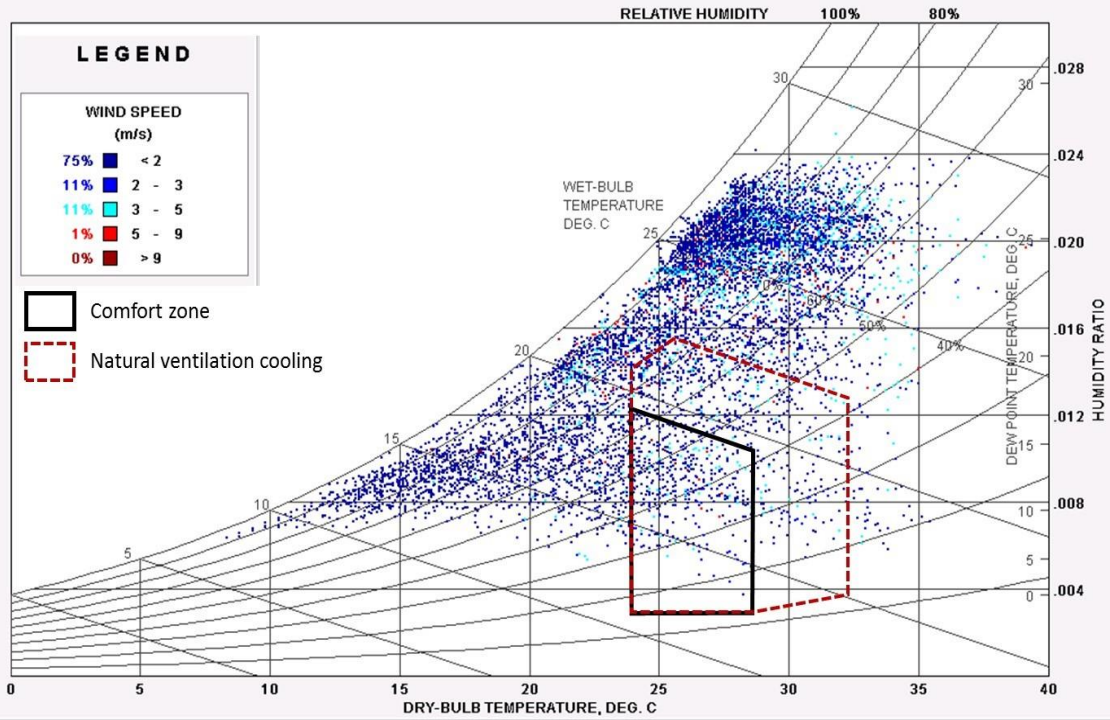


Figure 6-1: Psychrometric chart showing boundary for passive cooling offered by natural cooling (source: results from Climate Consultant 4)

6.4.3. Physical context, wind regime and the solar environment

Figure 6-2 illustrates that the wind approaches from the south, south-east and north sides during the warm-dry and cool-dry periods. The road to the west side of the case study building carries heavy traffic and so may be a source of noise and polluted air. Though the adjacent buildings are mainly one storied (Figure 6-2) the local wind regime may be affected by future development, as shown in the Noli-plan. These factors, plus the plan depth of the RMG factory mean that forced ventilation may be more applicable than only relying on the natural airflow for cross ventilation.



Figure 6-2: Morphological context and local wind regime considering future development (source: Google Maps with author's drawing using AutoCAD modelling and Autodesk Weather Tool 2011)

Figure 6-3 shows the sun-path and represents the shadow pattern at different time of day for the summer solstice, equinox and winter solstice. They also represent days of various seasons. For example in 2014 summer solstice (21 June) and equinox (22 September) represents days during warm humid season, winter solstice (21 December) represents a day during the cool-dry season and equinox (20 March) represents a day during the hot-dry season. The north side of the building is usually covered by shadows cast by the adjacent buildings. The south façade is subject to more exposure from the sun which is at its greatest during the winter solstice.

Figure 6-4 shows the distribution of direct solar radiation over the exposed surfaces of the building. The roof is subject to the maximum exposure to sun and hence, has a high solar gain. With the exception of the north facade the external surfaces require design treatments to control gains from solar radiation all the year round (Akbari, 2007) (Section 3.4.1).

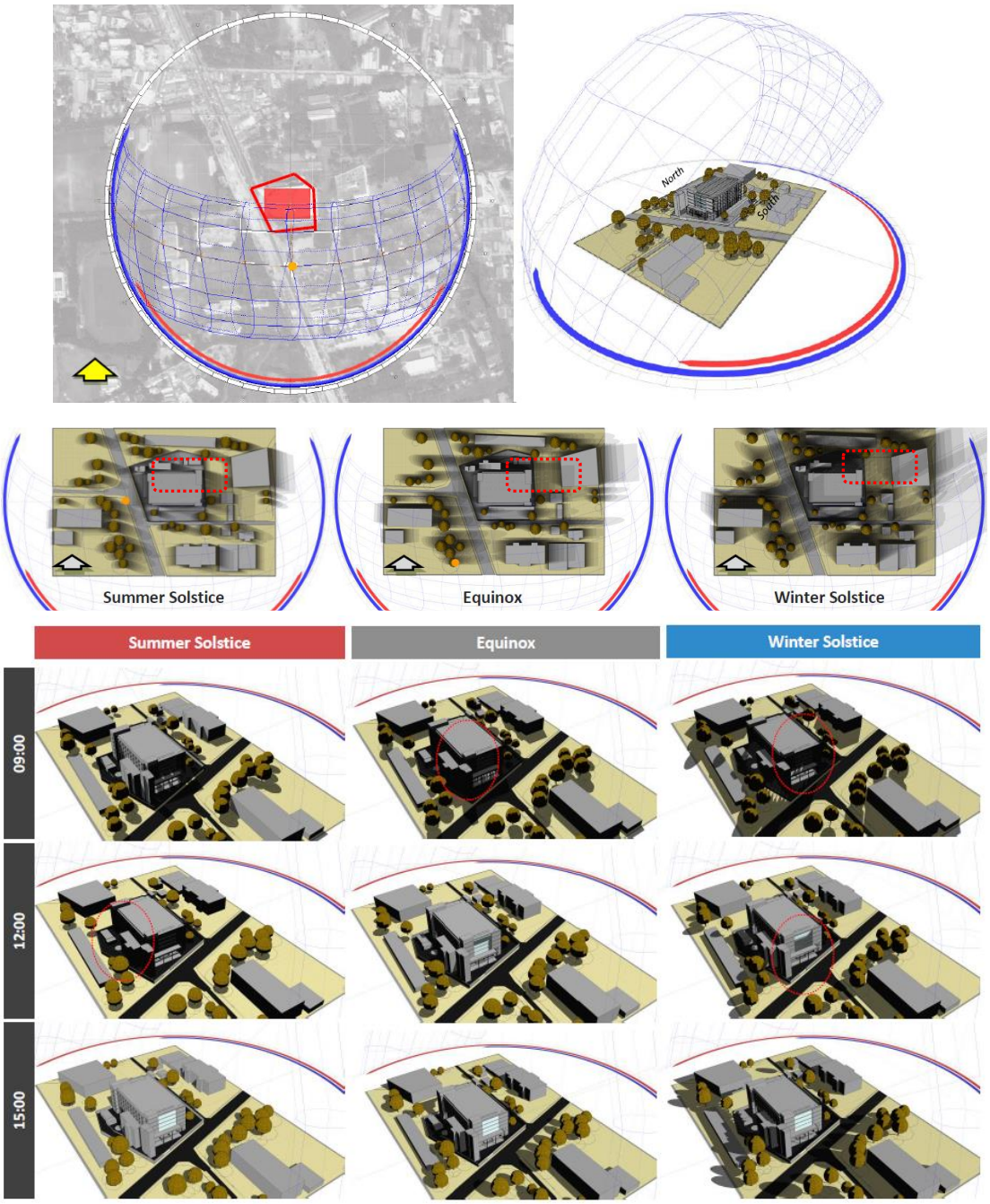


Figure 6-3: Shadow analysis of the case study building (source: Google Maps, author's photograph, Ecotect Analysis 2011)

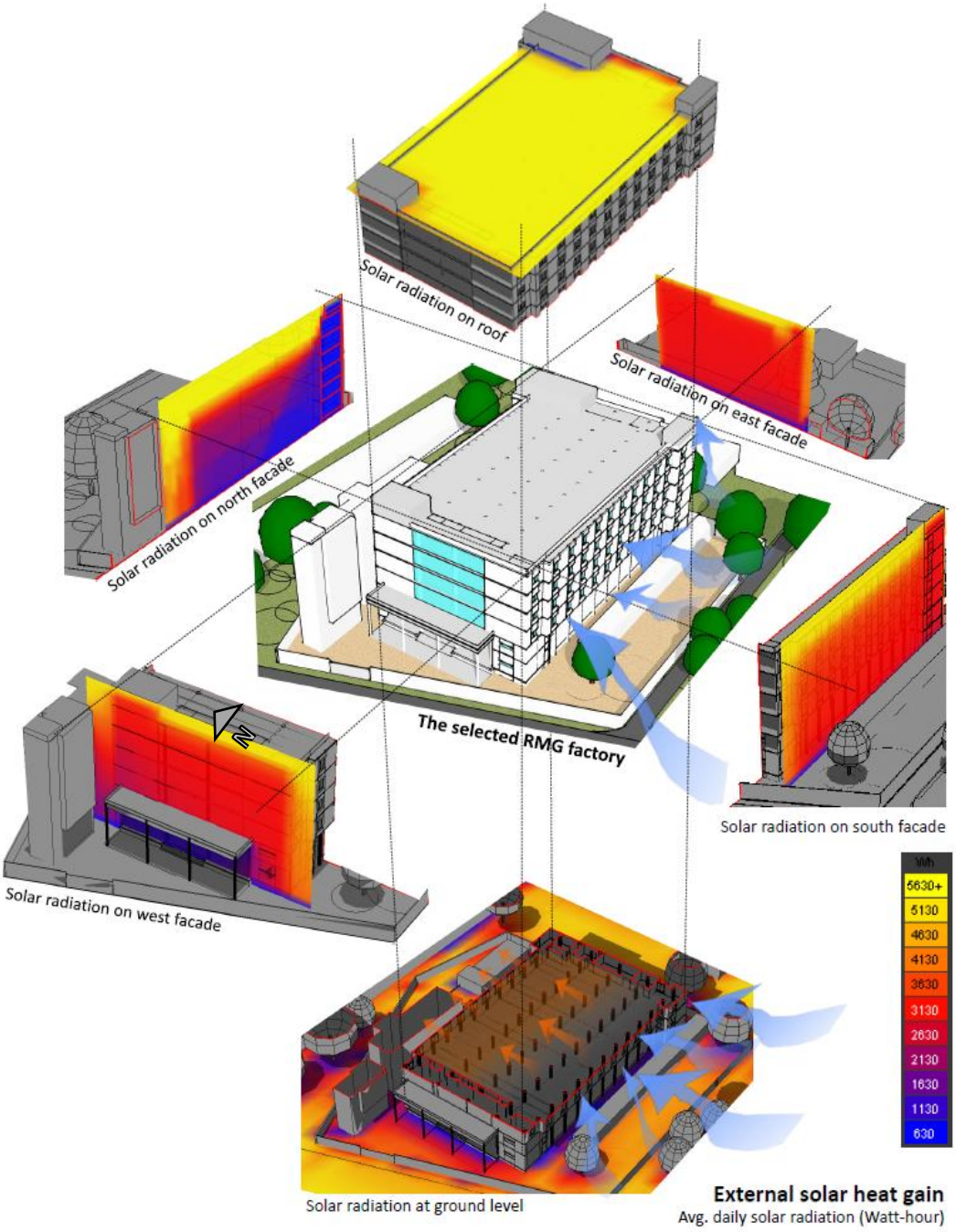


Figure 6-4: Distribution of Incident Solar Radiation on the hottest day (21 May) of the year

6.4.4. Street pattern, noise, vegetation and UHI

The existing street pattern and available vegetation, shown in Figures 6-2 and 6-4, illustrate that no ventilation inlets should be positioned on the west-side of the building. The existing vegetation to the south and south-east sides may help to both cool and clean the supply air. As the site is 20km from Dhaka city and very close to Savar (Figure 5-4), the Urban Heat Island (UHI) effect may affect the local site temperature. Hence, further data collection including outdoor AT may be required.

6.5. Indoor Condition and Environmental Aspects

Figure 6-5 illustrates the location of main three production sections in the case study building: the CS, SS and FS. It may be seen that 1st to 4th floors house the main production sections with a high density of workers (around 5m^2 per person) and equipment gains of up to 56W/m^2 in the SS and FS. The top floor suffers the highest heat gain due to the additional conductive solar heat (74 W/m^2) from the roof (Figures 6-3 and 6-5). All production floors have forced ventilation with large extract fans (Figure 6-5) located on the north façade and windows acting as inlets on the south facade. There are also ceiling and pedestal fans to improve workers' comfort by creating localised air movement. Typical production floors have WFR of 0.094. However, in relation to the ventilation these offer the effective opening area of the windows is 35%. The building has reinforced cement concrete (RCC) beam and column frame structure with exposed concrete floor/ceiling that offer access to thermal mass.

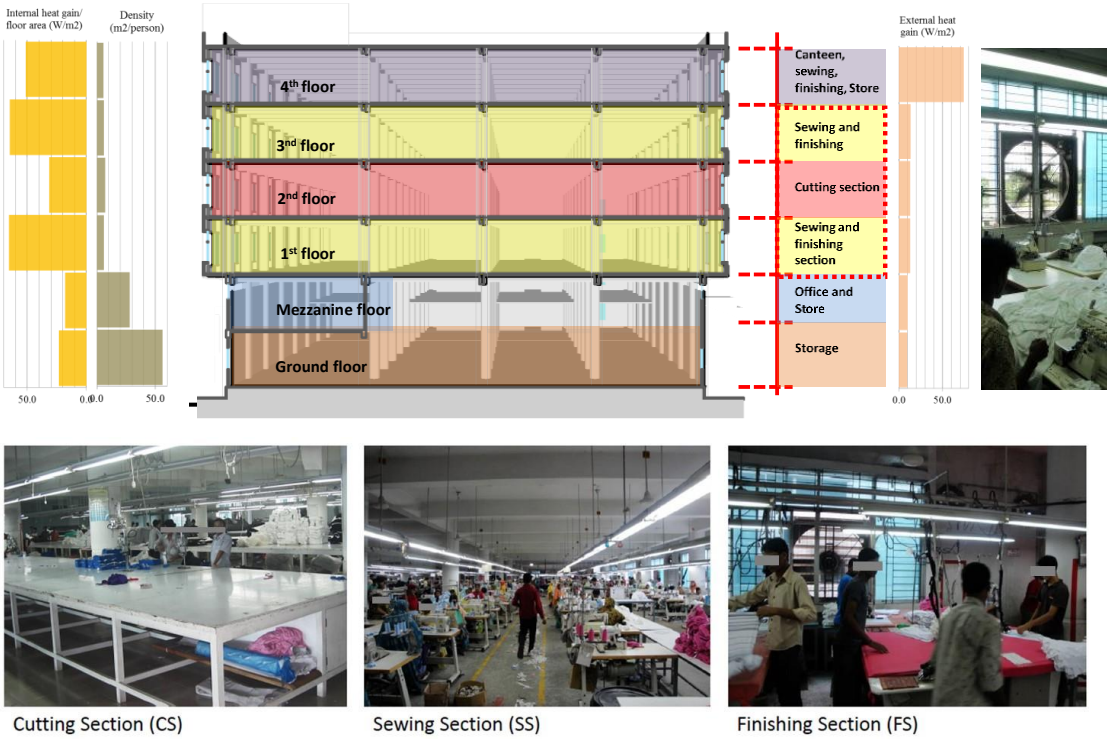


Figure 6-5: Functions, typical heat gains in the hottest season and occupancy density of the case study building (Source: Authors' previous field survey and collected data)

Figure 6-6 represents measured field indoor data and associated outdoor meteorological data taken during the cool-dry season. Figure 6-6(a) shows that the indoor AT increased up to 31.7°C during the occupied hours while outdoor AT also rose to its peak of 27.1 °C. Indoor AT rises during the daytime probably due to the

occurrence of internal gains, solar gains and increasing external AT. Forced ventilation during these periods probably prevents the internal temperature from rising higher and ΔT between inside and outside of around 2-3°C is observed. At night time the external AT drops significantly (by around 10°C) while internal AT is stable. This is probably due to the reduction in ventilation rate resulting from the fans being forced off. Heat stored in the building fabric during the daytime is released slowly maintaining a stable high indoor air temperature which does not respond to or track the change in external air temperature. The large ΔT at night suggest there is significant opportunity to use increased ventilation to have night cooling of the building fabric.

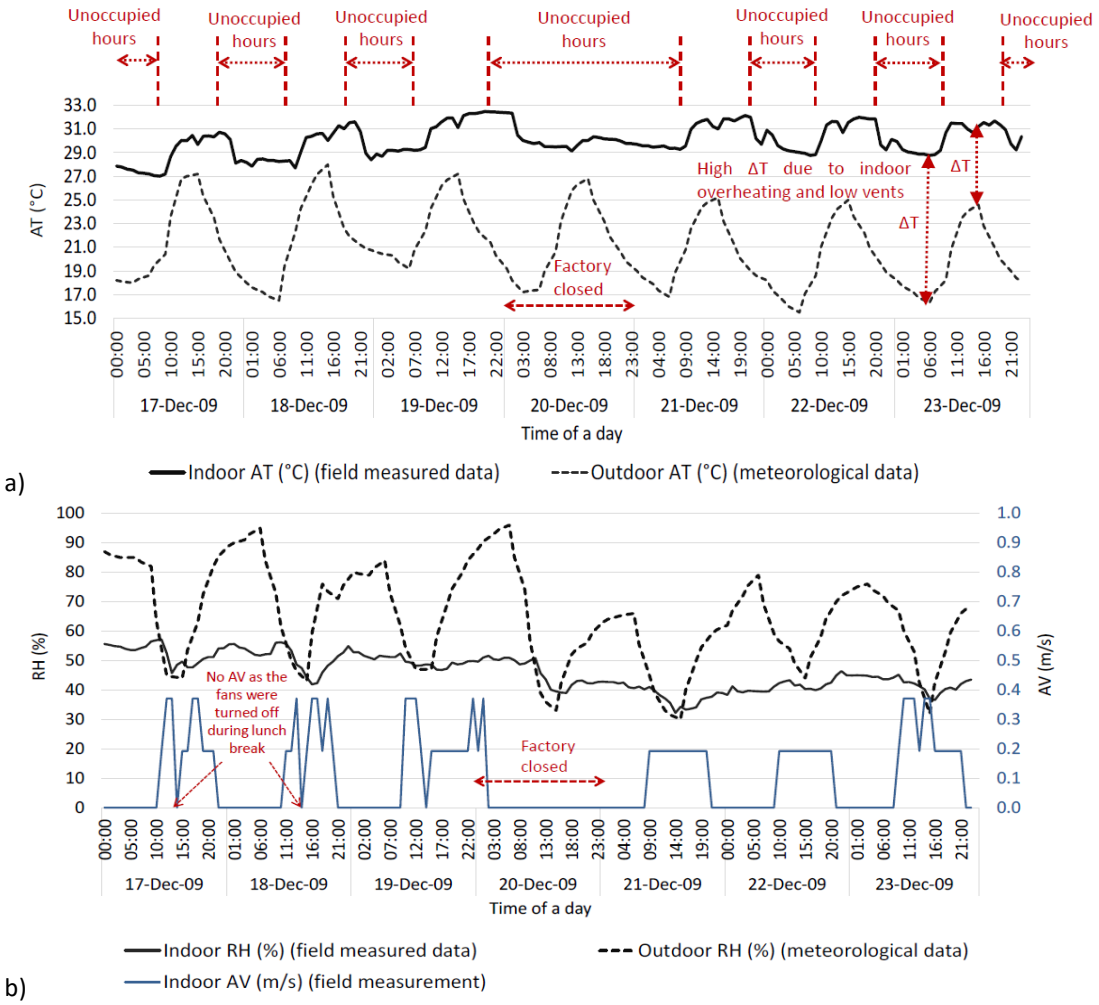


Figure 6-6: a) Air temperature profile and b) Relative humidity and Air velocity of inside a sewing section on 1st floor (Source: Hossain 2011, previous field survey in 2009, meteorological data 2009)

Figure 6-6(b) shows that the indoor RH remains relatively constant rising to no more than 55% even outdoor RH to level of around 95% during night times. Indoor and outdoor RH are similar during the daytime when the fans operate. The relatively stable internal AT and low ventilation rates at night, help to stabilise the internal RH. The

external RH rises at night in response to the decrease of external AT. For the case study building, data were only gathered for the cool dry season. It is reasonable to expect that for the hot-dry and warm-humid seasons, a higher indoor AT would be observed.

Previous research studies conducted in garment factories during warm seasons provide a range of empirical evidence suggesting that sewing and ironing sections could reach ATs as high as 35°C-39°C with a ΔT between inside and outside AT in the 3-5°C range (Fatemi, 2012, Naz, 2008). Under these condition, mechanical ventilation strategies on their own are unlikely to be effective in relations the high AT and need further investigation. Variations in RH and required AV for thermal comfort in different seasons also need to be explored further.

6.6. A Potential Ventilation Approach

Figures 6-7, 6-8 and 6-9 show the qualitative observations of the site's micro-climate and potential options for ventilation design strategies in different climatic seasons. The diagrams were developed based on the understanding from Sections 3.4, 3.5 and 3.7.

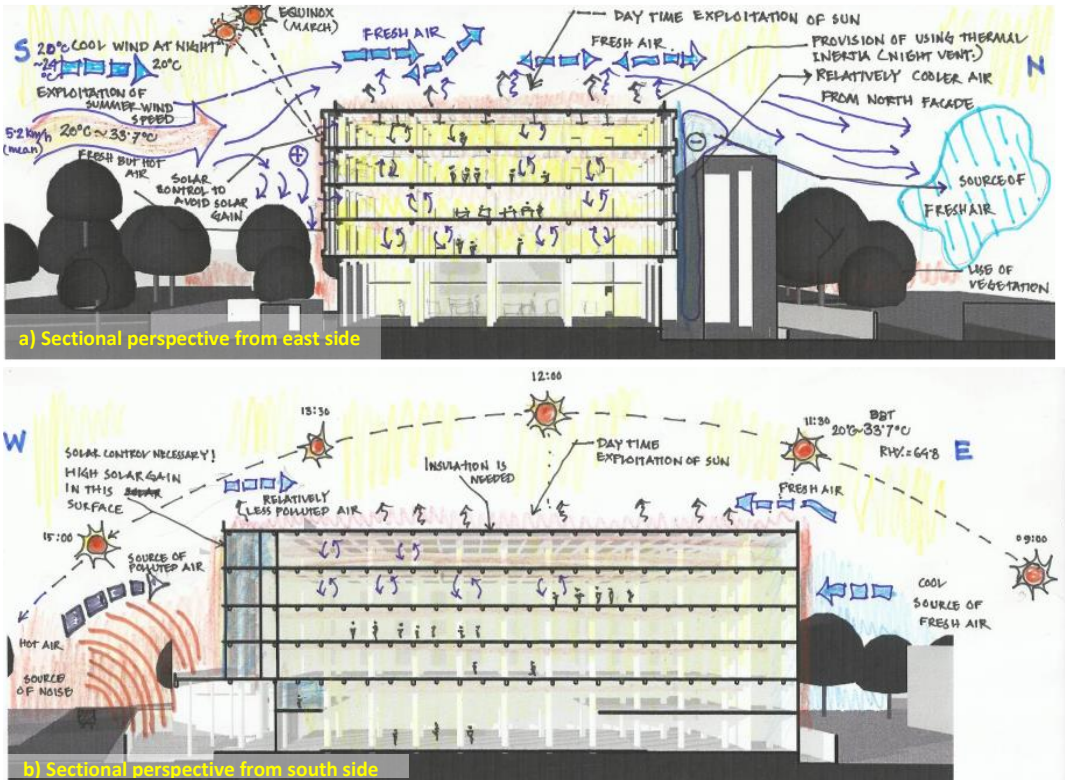


Figure 6-7: Summary observations of micro-climate and options for ventilation design strategies for the hot-dry season (source: author's drawing)

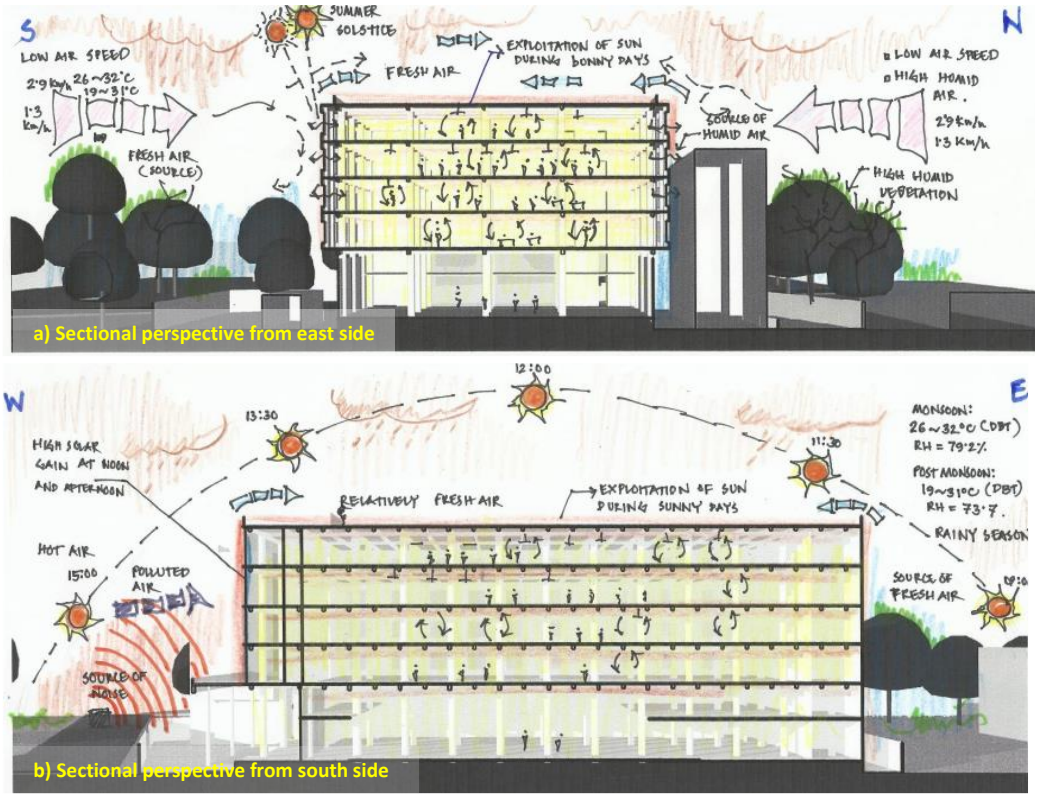


Figure 6-8: Summary observations of micro-climate and options for ventilation design strategies for the warm-humid season (source: author's drawing)

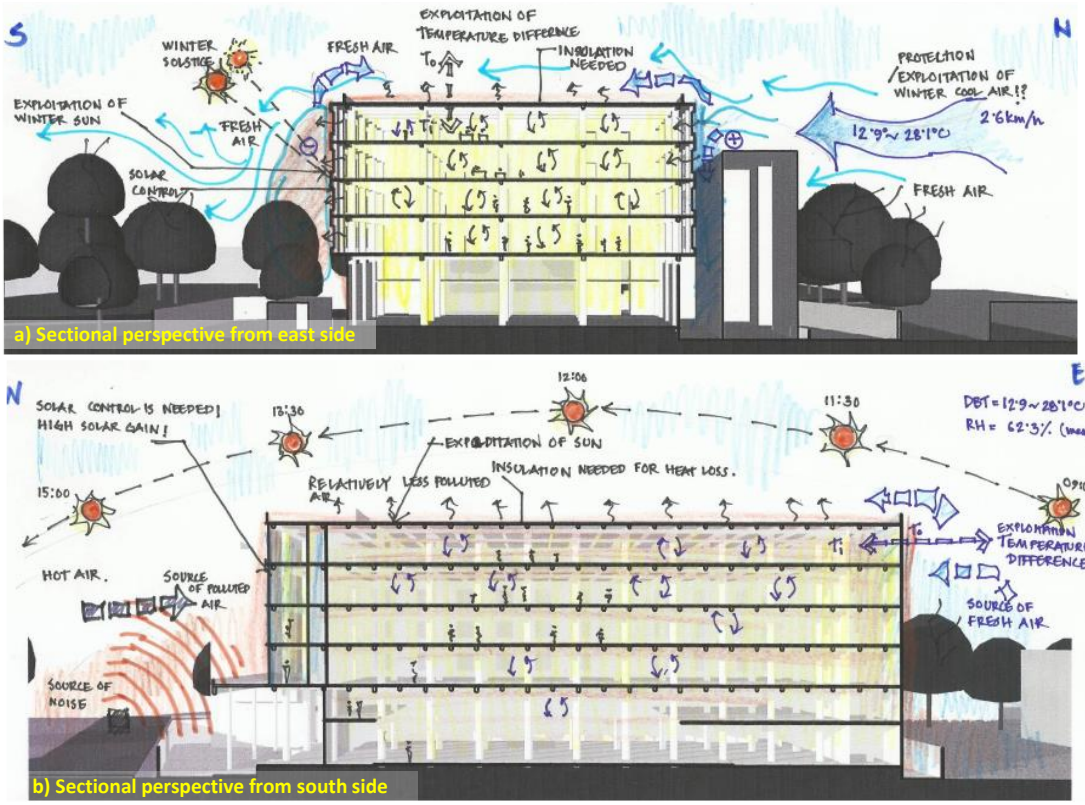


Figure 6-9: Summary observations of micro-climate and options for ventilation design strategies for the cool-dry season (source: author's drawing)

Common to all of the schematic diagrams is the potential to source fresh outdoor air

through the existing windows on both the south and north sides of the building. However, the outlets should be placed somewhere in between, such as centrally located ventilation shafts, to reduce the travel distance of the air from inlets to outlets (Heiselberg et al., 2001). The ceiling of the top floor needs to be protected from conductive heat gain caused by solar radiation. For certain extend solar control is required for the existing windows of the west and south sides.

Table 6-1: Proposed ventilation approaches and design considerations for the case study building

Climatic seasons	Months	Ventilation approaches suitable for the existing building	The principal of ventilation strategy	Source of outdoor air for the inlets	Required solar control
Hot-dry	March - May	- Stack induced passive ventilation - Night time ventilation with thermal mass	- Thermal force - Prevailing wind force - Mechanical ventilation	- Prevailing Wind from the south - Fresh air from north and south	West and south facades
Warm-humid	June - November	- Stack induced passive ventilation - Mechanical Dehumidification	- Thermal force - Mechanical ventilation	- Fresh air from north and south	West and south facades
Cool-dry	December - February	- Stack induced passive ventilation - Adding night time ventilation with thermal mass - Evaporative cooling	- Thermal force - Prevailing wind force - Mechanical ventilation	- Prevailing Wind from the North - Fresh air from north and south	West and south facades

Table 6-1 also illustrates the potential ventilation approaches that likely to improve the existing indoor thermal condition of the case study building. Since the prevailing wind from the south and north may only be relied upon during the cool-dry and hot-dry seasons, 'thermal force' can be considered as reliable alternative driving mechanism suitable for the three climatic seasons. Based on the finding from Section 3.7, the measured diurnal fluctuation of outdoor AT during the cool-dry and hot-dry seasons (Table 2-2) and the values of ΔT between indoor and outdoor conditions for the production spaces, full day ventilation with additional NTV may be considered as potential strategies to improve occupant comfort.

Therefore, 'Stack induced ventilation approach' can be proposed as a robust and commonly applicable ventilation approach for all climatic seasons based on the 'micro-

climate analysis' and limited empirical evidence available in the pilot study. The principal investigation (discussed in Chapters 7, 8 and 9) will require further empirical evidence to test the viability of this proposed approach to apply during the whole year.

6.7. Physical Viability Test

As described in Section 5.4.5, the relevant mathematic formulas (Equation 5-2, Equation 5-3 and Equation 5-4) indicate that the effective inlet and outlet areas (A), stack height (H) and temperature difference (ΔT) are the key design variables on determining the effectiveness of stack driven ventilation. The air volume flow rate inside the factory building is directly proportional to the A, H and ΔT. After considering a range of ΔT for each climatic season, the feasibility of identifying an appropriate opening area (A) and shaft height (H) can be tested to achieve the required design target air flow rate. A process of identifying combination of A and H that will provide the flow rates required to maintain air quality and provide improved thermal comfort will be explored in Section 6.7.1.

6.7.1. Initial investigation of integrating ventilation stack

Using 'required air flow rates' a range of outlet size can be calculated. For the case study building, the existing structural grid layout was considered as a reasonable as well as a practical reference point to start the preliminary design to determine the stack shaft size (Lomas, 2007). As a first stage, two neighbouring bays, each with dimensions 7.4m X 4m and representing around 4% of the floor area were investigated as the basis for providing a ventilation stack. The bays tested are located close to the centre of the floor plate and it was assumed that the resulting stack would draw air across the production areas from the perimeter windows. As a result, the effective perimeter was calculated as *(2×7.4m) + (2×9.2m) = 33.2m* and maximum horizontally effective area of the ventilation shaft was found as $7.4 \times 9.2 = 68.08 m^2$. Placing the stack near the centre effectively reduces the plan depth and makes natural ventilation feasible, following the rule of thumb (Section 3.5.1).

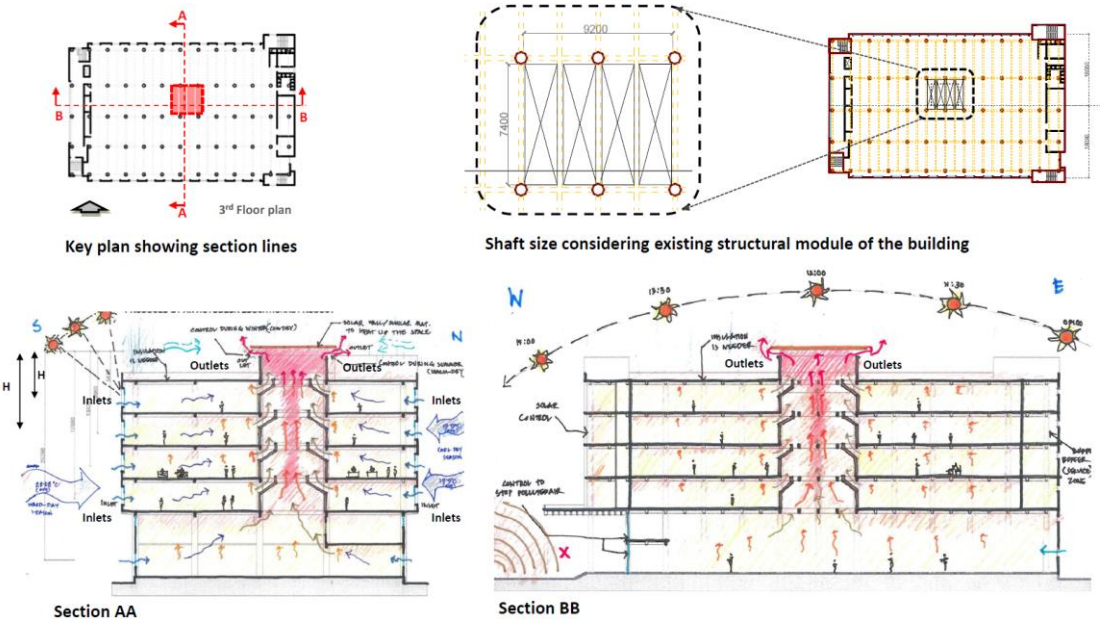
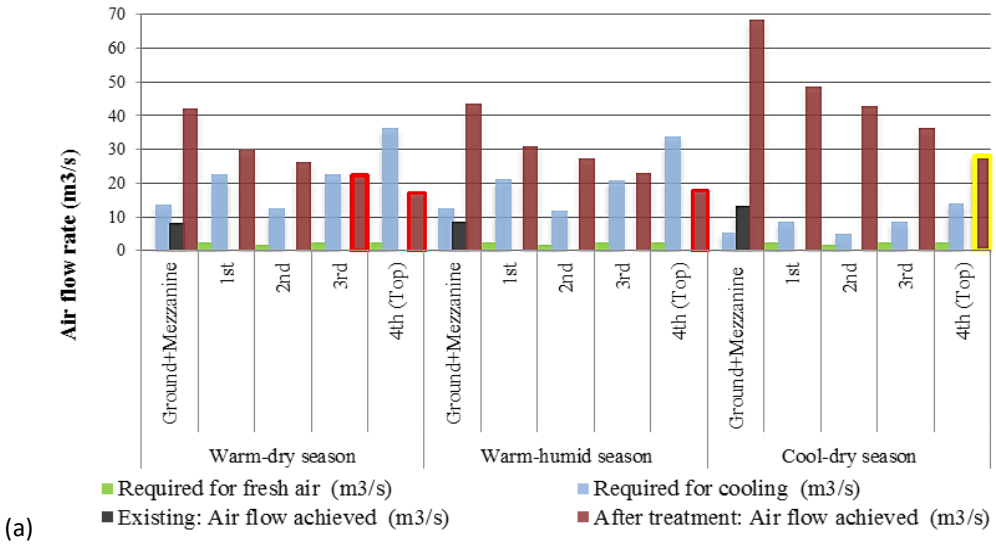


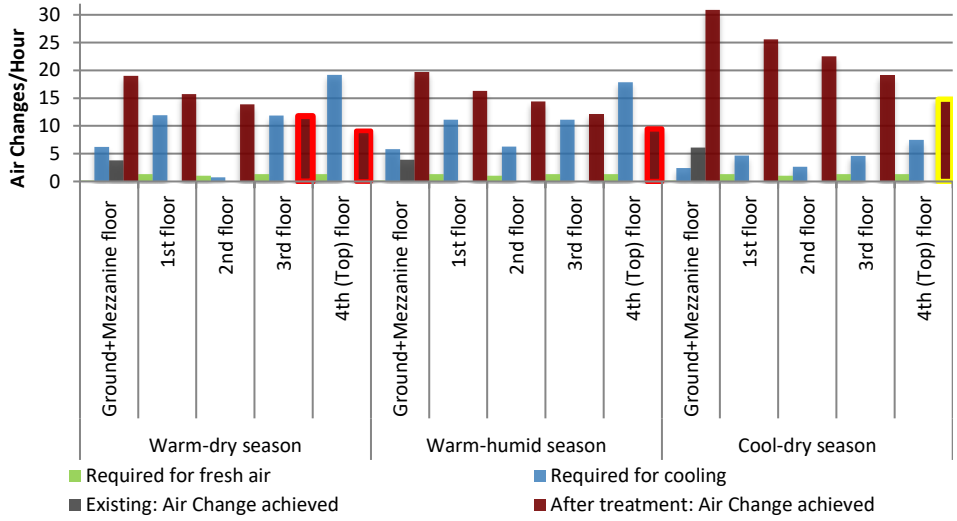
Figure 6-10: Considered structural modules and preliminary schematic design of proposed approach

The total area of the inlets (A_i) was a calculated from the existing windows located in the north and south facades. Each sliding window was estimated to have 35% effective opening area. In the case of ΔT, three scenarios were initially considered. They were 5.2°C, 5.6°C and 13.4°C for three climatic seasons of hot-dry, warm-humid and cool-dry respectively. These were determined based on the difference between average outdoor AT (Table 2-2) and upper range of comfort AT target. The height of the ventilation shaft was initially assumed as a fixed parameter (Figure 6-10). Hence, the height (H) of the stack was at it's a minimum of 6m for the 4th-floor level and had a maximum of 25.3m for the ground floor.

Figure 6-11 summarises the preliminary results found by using the 'Optivent' tool. Figure 6-11(a) reveals that the preliminary shaft successfully meets the target air flow rate for maintaining air quality during all climatic seasons. However, the air flow rate requirement for cooling was not achieved on the 3rd and 4th floor during the hot-dry season. During the warm-humid season, the target was not achieved on the 4th floor. On the other hand, the required air flow rate for cooling was achieved for all floors during the cool-dry season ranging from 18m^3/s to 68m^3/s across the different floors. Figure 6-11(b) additionally shows similar results in terms of Air change per hour with a range from minimum 9ACH to maximum 31ACH. Therefore, stack height (H) needs to be increased to achieve the required air flow rate during warm seasons.



(a)



(b)

Figure 6-11: Comparison of air flow and air change rates generated by stack induced ventilation

6.7.2. Investigation of integrating a ventilation stack using effective area (A) and shaft height as design variables

In the second stage of analysis the stack height was varied to explore its effect on ventilation rate. The stack was increased from 6m to 11m on the 4th-floor level and from 25.3m to 30.3m on the ground floor level. The effective outlet of the central shaft referred to the 50% of the designed opening area on every building floor. The effective outlet of the shaft was located on the top part of the shaft to remove the hot air. Targeting the air flow for cooling in warm seasons also triggers to a requirement to ensure effective opening (Lomas, 2007).

Two scenarios were considered. The first represents the warm season with a ΔT of 5°C, while the second represents the cool season with a ΔT of 11°C. The effectiveness of

outlets on each floor is defined by the available perimeter around the shaft rather the area available in the cross section of the shaft (Lomas, 2007). Hence to ensure the viability of construction of the stack induced ventilation system, the maximum value of the effective opening or outlet required to fulfil two criteria:

- *The targeted air flow rates (38.1-13.4 m^3/s) have to be achieved*
- *The shaft perimeter cannot exceed 33.2m per floor as mentioned in Section 6.7.1.*

Table 6-2: Estimation of structural and effective size of the outlets' to test physical viability

Floor	**Structural inlet size**: existing window in North and South facades (m^2)*	**Scenario 1: Hot season** **ΔT = 5°C** (represents hot-dry and warm-humid seasons)				**Scenario 2: Cool season** **ΔT = 11°C** (represents cool-dry season)				**Required max. shaft perimeter:** when outlet height=1.2m (m)
		Required structural outlet for cooling (m^2)	Effective outlet : 50% of structural area	Effective outlet at shaft top: 50% structural area (m^2)	structural outlet area at shaft top (m^2)	Required outlet area for cooling (m^2)	Effective outlet area: 50% structural area	Effective outlet at shaft top: 50% structural area (m^2)	structural outlet area at shaft top (m^2)	
4th	97	152.4**	76.2**	125.6**	251.2**	19.6	9.8	23.6	47.2	**127.0****
3rd	97	37.7	18.9			10.2	5.1			**31.4**
2nd	97	17.2	8.6			5.1	2.6			**14.3**
1st	97	29.2	14.6			8.2	4.1			**24.3**
Gr+Mz	49	14.7***	7.35			4.1	2.1			**15.4*****

**Effective inlet size (opening area) is assumed to be 50% of the total structural inlet size*

***In 4th floor, the required effective outlet area and shaft perimeter are not feasible to achieve, since it required high shaft perimeter.*

****In Ground-Mezzanine floor, the outlet would be a horizontal opening in the ceiling (Figure 6-10). Hence, the perimeter has been calculated directly from required structural area (14.7m) assuming area 14.7m^2 =4m×3.68m and perimeter 15.35m=2×4m+2×3.68m. Hence, the 1.2m height of outlet is not applicable here.*

Table 6-2 shows the results obtained using 'Optivent' using the existing effective inlets as inputs to test the physical feasibilities. According to the two criteria mentioned

previously, the 4th floor does not fulfil the requirement, or in particular, exceeds the limit of 33.2m of the perimeter. This result caused by the high density of workers (5.6 m^2/person), high heat gains (125.9 W/m^2) and the relatively short stack height (H) of 11m. The required effective outlet size is lower for the 'ground and mezzanine' floor where the stack height (H) is higher. The required outlet size on the 2nd floor is also low due to the relatively low density of workers (7.2 m^2/person) and modest heat gain (44.2 W/m^2) in CS (Figures 6-5 and 6-12).

In scenario one, the theoretical calculation suggests reveals that the effective outlet areas are achievable on the case study building's ground to 3rd floors however cannot be achieved on the 4th floor. Reducing total heat gains and changing the functional layout on 4th floor may make it possible to meet the required of airflow rate. In scenario two where the ΔT driving ventilation is assumed to be greater effective outlet areas are achievable on all the floors of the case study building.

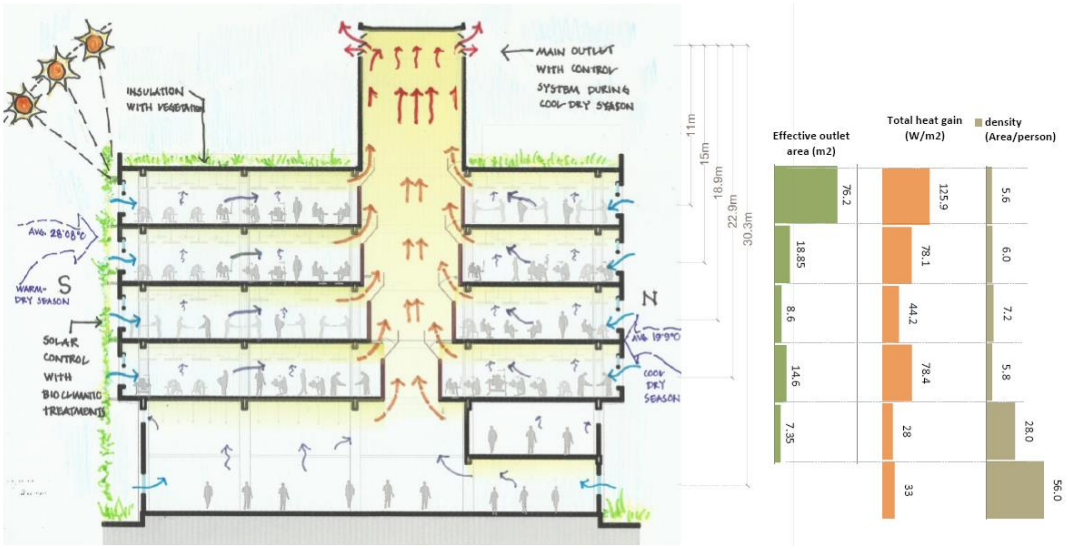


Figure 6-12: Conceptual drawing of the proposed ventilation strategy

Figure 6-12 illustrates a conceptual design based on the existing building with the proposed stack ventilation strategy. The effective size of the outlets and required cross-sectional area of each floor are also reflected in this figure. Additional green screening has been added to the south façade and roof surface as a potential strategy to reduce external solar heat gain. Both analyses of Sections 6.7.1 and 6.7.2 theoretically revealed that a central ventilation stack can incorporate appropriately sized outlets and can provide required ventilation flow rate for cooling in major

production floors. Hence this approach involves minor, intermediate and major intervention (Ford, 2010) and associated building refurbishment. Having determined the technical feasibility of this passive strategy feedback is required from the RMG factory owners to understand whether these proposed refurbishments are practically viable for when viewed from their perspective.

6.8. Practical Viability Test

Tables 6-3, 6-4 and 6-5 present the quantitative results from the structured questionnaire survey (Section 5.4.6) administered to concerned stakeholders, such as owners, managing directors and managers of a number of multi-storied factories. The results revealed that 33% and 61% of the selected factories have monthly electrical energy demands of 1000-2000KWh and above 2000KWh respectively. Of these factories 39% and 56% have 2,00,000-5,00,000Tk (2500-6250US$) and above 5,00,000Tk (6250US$) annual expenditures respectively to pay the annual energy bills. All of the surveyed factories use mechanical extractor fans and ceiling fans for ventilation and enhancement of thermal comfort, despite awareness of the significant amounts of electrical energy them consume.

44% of the participants admitted that they were unsure about the advantages of natural ventilation strategies while 28% claimed to understand the advantage very well. 72% of the participants claimed that they would like to implement any passive ventilation approach in their RMG factory building. Moreover, 78% of the participants claimed they would also consider renovation works for increasing the ventilation performance of their existing RMG factory buildings.

In terms of financial investment, 72% of the participants would be prepared to spend 500000-100000Tk (6250-12500 US$) to implement refurbishments. However, 50% and 44% of the total participants expected a payback of below 2 years and 2-5 years respectively. Finally, 50% and 17% of the respondents highlighted construction and the internal functional layout respectively as possible constrains to implement of the proposed strategies. Other issues were the disruption of production and ventilation during renovation and reduction of the floor area inside of the building.

Table 6-3: Owners' feedback on their factory's current operating conditions

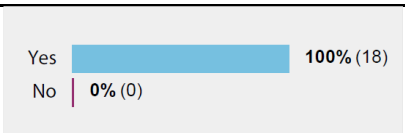
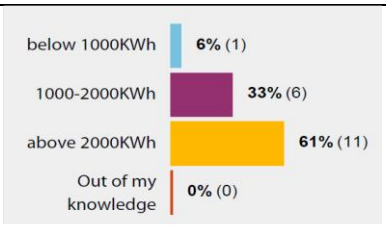
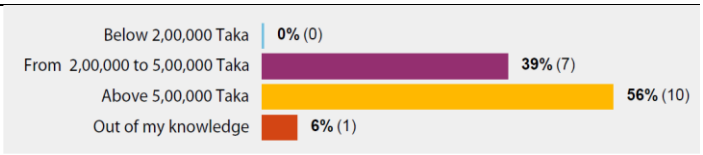
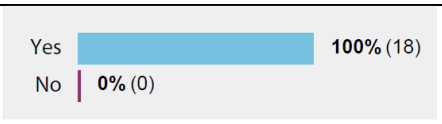
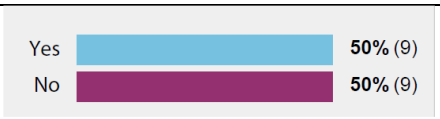
Questions	Online survey results
01. Do the RMG production spaces of your company use ceiling and mechanical exhaust fans?	
02. What is the approximate 'monthly average electrical energy consumption' (in a unit of 'Kilowatt per hour') of your company's RMG factory building?	
03. How much approximate annual electricity bill that your company usually pays for the RMG factory?	
04. Do you know that mechanical fans in production space consume a significant amount of energy?	
05. Do your company's RMG production spaces have any emergency smoke removal system?	

Table 6-4: Owners' perception on natural ventilation and implementing the proposed strategy

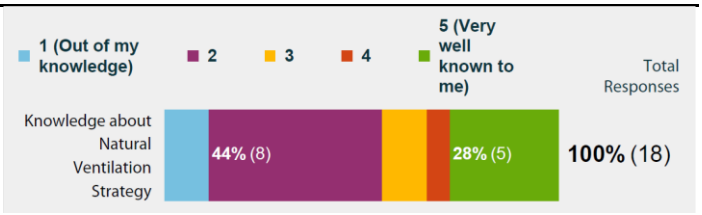
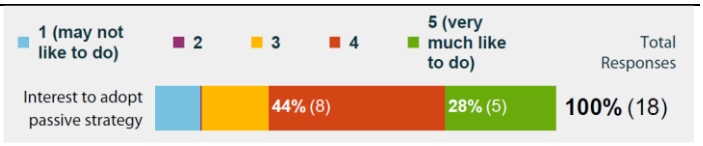
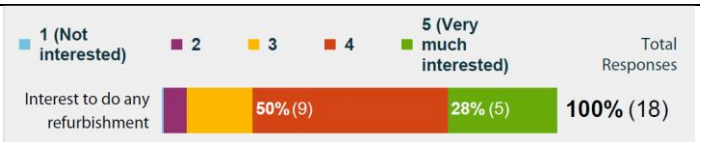
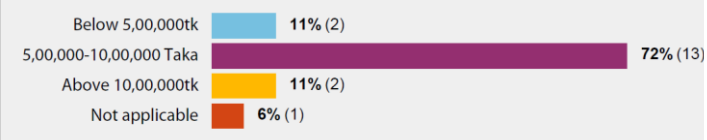
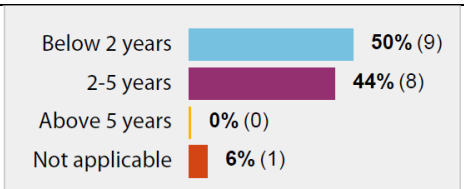
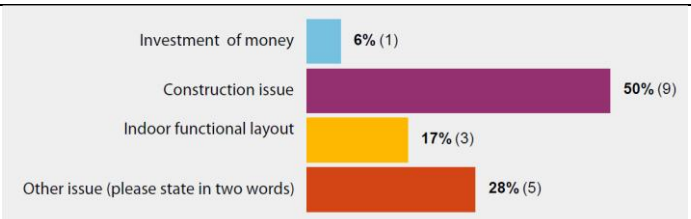
Questions	Online survey results
06. To what extent do you know that natural ventilation strategy may improve the indoor environmental performance, workers' work efficiency and save energy consumption of the RMG building?	
07. To what extent may your company be interested in adopting a passive strategy in existing building, if your company's production spaces do not need to use mechanical ventilation system?	
08. To what extent may your company do any refurbishment to the existing building (such as adding ventilation shafts, changing window size, etc.) and/or reshuffle functions within the building, if it improves the existing ventilation condition?	

Table 6-5: Owners' views on budget, payback plan of associated with introducing the proposed natural ventilation strategy

Questions	Online survey results
09. How much money may your company like to invest in implementing above effective refurbishment in your existing building?	
10. How long may your company wait to get the 'invested amount' returned through saving the energy after successful completion of above refurbishment in the existing building?	
11. What would be the most critical issue for your company in implementing the above refurbishment in the RMG factory building?	

The results for this online survey indicate that refurbishment for improving the thermal performance of existing buildings is partially viable. However, due to the nature of structured questions and sample size, these results may not avoid biases among the participants and are unlikely to be representative of all factory buildings. Hence, a further explicit method of interview is required in the principal investigation to validate these answers.

6.9. Summary and Further Scope of Principal Studies

This chapter provided detail on a pilot study that was completed to inform the principal investigation stage of this research. Table 6-6 provides a summary of the findings of this pilot study. It also includes the limitations of the methods and the outcome so that the shortcomings can be addressed in the next steps of this research.

The pilot study reveals that a passive ventilation strategy with major to minor interventions, such as changing the inlet outlet size, adding a shaft for stack induced ventilation, may be physically viable to improve the 'indoor air flow rate' for building the building and meeting workers' comfort need.

Table 6-6: Outline of the key findings from the pilot study, limitations and further scope of research

Topic	Key findings	Limitations	Further study
Site and micro-climate analysis	- Diurnal ranges of outdoor AT and local wind regime (N and S side) can be utilised for passive ventilation. - Solar control is required in roof-top, S and W façades).	- One case study building with fixed site context. - Outdoor data from meteorological office (measured 26km away from the site).	- Field studies in more than one case study buildings. - Outdoor field data collection.
Indoor environmental aspects	- Indoor AT is high due to high heat gains and low effective area of window. - The value of ΔT is positive and useful for passive ventilation.	- Field data only represent indoor AT, RH and air speed within the SS during the cool-dry season only.	- Detailed field data collection within three types of workspaces and seasons.
Potential passive approache	- Stack ventilation, NTV with thermal mass can be utilised during all seasons.	- No study on air flow performance with ceiling fans. - Lack of field evidence.	- Studying effect of all the proposed approaches (Section 3.7)
Physical viability study	- A designed central shaft is theoretically viable for a successful stack ventilation. - It may not provide comfort cooling at the top floor during the warm-humid season.	- Thermal comfort range was assumed. - No valid simulation study. - No viability testing of other design parameters (Section 3.7).	- Actual thermal comfort perception from workers during all seasons. - A validated simulation study.
Practical viability study	- 78% of the subjects (factory managers) would undertake building refurbishments. - Possible constraints are disruptions for construction and fixed functional layout.	- Structured questionnaire (online) may not avoid biases. - Workers' feedback on adaptive control strategies are absent.	- Semi-structured interviews and extended discussions with the stakeholders.

The pilot study showed that a stack induced ventilation strategy may be possible by integrating a ventilation stack positioned in the centre of the floor plan offered the potential to improve the comfort condition of production spaces. However, the pilot study had limitations in terms of the methods followed and empirical nature of the evidence gathered (as shown in Table 6-6). Therefore, the following considerations were addressed during these field studies and simulation studies to overcome the limitations from the pilot study and to provide answers that address the main research question:

- Selection of more than one case study buildings
- Field studies carried out over the three different seasons
- Field studies in three different site contexts in Bangladesh

- Collection of indoor environmental data from different production sections which are typically located on different floors in the buildings
- Simultaneous collection of outdoor environmental data from the vicinity of the case study buildings
- Occupants' response on their thermal perception and adaptive comfort strategies
- Building owners' comprehensive feedback in response to a range of proposed design strategies
- A validated simulation study to measure the improvement of proposed design strategies in an existing case study building.

The principal investigations and results will be presented in Chapters 7 - 11.

CHAPTER 7. FIELD STUDIES: *RMG FACTORY 1*

This chapter presents the results from the field studies conducted in the first case study building, RMG factory 1, during three climatic seasons in Bangladesh. Exiting issues related to thermal environment and a number of improvement strategies are proposed at the end of the chapter based on the field evidence, including measured environmental data and workers' subjective responses.

CHAPTER 7. FIELD STUDIES: *RMG FACTORY 1*

7.1. Introduction

This chapter takes an account of a case study building *RMG factory 1*, one of the three case study buildings used in this research (Section 5.5.2). It focuses on evaluating the existing indoor environmental condition and thermal performance of the production spaces in this factory through analysis of a range of environmental data, onsite measurements and workers' feedback. The data and outcomes presented in this chapter are both qualitative and quantitative. This chapter highlights the existing issues related thermal performance of the production spaces and a number of possible design strategies that may be employed to improve the existing conditions.

7.2. Chapter Aim and Scope

The main aim of this chapter to address the following sub-question of this research:

> *"What are the factors that influence the thermal environment within workspaces in RMG factories and how do these vary between the seasons of Bangladesh?"*

This chapter addresses this research question through detailed field studies conducted in an existing multi-storey RMG factory building (*RMG factory 1*): one of the three case study buildings used in this research. The objectives of the field investigation are to evaluate the existing indoor thermal performance of the production spaces during the three different climatic seasons and identify applicable design interventions that may improve the existing environmental conditions within production spaces in this factory. This chapter also includes workers subjective feedback on their thermal comfort. However, this chapter will not include the cross tabulation between the spot measurement data and workers' subjective response data. These analyses will be provided in Chapter 10 including the detail statistical analyses to recommend preferred thermal comfort ranges and required environmental conditions for all three case study buildings including *RMG factory 1*. Based on the methodologies applied for the field studies (Section 5.5), the preliminary observations, assumptions and field results are provided in the Sections 7.3– 7.9.

7.3. Site and Micro-climate Study

RMG factory 1 is a 5-storey building located near Joydevpur within the Dhaka region, 25km away from the Dhaka meteorological Department. The total site area is 10900m^2 and the building footprint is 4100m^2. Figure 7-1 shows the footprint of the case study building with its site and surroundings.



Figure 7-1: The case study building: *RMG factory 1* within its site area (source: Google Map)

The meteorological data of the Dhaka region from the year 2008 to the year 2015 reveal that the extremes of outdoor air temperature vary between 12-36°C during this period. Figure 7-2 shows the three main climatic seasons. The cool-dry season has a mean AT of 20.6°C (December to February), the hot-dry season has a mean AT of 28.3°C (March-May) and the warm-humid season has a mean AT of 27.9°C (June-November) (Meteorological Department of Dhaka, 2015). The warm-humid season has a high mean RH of 98% due to the monsoon with minimum RH of 70%.

Figures 7-3 and 7-4 illustrate the outdoor AT and RH recorded covering three field studies. It can be observed that the outdoor ATs varied by season ranging 12-36°C, 17-41°C and 24-37°C during the cool-dry, hot dry and warm-humid seasons respectively. Outdoor RHs also varied ranging 15-95%, 12-96% and 43-100% during the cool-dry, hot dry and warm-humid seasons respectively. Comparing data set presented in Figures 7-2, 7-3 and 7-4, it can be observed that maximum ATs are up to 4°C, 5°C and 2°C higher than the meteorological data during the cool-dry ,hot-dry and warm-humid seasons respectively. As described in Sections 5.4.3 and 6.4, other external factors of micro-

climate, such as incident solar radiation, wind regime and shadow profile for the case study building and adjacent buildings, might have also affected the local outdoor AT.

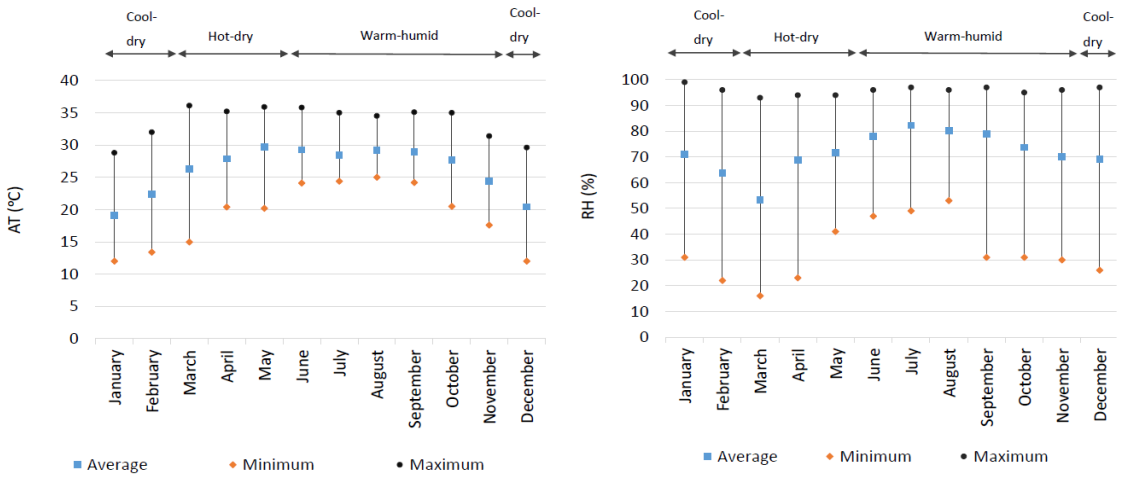


Figure 7-2: Measured AT and RH ranges in Dhaka region (source: meteorological data - year 2015)

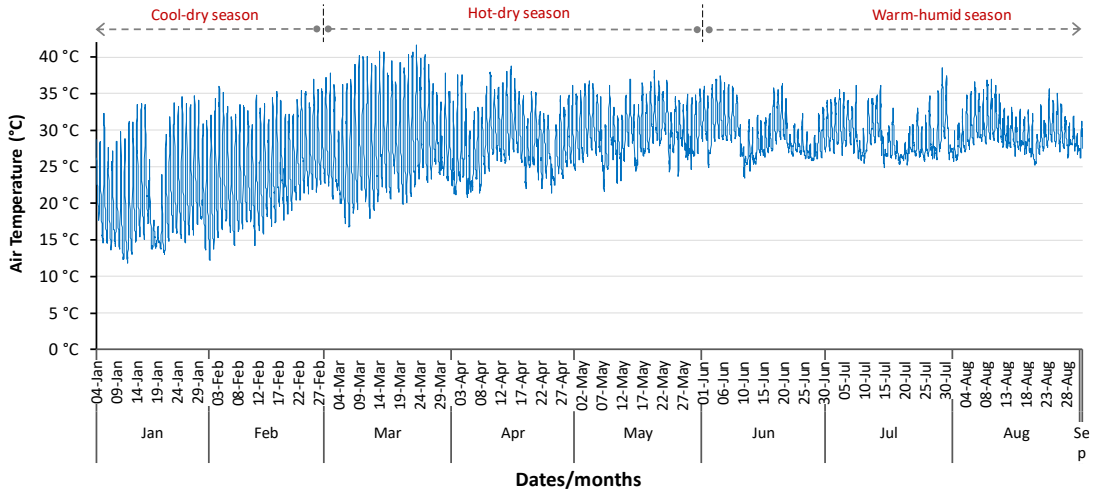


Figure 7-3: Measured outdoor AT during field studies in 2015

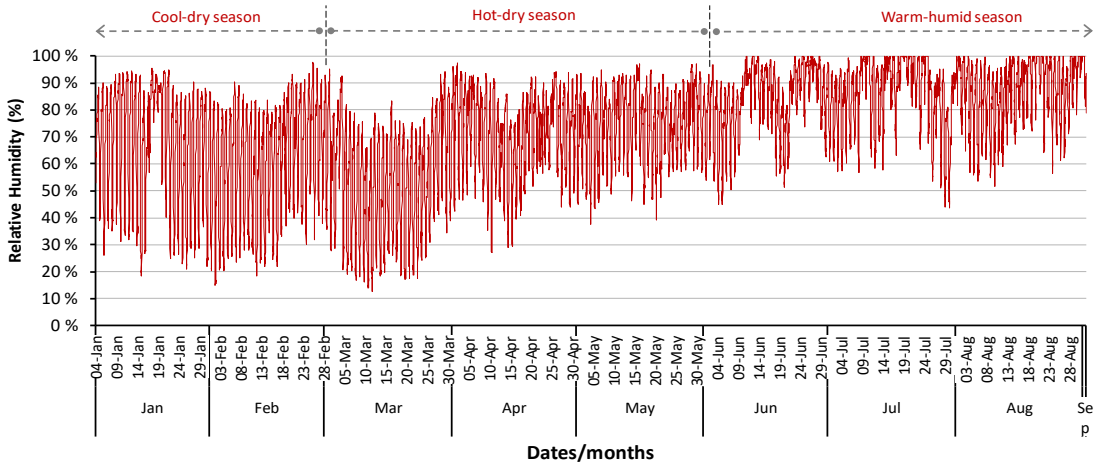


Figure 7-4: Measured outdoor RH during field studies in 2015

Figure 7-5 presents daily climatic parameters (AT and RH) for a representative day from each of the seasons. These reveal that outdoor AT rises to its maximum and outdoor RH falls to its minimum during the occupied hours of the RMG factory. There are diurnal variations of around 12°C, 9°C and 6°C during the cool-dry, hot-dry and warm-humid seasons.

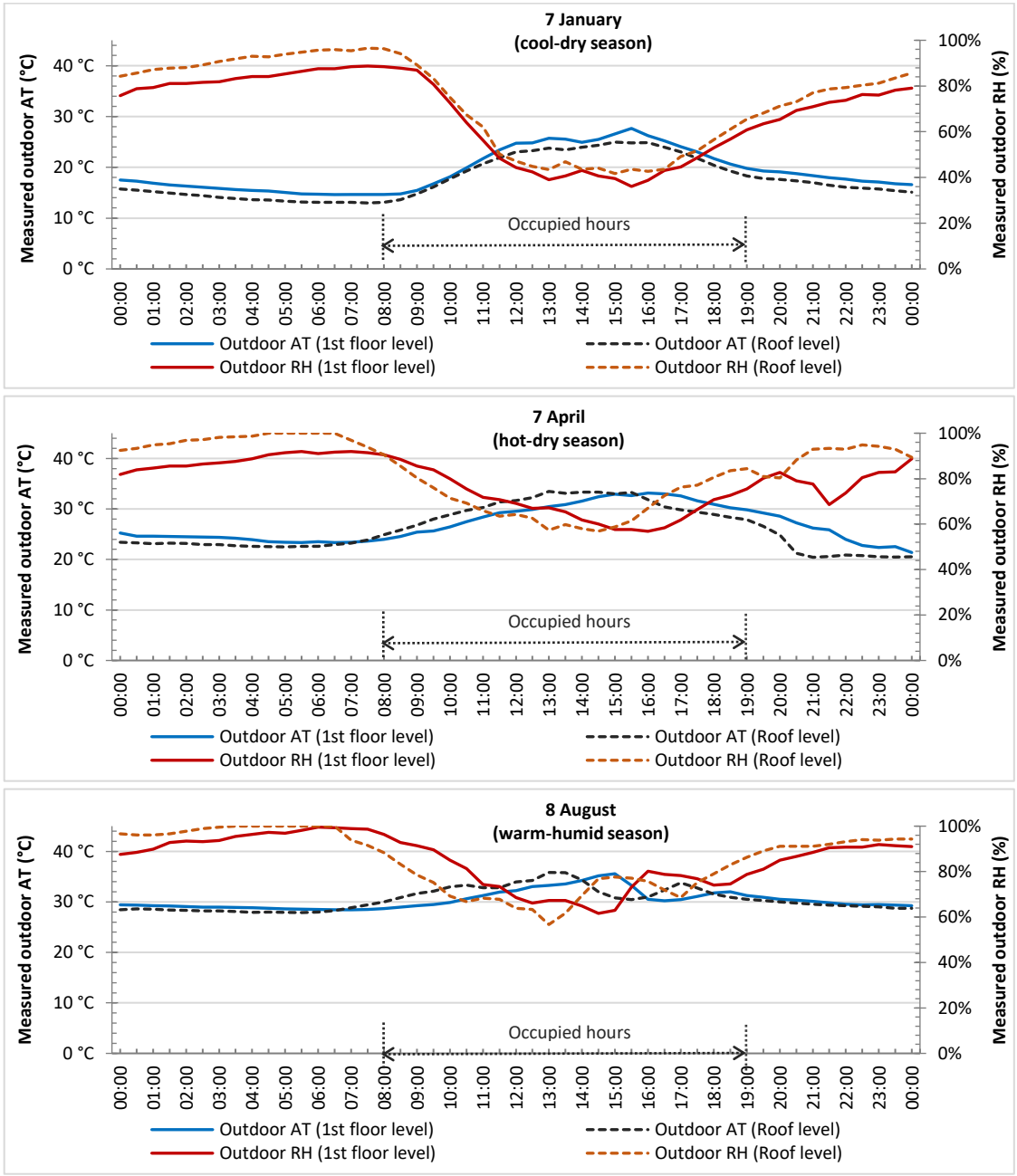


Figure 7-5: Micro-climate data representing a day during each season (Source: field study in 2015)

A temperature difference of up to 6°C and time lag of up to 2 hours can also be observed between the measured AT on 1st floor and roof level. Similarly, a difference of up to 25% in RH can be observed between outdoor RH on the 1st floor and roof level.

These differences indicate that the building surroundings, incident solar radiations, shadow pattern and wind regime may affect the outdoor AT and RH of this building and cause variations in its micro-climate.

Figure 7-6 illustrates the annual sun-path diagram and wind-rose shown relative to the case study building on site. It reveals that the north building facades remain mostly shaded over the course of a year and that the south, east and west facades are exposed to sun for longer periods of a year. This figure also indicates that winter winds from the north or north-west direction and summer winds from the south represent the sources of prevailing wind for the building.

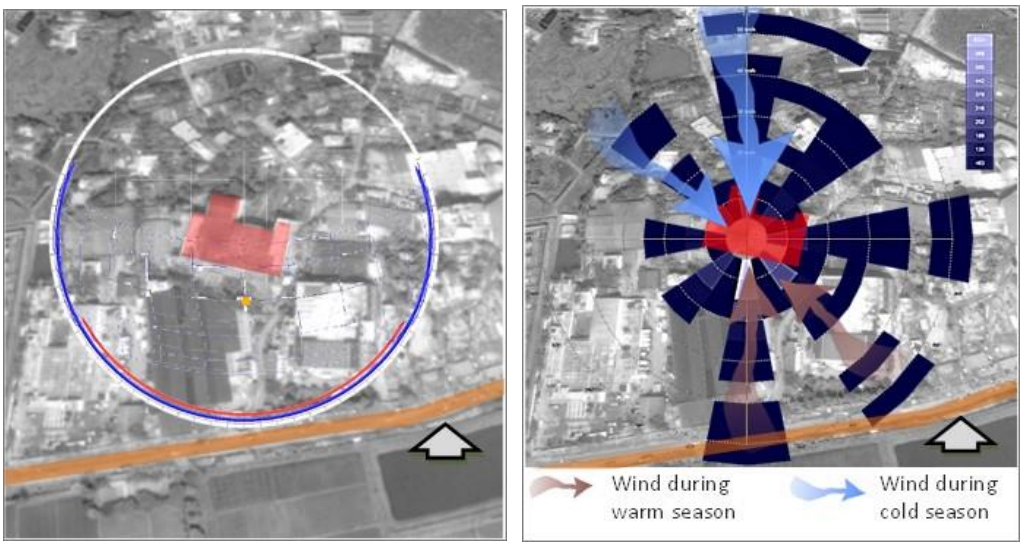


Figure 7-6: Sun-path diagram and wind-rose (source: Google Maps, author's 3D modelling and Ecotect Analysis 2011)

Figure 7-7 shows the shadow pattern at different times of day for the summer solstice, equinox and winter solstice. As mentioned in Section 6.4.3, these days sit within each of the three main seasons. The north side of the building is subject to self-shading during the cool-dry and hot-dry seasons. The south and west façades are subject to the greatest levels of exposure from the sun, which is at its greatest during the winter solstice on the south façade and throughout the year on west facade. The east and west facades are subject to low angle sun in the morning and evening respectively throughout the year. The south is then midday exposure that varies with the seasons. The east façade is subject to shading cast by the adjacent 6 storey building (Figure 7-8) during morning hours in the cool-dry seasons.

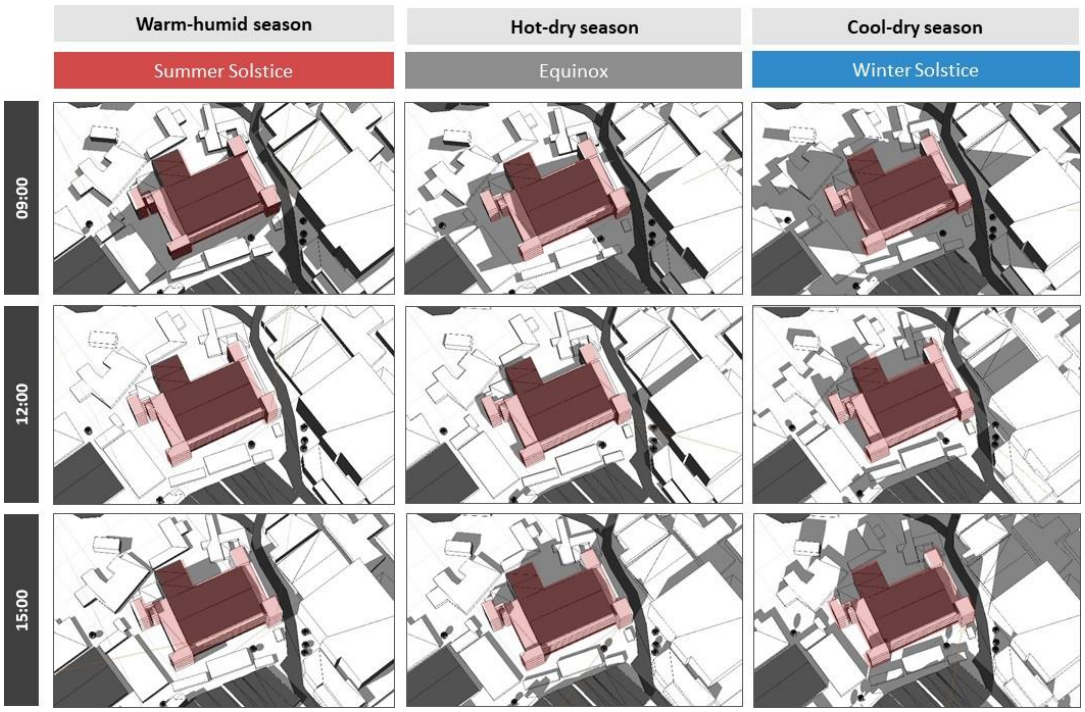


Figure 7-7: Shadow analysis of the *RMG factory 1* (source: Google Maps, author's 3D modelling and Ecotect analysis 2011)

Figure 7-8 represents the morphological context of the case study building. The building is sited in a semi-urban environment where adjacent buildings are a mixture of industrial and residential. This figure indicates that prevailing winds should experience no major obstruction from north and south sides of the building. Since the building orthogonal with north and south, all the façades may get solar exposure, particularly during the hot-dry season. Hence, a major issue is the incident solar radiation on and round the building (previously explained in Section 3.4.1).

Figures 7-9 and 7-10 show estimated distribution of incident solar radiation and field measured surface temperature (in °C) on all façades on a same day of the year in 2015. The date was chosen to compare simulated results and field measured thermal images. The first figure includes solar radiation on ground and roof levels. Figure 7-9 reveals that roof gets the highest incident solar radiation (4760Wh) on the day, while south the side at ground level receives up to 3920Wh radiation. It may also explain the difference between the measured outdoor AT in 8m level and roof level where the top two floors of all of the facades receive more solar radiation in terms of hours. With the exception of the north façade, all facades tend to receive above 3000Wh of sun exposure.



Figure 7-8: Morphological context views from the case study building (source: author-generated 3D models and photographs)

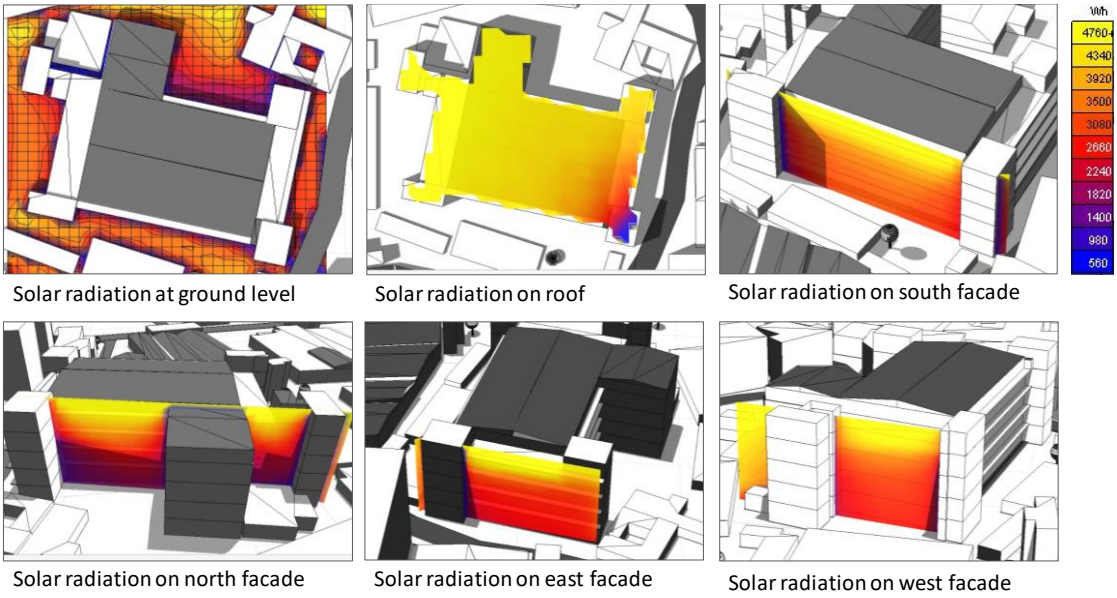


Figure 7-9: Distribution of Incident Solar Radiation on a clear sky day of the year (source: Ecotect analysis on 8 August 2015)

Figure 7-10 reveals that west façade reached maximum surface temperatures of up to 63.6°C during mid-day of 8 August 2015. The south façade is always above 40°C. It was predicted that the north façade would get less heat and therefore exhibit the lowest temperatures due to self-shading. However, in practice this façade shows the highest surface temperature. It was found that it was due to the presence of external boilers located on this façade (which can be also considered as source of heat). Similarly, an

allocated electricity generator near the east façade also produced additional heat affecting the temperature profile close to ground level.

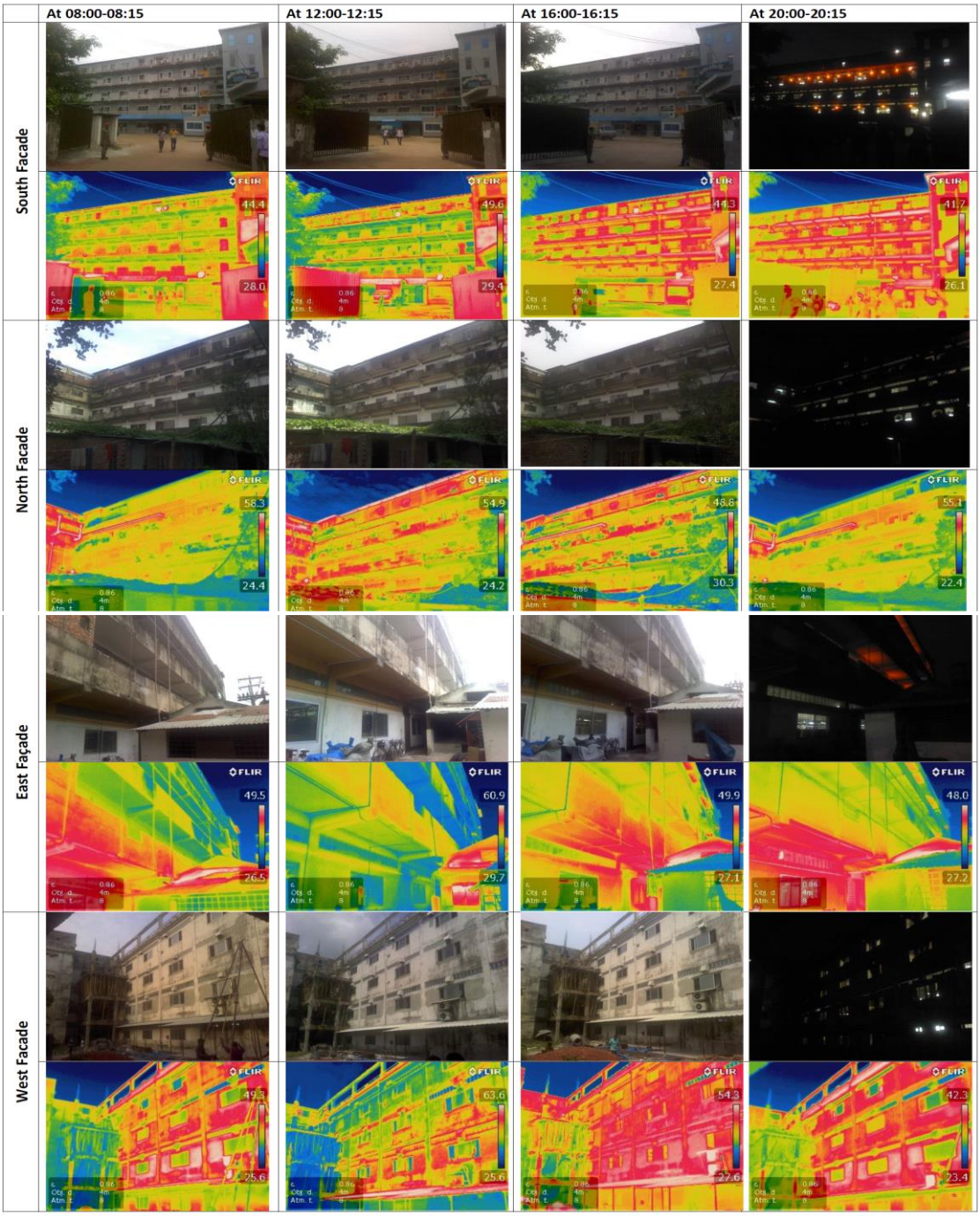


Figure 7-10: Surface temperature profile (not in same temperature scale) of all façades of the case study building (source: field study on a partly sunny day, 10 August 2015)

Initial observation on the building morphology, solar exposure and air flow regime indicate that the west and south sides of the building, including the external walls and

glazing elements are vulnerable to incident solar radiation and solar control should be considered as a strategy to reduce external conductive heat gain.

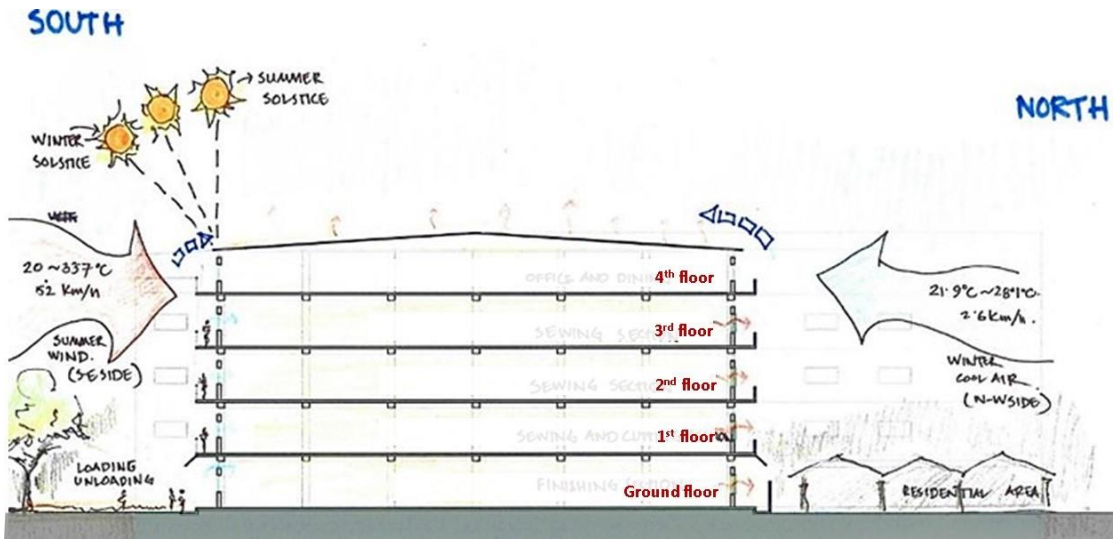


Figure 7-11: Observation of microclimate on *RMG 1 factory* (source: author's schematic drawings)

Figure 7-11 provides a section through the building indicating the prevailing winds and position of the sun relative to the north and south facades. The presence of buildings and other surfaces over which the prevailing wind can flow before entering the building may result in preheating of the ventilation air before it enters the building during working hours. The measured outdoor data suggest that it may be possible to utilise the lower AT range during night time to pre-cool the building fabric before the workforce arrives.

7.4. Building Observation

7.4.1. Functional layouts and workspaces

The case study building comprises five stories with the main production floors (i.e. cutting, sewing and finishing sections) located on ground (1620m^2), 1st (3390m^2), 2nd (2380m^2) and 3rd (2020m^2) floors. The 4th floor contains administrative offices, storage areas and a dining room for workers. Figure 7-12 shows a typical floor plan (1st floor) including the rectangular production spaces and functional flow diagrams. Cutting sections are located on the 1st and 2nd floors. Sewing sections are located on the 1st, 2nd and 3rd floors and Finishing sections are located on the ground and 3rd floors. Two types of production space can be observed on the same floor on the 1st, 2nd and 3rd

floors. From Figure 7-12, it can be observed that loading and unloading of goods and RMG products are held on the south side of the building. Raw goods for production are initially stored in the storage provided on 4th floor. Ideally the raw fabrics are placed in the CS, then to the SS and finalised in the FS. After the production process, the end products are packed in the packing area to get ready for shipment.

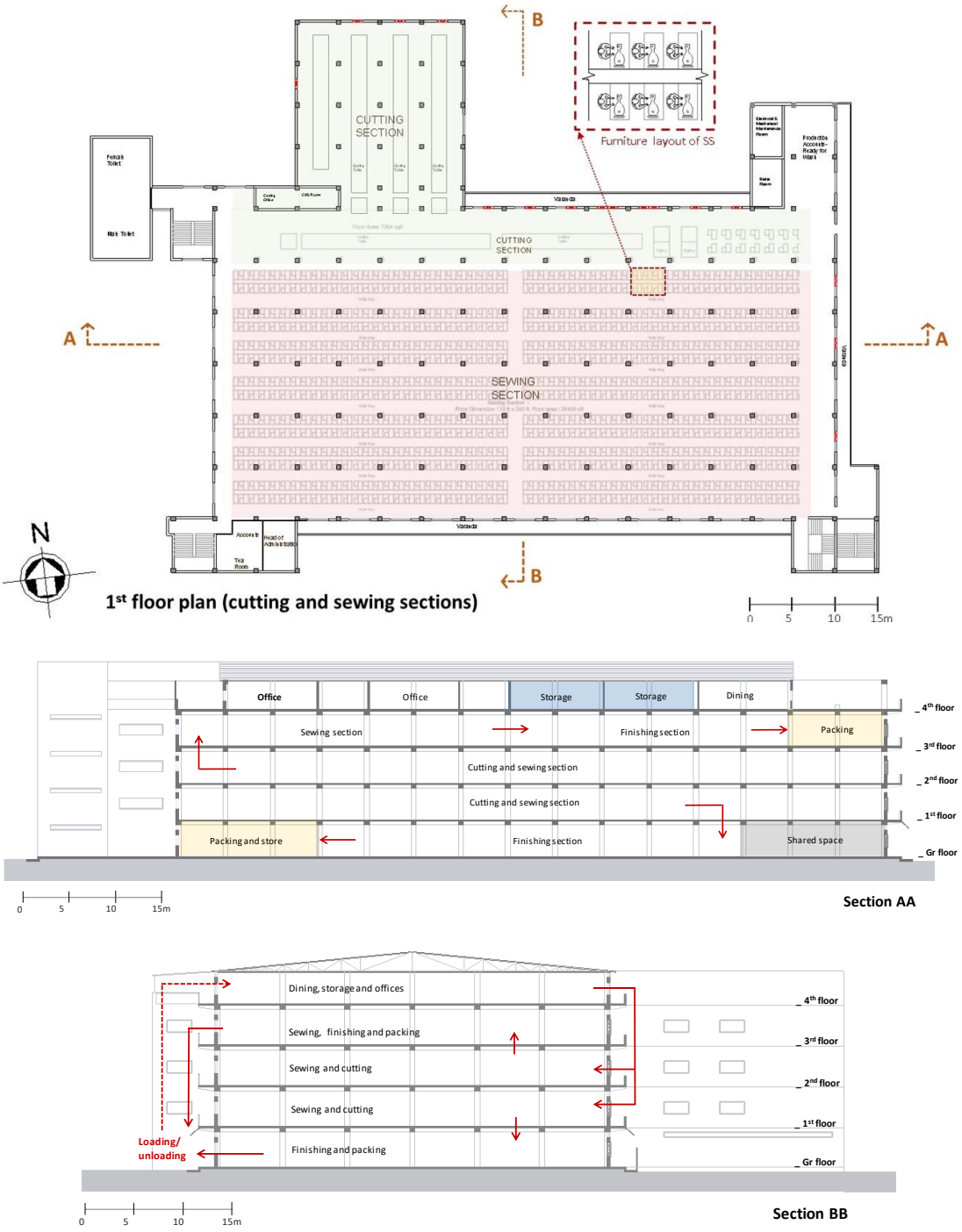


Figure 7-12: Location of the production spaces and activity flow in *RMG factory 1*



(a) Cutting section (CS)



(b) Sewing section (SS)



(c) Finishing section (FS)

Figure 7-13: Panoramic views of (a) Cutting, (b) Sewing and (c) Finishing sections of *RMG factory 1*

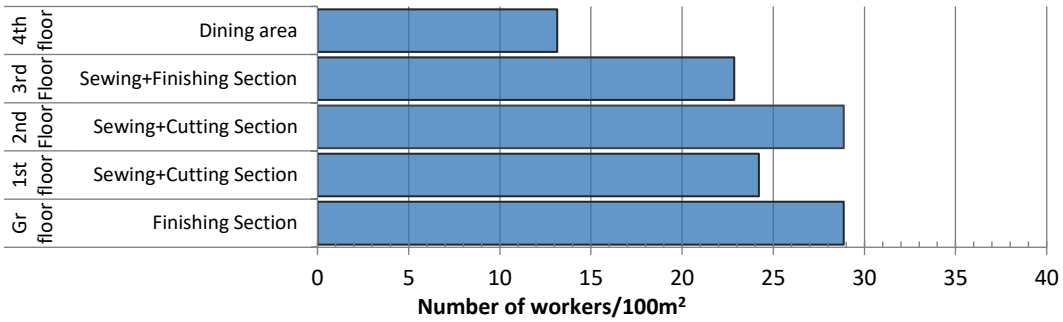


Figure 7-14: Estimated density of the workers in *RMG factory 1*

Figure 7-13 represents the panoramic views of three main production space of the case study building. From this figure, it can be observed that the density of workers is less in the CS and very high in the SS and FS. Figure 7-14 shows estimated density of workers per floor. The Dining room is included in this estimation since this area is also occupied by the workers during lunch time. On average there are 880 workers per production floor excluding the office spaces. Due to combined production sections, such as the SS and CS sharing the same floor, the density of workers varies from 24 to 29 workers per 100m^2. Moreover, the different type of production equipment, such as cutting, sewing and irons, are also different in layout and impose different thermal loads in the different production spaces (explored in Section 7.4.3).

7.4.2. Existing ventilation strategy

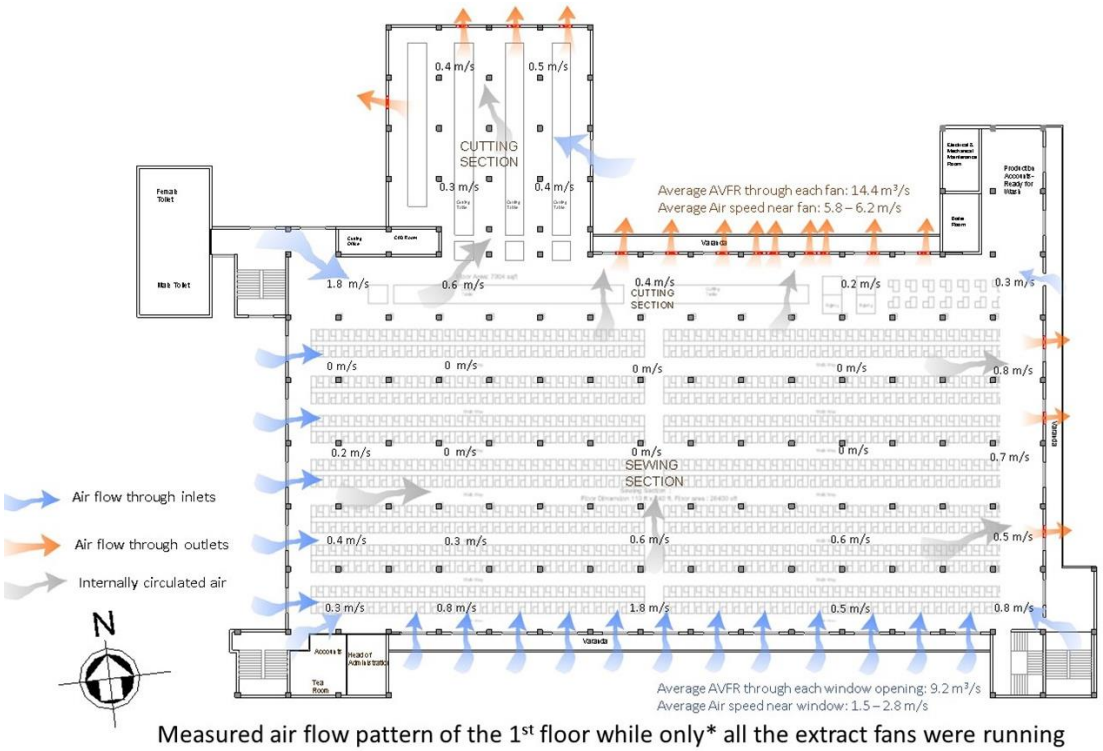
The case study building is ventilated mainly by total 42 large (1.4m diameter) mechanically controlled extract fans placed mainly on the north and east facades of the building. The location of these dictates the indoor air flow regime, which was recorded as flowing from south to north direction and west to east direction. This active ventilation system make the windows and doors act as inlets that bring fresh air from immediate outdoor area. The width of the floor is 40m. Natural cross ventilation was not found to be occurred inside the production floors, as the building ceiling height to floor-plate width ratio (1:10) exceeds the threshold ratio (1:5), the rule of thumb cross for ventilation (Section 3.5.1). Figure 7-15 shows the south and north zones of a production floor (1st floor) with inlets and outlets respectively. Ceiling fans were also available as a provision of providing additional cooling for workers in the production spaces during working hours.

Figure 7-16 shows the 1st floor plan and the typical horizontal air flow pattern at work plane level in the 1st floor's production space. Each extract fan was found to be capable of extracting air by 14.4 m^3/s volume flow rate (Section 5.4.5). Average air speed near these fans were recorded at 5.8 - 6.2 m/s. Average air volume flow rate at each window (45% of the openable area) was measured 9.2 m^3/s. Air speed through each window also found ranging from 1.5 and 2.8 m/s.

An approximate schedule of active ventilation (extract fans) and estimated volume flow rate (AVFR) recorded during three field surveys in the year of 2015 can be found in Appendix F-1. It was observed that the extract fans were commonly switched on at 10:00, 9:00 and 8:00 during the cool-dry, hot-dry and warm-humid seasons. However, these schedules varied on different production floors due to the number of extract fans. During all seasons, the fans were switched of during the lunch period (usually 13:00-14:00). The existing ventilation strategy was only practised during working period (08:00am-20:00) which might simultaneously gain heat through convection by pulling hot outdoor air, particularly during the hot-dry season. No ventilation was provided during unoccupied hours (20:00-07:00) including 24 hours of the weekend during which time all the windows were kept closed.



Figure 7-15: Workspaces with ventilation inlets (windows), outlets (extract fans) and ceiling fans



Measured air flow pattern of the 1st floor while only* all the extract fans were running

**Ceiling fans were not operating during the field study to understand the horizontal air flow pattern solely for the extract fans*

Figure 7-16: Measured air flow pattern of 1st floor of *RMG factory 1* with active ventilation (source: field studies in 2015)

The existing ventilation strategy of *RMG factory 1* indicated that there should be a significant difference in thermal performance of the production floors between the occupied and unoccupied hours of the factory.

7.4.3. Impact of internal heat gains

A key feature that distinguishes a RMG factory from other non-domestic buildings is the high internal heat gain. The main sources of internal heat gain are lighting equipment, production equipment and high density of workers (Figure 7-14). Table 7-1 provides an overview of the sources of heat gain and their surface temperatures during working hours measured on a typical day during the hot-dry season. The highest surface temperatures (ST) were observed in the FS and SS where values of up to 180°C were recorded for Irons and up to 73.3°C for sewing machines. Given that the number of sewing machines (all types) are relatively high in production sections, a significant amount of heat could be generated in the SS resulting in environment with high AT (Section 3.4.3). On the other hand, number of cutting machines is relatively low in the CS, which should result in less heat being generated inside this space (Appendix H-1).

Figure 7-17 shows thermal images of three production spaces (CS, SS and FS) and reveals that surface temperature ranges of 37.5-44.1°C, 39.2-53.3°C and 36.8-108°C were recorded in the CS, SS and FS respectively. Given that these various thermal profiles in different sections were recorded during working hours, this would have an effect on indoor AT and RH during working hours and might cause high temperature.

Figure 7-18 illustrates internal heat gains that were estimated for different floors of the building excluding the service and office areas (Sections 5.4.5 and 5.5.5). It reveals that the 3rd and 1st floor had the high internal heat gains of 320.6 W/m^2 and 185.1 W/m^2 where heat gains from factory equipment could be significant. Comparing the Figure 7-17 and Figure 7-18, it also can be observed that the fans that were provided for additional comfort also contribute to increase the internal heat, particularly in the FS. It can also be assumed that combine impacts of internal heat gain and external conductive gains, such as through building fabric and glazing during day time (Sections 3.4 and 7.4.4), can result in high indoor AT during working hours.

Table 7-1: Sources of internal heat gain in RMG factory 1 with their surface temperatures (source: field studies)



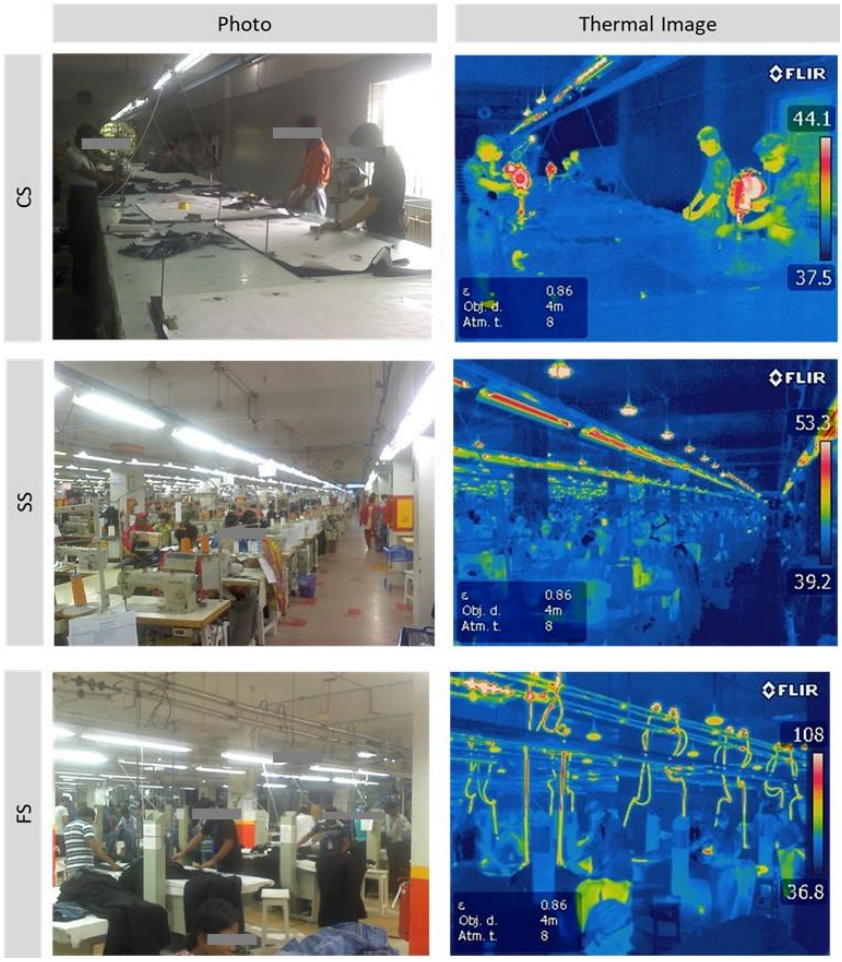
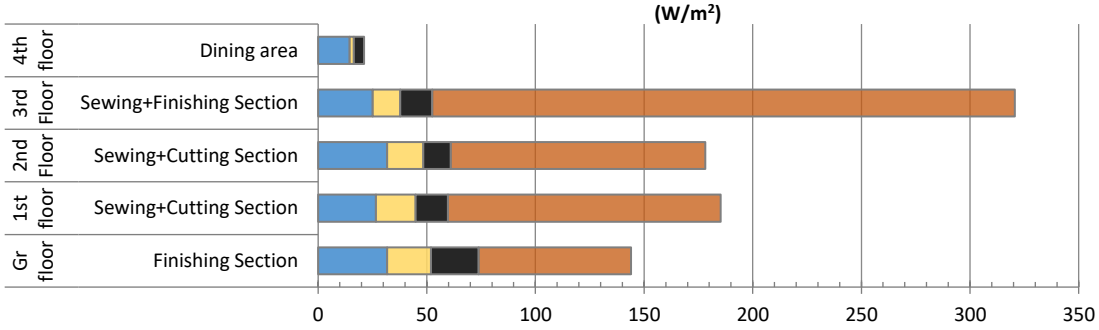


Figure 7-17: thermal images of key production sections in *RMG factory 1*



	Gr floor	1st floor	2nd Floor	3rd Floor	4th floor
	Finishing Section	Sewing+Cutting Section	Sewing+Cutting Section	Sewing+Finishing Section	Dining area
Occupant heat gain	31.7	26.6	31.8	25.1	14.5
Heat gain from lights	20.2	18.3	16.7	12.7	1.9
Heat gain from fans	21.8	14.8	12.6	14.7	4.7
Heat gain from Equipment	70.1	125.4	117.2	268.1	0.0

Figure 7-18: Estimated internal heat gain (in W/m^2) of RMG factory 1 building

Field evidence from the thermal images and estimates of internal heat gain profile suggest that there is a risk of high temperature unless a substantial amount of air change are provided through ventilation to flush out the hot air caused by equipment and occupants.

7.4.4. Material and construction

The building was constructed and renovated around the year of 1998-2000. The main construction type is reinforced concrete (RC) beam-column structure with concrete floor plates and 125mm thick external brick walls. Sliding windows with single glazing panes are located on all facades all of which have the same sill height (1.3m), however, the windows on the south and west facades are openable. These windows have maximum effective opening of 45%. The effective WFR is 1:45 which is low for natural ventilation (Sections 2.7 and 3.5.1). The spaces also have clearstory windows which are also not openable. Since the effective area of windows play significant role for passive ventilation, the effect of window configuration on indoor thermal environment should be explored further.



Figure 7-19: Various construction elements of *RMG factory 1*

Figure 7-19 and Table 7-2 provide an overview of the main construction materials of the case study building with their brief description and estimated thermal properties. The suspended floor slabs consisted of RC with floor finishes that allow access to their thermal mass (i.e. homogenous ceramic tiles). External walls and doors have relatively low thermal mass (75.5 and 64.29 KJ/m^2 K respectively). All facades of the building were found to have an extensive area of glazing materials with an estimated U-value of 5.17W/m^2K.

Table 7-2: Main construction elements of *RMG factory 1* (source: author, based on field study)

Main construction elements	Description	Total Thickness (mm)	U-value (W/m^2K)	Thermal mass (KJ/m^2 K)	Specific heat capacity J/ (kg K)
Ground floor slab	0.100m thick concrete floor with 10mm cement mortar (floor), 8mm ceramic floor tiles, 0.6m brick soling and sand filling underneath	378 *(including sand fill above the ground)*	1.81	310.0	800 (tiles) 800 (mortar on floor) 840 (concrete) 837 (brick soling) 1550 (Sand filling)
Suspended floor slab (floor/ ceiling)	0.15m thick reinforced concrete floor with 12mm thick light plaster (ceiling), 10mm cement mortar (floor) and 8mm ceramic floor tiles	180	2.43	186.6	800 (tiles) 800 (mortar on floor) 1000 (RC) 1000 (fired clay)
External walls	0.1m brick work with 12.5mm medium weight plaster each side with paint	125	2.25	75.5	800 (brick work) 1000 (plaster)
Glazing with frames	Clear float 6mm glass, single glazed (G-value: 0.82, transmittance 0.78) with aluminium frames and recessed local shade	6mm	5.17 (including frame) 5.69 (glass)	-	-
Door	40mm thick steel swing doors	40mm	5.85	64.29	418.0
Local shading element (north and south facades)	0.15m thick reinforced concrete floor with 12mm thick light plaster (ceiling), 10mm cement mortar (floor) and 5mm cement coating	177	2.42	186.1	1000 (cement coating) 800 (mortar on floor) 1000 (RC) 1000 (fired clay)
Roof slab (type 1)	0.15m thick RC with 5mm cement coating	155mm	4.65	178.25	1000 (cement coating) 1000 (RC)
Roof (type 2)	Corrugated metal sheet with metal truss and 3mm thick bamboo matting as suspended ceiling	Varies	7.14 (metal sheet)	-	480 (metal sheet)

Figure 7-9, Figure 7-10 and Table 7-2 indicate that the building would be subject to conduction heat transfer through the building envelope including roof slab (U-value of 4.65W/m^2K), external walls (U-value of 2.25W/m^2K) and glazing materials. It might result in significant external solar gain through exposed area of the building envelope, which could contribute to high temperature inside working environment during day time. Moreover, this is a heavy-weight building which indicates the potentiality utilising thermal mass as cooling strategy.

7.5. Preliminary Assumptions

For further investigation, a few assumptions can be made based on the preliminary observations of the case study building, its operation and temporal varieties of its micro-climate (Sections 7.3 - 7.4). They are as follows:

- Incident solar radiations on south and west façades and preheated outdoor air may affect the indoor thermal environment.
- High heat generating equipment and density of workers within the SS and FS may result in high temperature in these workspaces.
- Workers' thermal comfort may also be affected by the poor air flow pattern within deep floor plate and limited ventilation control strategy.
- Despite having low outdoor AT throughout the year, this heavy-weight building may store heat resulting in high indoor AT during night time.

The physical measurements and subjective field data, presented in Sections 7.6 - 7.9, will be tested considering these assumptions and scope of improvements will also be proposed in Section 7.9.

7.6. Continuously Monitored AT and RH

A comprehensive summary of continuously recorded AT and RH of the *RMG factory 1* buildings is presented in Table 7-3 in respect to the immediate outdoor thermal environment. These data included both occupied and unoccupied hours. Recorded indoor AT and RH data from the three types of production space reveal that the mean indoor ATs varied within the ranges of 24.3-25.9°C (mean RH: 45.7-51.7 %) during the cool-dry season, 30.2-33.2°C (mean RH: 60.5-61.7%) during the hot-dry season and 32.3-33.2°C (mean RH: 68.7-71.7%) during the warm-humid season.

Table 7-3: Descriptive statistics of the continuously recorded indoor and outdoor environmental data (i.e. TA and RH)* in all seasons (source: three field studies in 2015)

Season	Work section	Avg. AT_{in} (°C)		Avg. AT_{out} (°C)		Avg. RH_{in} (%)		Avg. RH_{out} (%)	
		Min - Max	Mean (SD)	Min-Max	Mean (SD)	Min - Max	Mean (SD)	Min - Max	Mean (SD)
Cool-dry	CS	21.0 - 28.1	24.3 (1.3)	11.8 - 32.3	19.3 (5.2)	41.1 - 69.1	51.7 (4.4)	26.1 - 94.6	71.2 (19.6)
	SS	21.2 - 30.7	26.6 (1.7)			34.9 - 67.3	45.7 (4.3)		
	FS	23.5 - 28.1	25.9 (0.8)			37.7 - 67.0	51.3 (5.3)		
Hot-dry	CS	26.2 - 33.9	30.0 (1.5)	20.9 - 37.9	27.4 (4.3)	44.9 - 75.6	60.9 (4.9)	27.1 - 97.5	74.2 (15.8)
	SS	26.5 - 34.3	30.2 (1.7)			40.8 - 77.5	60.5 (6.2)		
	FS	26.2 - 34.2	30.3 (1.5)			43.3 - 75.4	61.7 (5.1)		
Warm-humid	CS	30.7 - 34.7	33.2 (0.7)	25.7 - 36.9	30.1 (2.6)	58.7 - 79.8	68.7 (3.5)	51.8 - 100	84.2 (12.8)
	SS	29.8 - 35.0	32.8 (0.9)			56.7 - 82.3	69.0 (4.4)		
	FS	29.7 - 34.9	32.3 (1.1)			58.6 - 87.2	71.7 (5.5)		

**Logged data of the typical production (sewing) floor including the data of unoccupied hours (i.e. out of production hours and the hours during weekends)*

***AT and RH were the average values logged at two different levels (e.g. 1.2m and 2.5m heights from the floor level) in the centre of a workspace at 30 minutes intervals*

The Standard deviation (SD) of the outdoor conditions both during the cool-dry and hot-dry seasons showed higher fluctuations of AT (SD: 4.3 - 5.2°C) and RH (SD: 15.2 – 19.6%) compared with those observed during the warm-humid season (SD of AT: 2.6°C, SD of RH: 12.8%). These higher SDs are the result of the wider diurnal range of AT observed during the cool-dry and hot-dry seasons, which can be also observed from Figures 7-3 and 7-20. These scenarios represented the meteorological data as described in Section 7.3 aside from the RH is relatively higher during the warm-humid season (highest AT: 36.9°C and RH: 100%). However, SDs of indoor condition did not indicate any significant fluctuation of AT (0.8-1.7°C) and RH (3.5-6.2%) compared with the variations observed in the outdoor condition. As the above observations only represent data collected over a week during each field study, this can be more explicitly visualised in Figures 7-20 and 7-21.

Figure 7-20 shows the indoor AT (in the SS) and outdoor AT. It can be observed that the diurnal range of outdoor AT was high ranging between 11.8-42°C during the hot-dry and cool dry seasons. However, the diurnal range of indoor AT (24-36°C) was not as high as the outdoor AT. Similarly, from Figure 7-21, it can be observed that the

diurnal range of outdoor RH was high ranging 12%-93% during the hot-dry and cool dry seasons. However, indoor RH ranged between 20% and 80% during these two seasons. Compared with the assumed thermal comfort range, as referred in Section 2.5.2, mean values of indoor AT exceeded the targeted comfort range (general target: 24-28.5°C) during the hot-dry and warm humid seasons, however, they met the moderated comfort range. RH during the warm-humid season also exceed the targeted RH (below 65%).

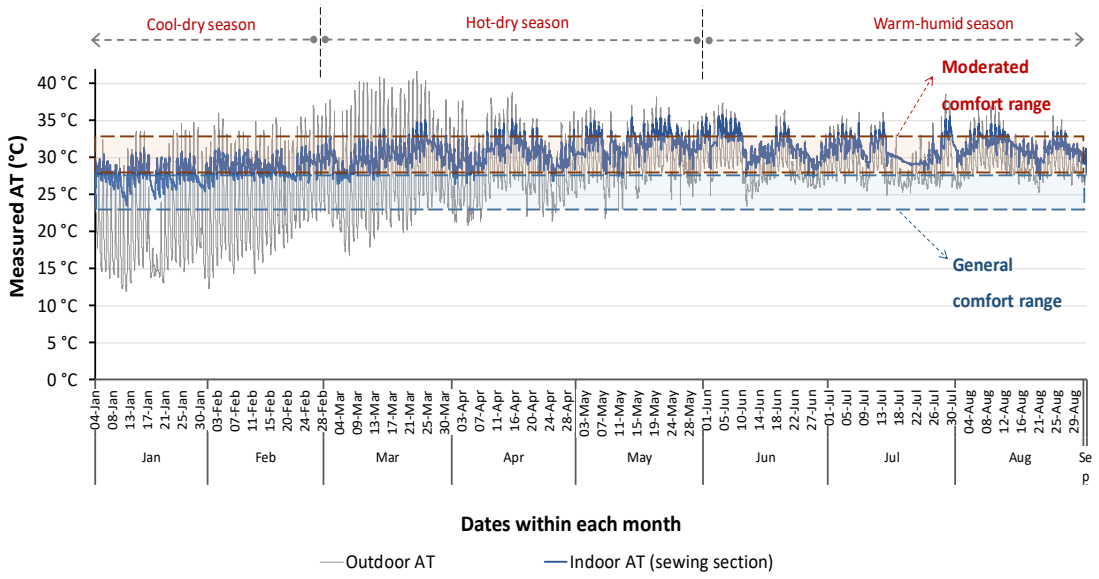


Figure 7-20: Continuously logged AT in the case study building: *RMG factory 1* (SS and outdoor)

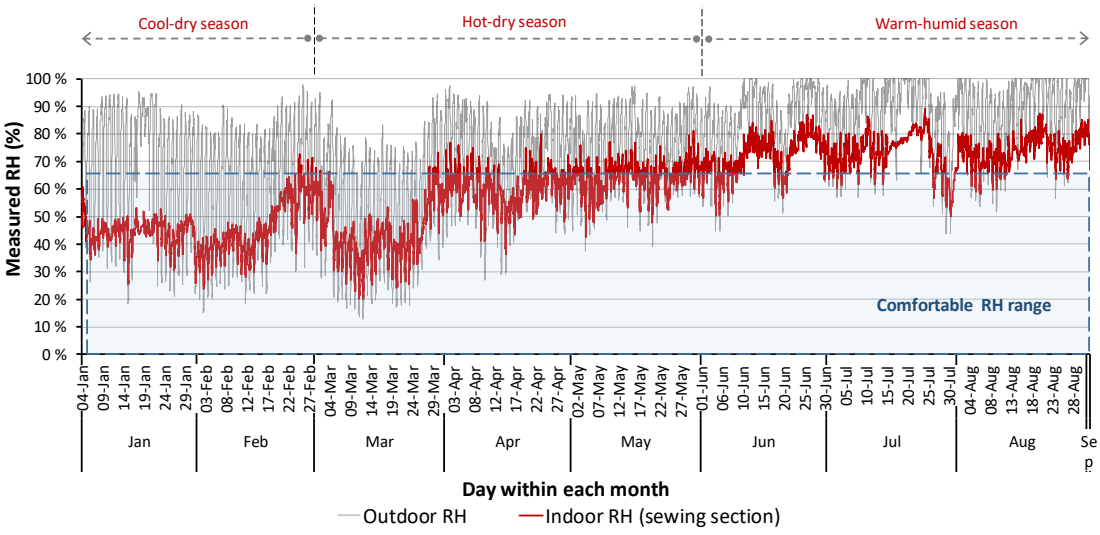


Figure 7-21: Continuously logged RH in the case study building: *RMG factory 1* (SS and outdoor)

Continuously measured data reveals that the indoor AT and RH varied across the production spaces and time of a day. Hence the further data set will be analysed below for individual production sections. The recorded data from the 1st floor (the SS and CS)

will then be assessed further, focusing on the horizontal and vertical profile of AT and RH produced by the different data logger sensors, the position of which are shown in Figure 5-10.

7.6.1. Cool-dry season

Figure 7-22 reveals that the CS had a relatively low AT profile (ranging 24-27°C) while the SS had higher range (25-30°C) probably due to the high internal heat gain (Figure 7-18) from the sewing machines. Remarkably, during the weekend and non-working hours deviations in AT that correspond to the pattern of use of the building can also be observed. It was observed that positions remote from the building perimeter exhibited a smaller variation in temperature in response to occupant use patterns. This is probably due to deep floor plate (40m) and lack of natural infiltration (i.e. windows were shut, and fans were switched off), which results in the high AT gained internally during working hours being trapped inside the production floors. In contrast, RH values in the SS also dropped below 40%, which was lower than other production spaces, due to higher AT in the SS.

To understand explicitly the impact of internal heat gains from different production spaces on indoor AT, AT variations for a representative day with gains (weekday) and a day without gains (weekend) are compared in Figure 7-23.

Comparing the Figures 7-24(a) and 7-24(b), it can be easily noticed that due to the internal heat gains the indoor AT was elevated from 25°C to 28°C for the weekday while in similar outdoor temperature conditions, the indoor AT was a steady (24-25°C) during the weekend. It may also be seen that even with the large diurnal variation of outdoor AT (minimum 12°C), the indoor AT did not drop below 23°C during night time. This indicates that the natural infiltration rate might be inadequate to cool down the indoor fabric including machinery and reduce the indoor AT to match low night time outdoor AT.

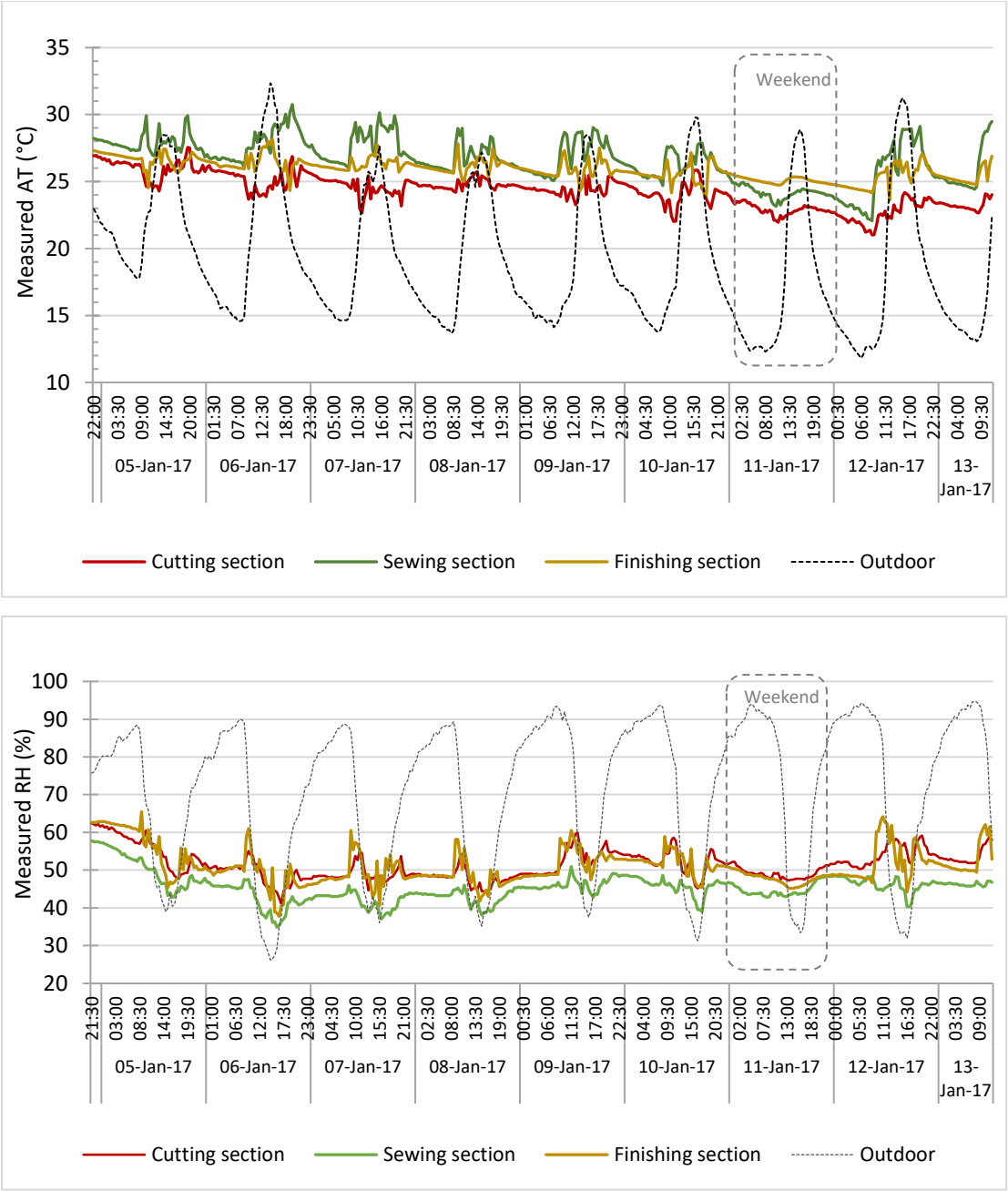
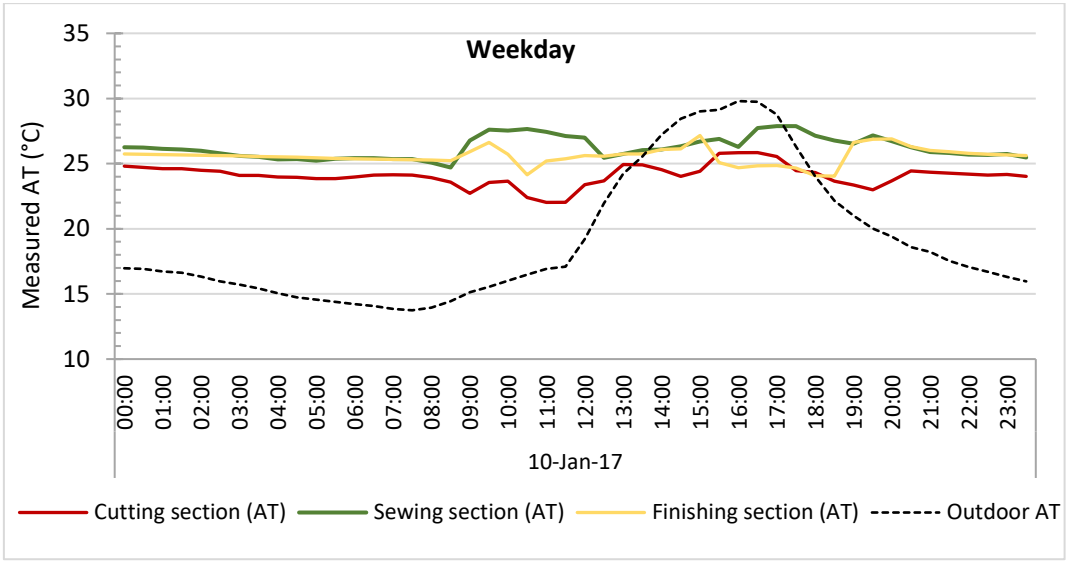
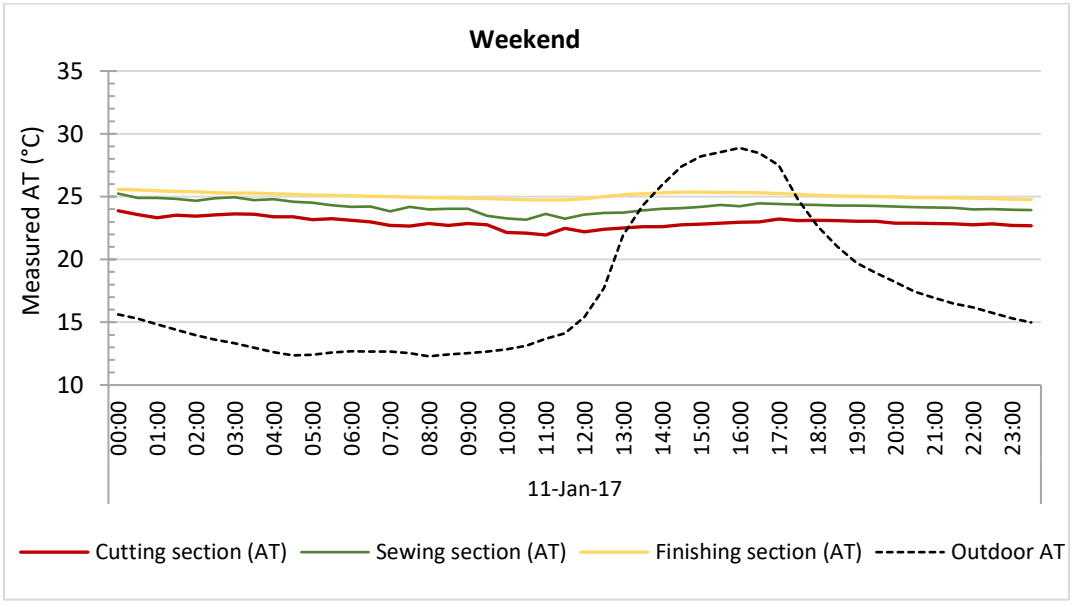


Figure 7-22: Measured AT and RH for production spaces during the cool-dry season (source: field study, year 2015)



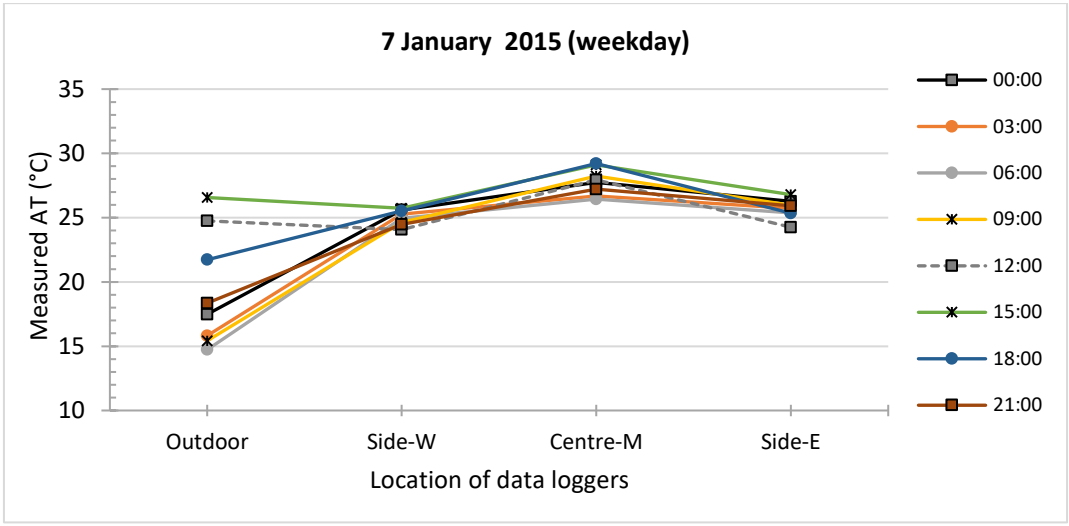
(a)



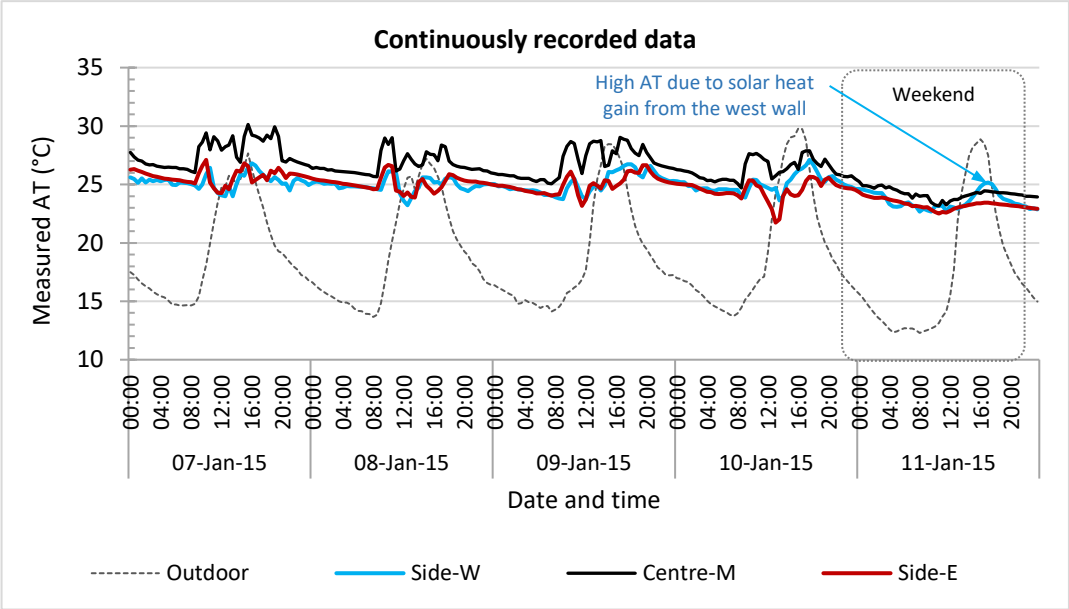
(b)

Figure 7-23: Measured AT for a typical weekday and weekend during the cool-dry season (source: field study, year 2015)

Data loggers were also placed in a few positions (shown in Figure 5-10) to understand horizontal variation of indoor AT. Figure 7-24(a) reveals that AT values in Centre-M position (middle zone) of the floor were at least 2-4°C higher than positions near the west and east sides of the production floor and reached to its peak between 15:00 and 18:00 with a deviation of 7°C with the outdoor AT (at 18:00). Figure 7-24(b) also reveals that AT values at the centre of the floor remain about 2-3°C higher than those for the west and east sides of the floor-plate.



a)



(b)

Figure 7-24: Measured AT profile recorded along the west to east axis of the 1st floor during the cool-dry season - (a) data for different times of day and (b) continuously recorded data

Similarly, Figure 7-25(a) shows that AT values in Centre-M position of the floor were at least 2-3°C higher than those recorded near the south and north sides of the production floor. Figure 7-25(b) also shows that AT values at the centre of the floor kept this deviation of 2-3°C from the south and north side of the floor during working hours (08:00-20:00).

Both Figure 7-24 and Figure 7-25 suggest that the indoor air in the middle zone of the floor plate remained hot as compared with the zones near all facades both during day and at night time.

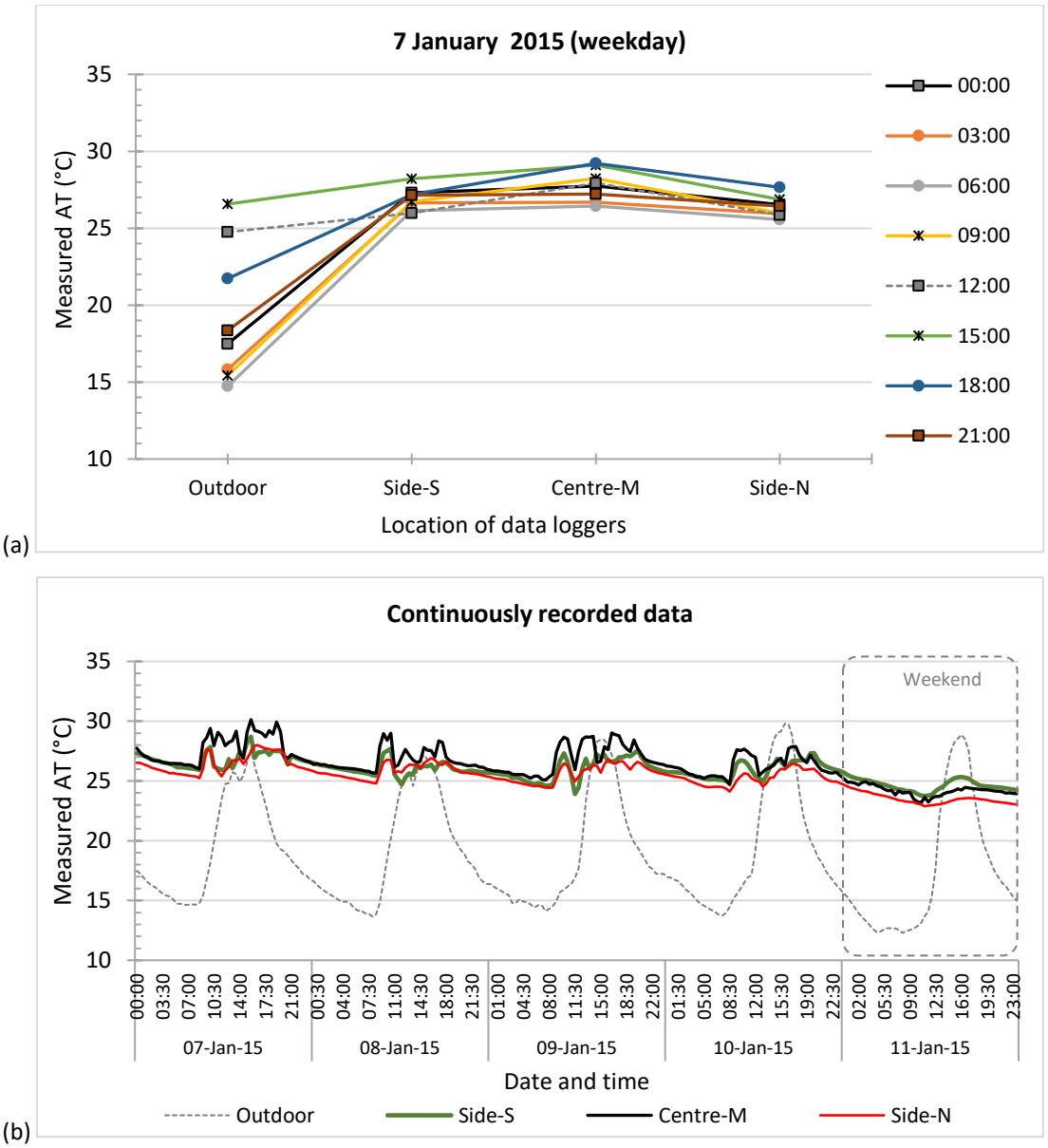


Figure 7-25: Measured AT profile recorded along the south to north axis of the 1st floor during the cool-dry season - (a) data for different times of day and (b) continuously recorded data

7.6.2. Hot-dry season

Figure 7-26 illustrates that the CS had relatively low AT profile (maximum 33°C) while the SS and FS had 1°C higher values (34°C) during peak hours (12:00-16:00) probably due to the high internal and external heat gains. However, during the weekend and non-working hours, these deviations were found to vary by up to 2°C. It can be observed that during the night time the difference in AT values between the FS and outdoor by up to 5°C. There were no significant deviations of RH values between production sections. It also indicates that the floors might have stored the heat during the night time due to absent of ventilation (Appendix F-1). This is suggesting that the

fabric has stored sufficient heat to maintain a stable indoor temperature by balancing with the rate of ventilation.

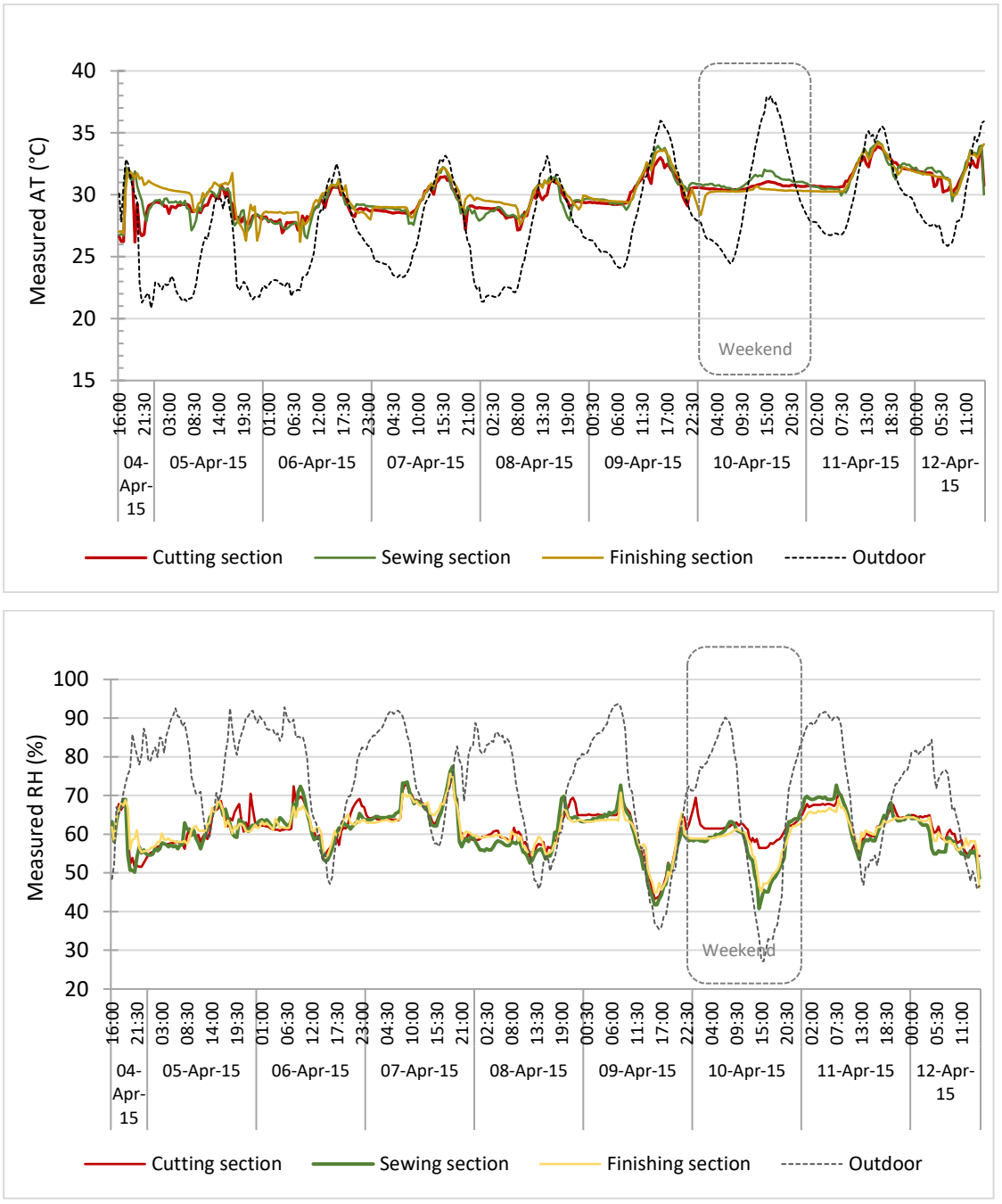
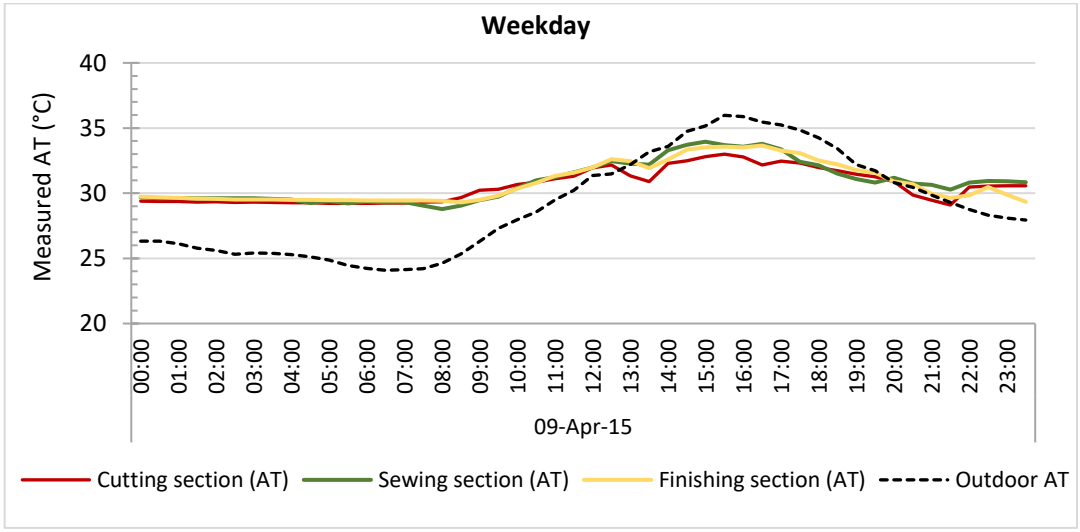


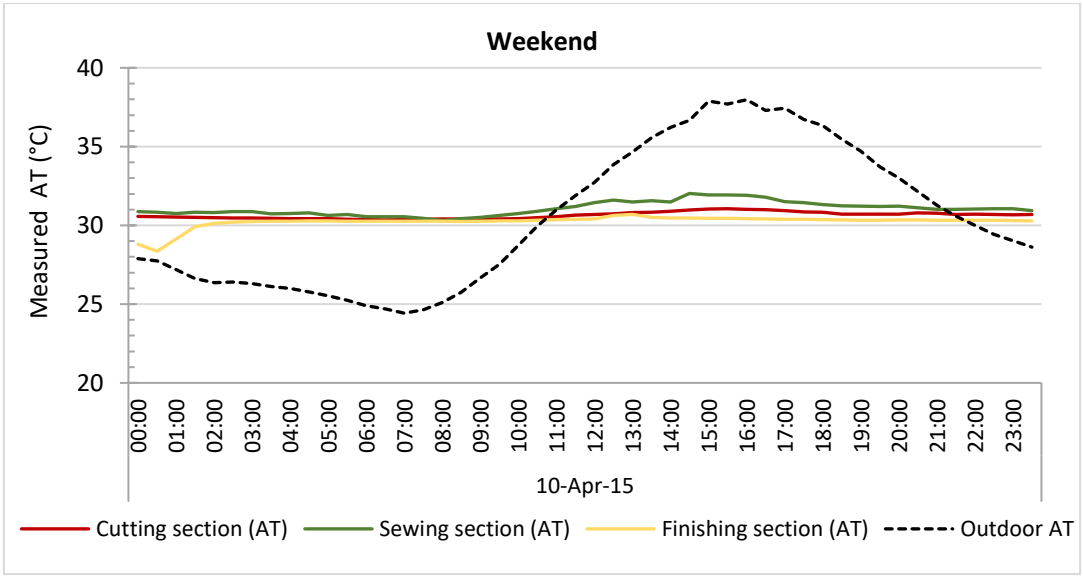
Figure 7-26: Measured AT and RH for production spaces during the hot-dry season (source: field study, year 2015)

Similar to previous section, continuously measured AT values from different production spaces of a typical weekday and a weekend were compared in Figure 7-27. They are presented to help understand the indoor AT pattern corresponding to the changing outdoor AT during the hot-dry season. Figure 7-27(a) and Figure 7-27(b)

indicate that the indoor AT in the SS and FS increased from 29.5°C to 34°C during working hours of the weekday while when subject to a similar AT fluctuation at the weekend, the indoor AT remained steady showing a variation of only 30-31.5°C in the weekend. However, it explicitly shows that even with the variation of outdoor AT (minimum 24.5°C at 06:00), indoor AT did not drop below 30°C during night time. Like the cool-dry season, this indicates the response as heavy-weight building and the natural infiltration rate might be inadequate to cool down the indoor fabric including machinery and reduce the indoor AT to match low night time outdoor AT.



(a)



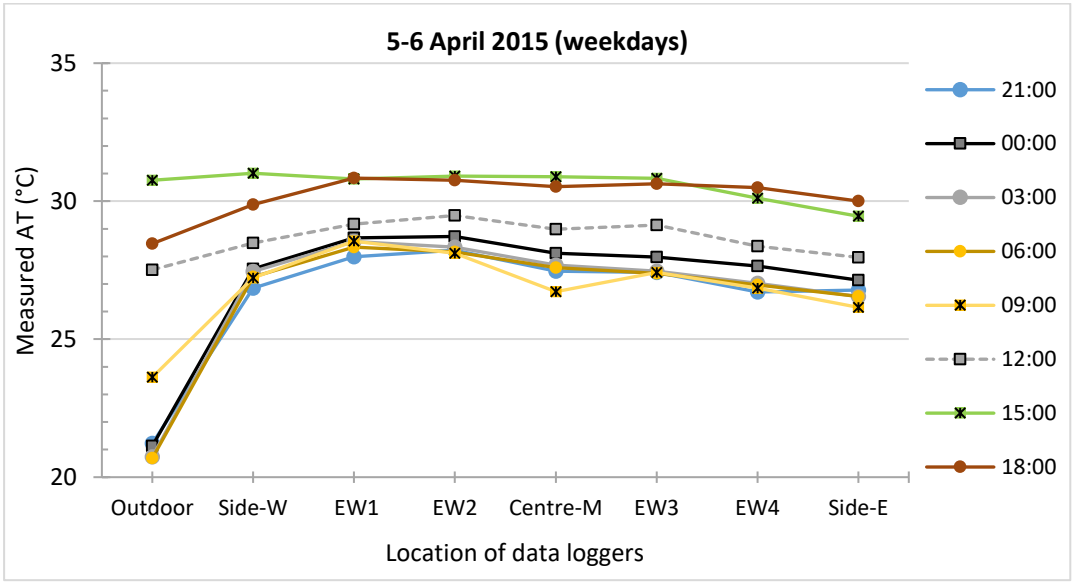
(b)

Figure 7-27: Measured AT for a typical weekday and weekend during the hot-dry season (source: field study, year 2015)

Data loggers were located as shown in Figure 5-10 to understand horizontal distributions and variations of indoor AT. Figure 7-28(a) reveals that the AT values at

EW1 and EW2 positions on the 1st floor were at least 1°C higher than those near the west and east sides of the production floor reaching a peak between 15:00 and 18:00 of the day and exhibited a minimum deviation of 2.5°C from the outdoor AT (at 18:00). Figure 7-28(b) also reveals that AT values at positions EW1 and EW2 deviated by a constant 1.5-2°C from the west and east sides of the floor plate.

(a)



(b)

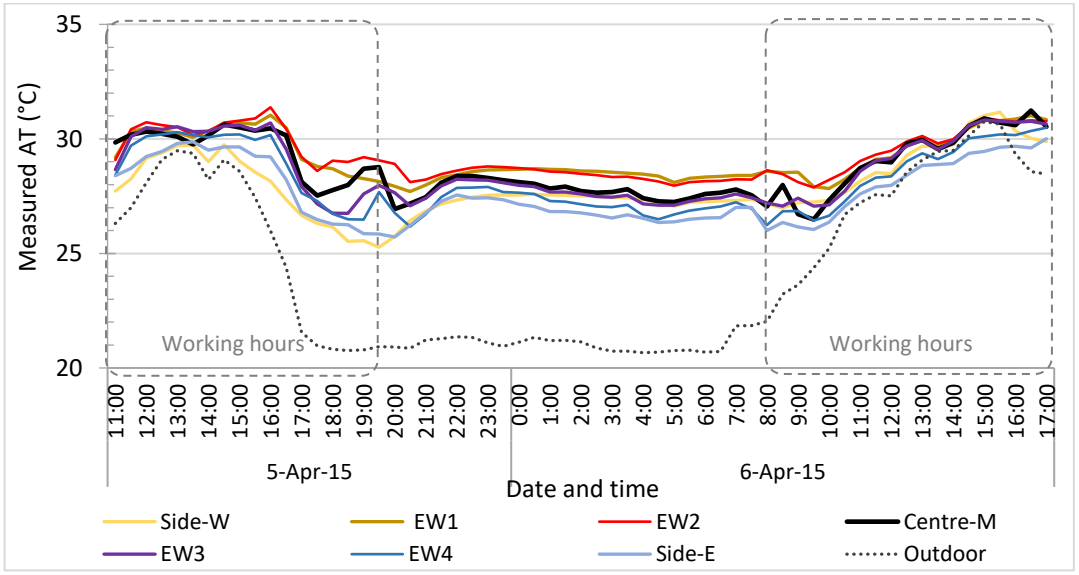


Figure 7-28: Measured AT profile recorded along the west to east axis of the 1st floor during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

Similarly, Figure 7-29(a) illustrates that the AT values at position NS2 at least 1-2°C higher than those near the south and north sides of the production floor. Figure 7-29(b) also shows that AT values at position NS2 deviated by around 3-5°C from the south and

north sides of the floor during working hours (08:00-20:00) and the deviations were lower during unoccupied hours.

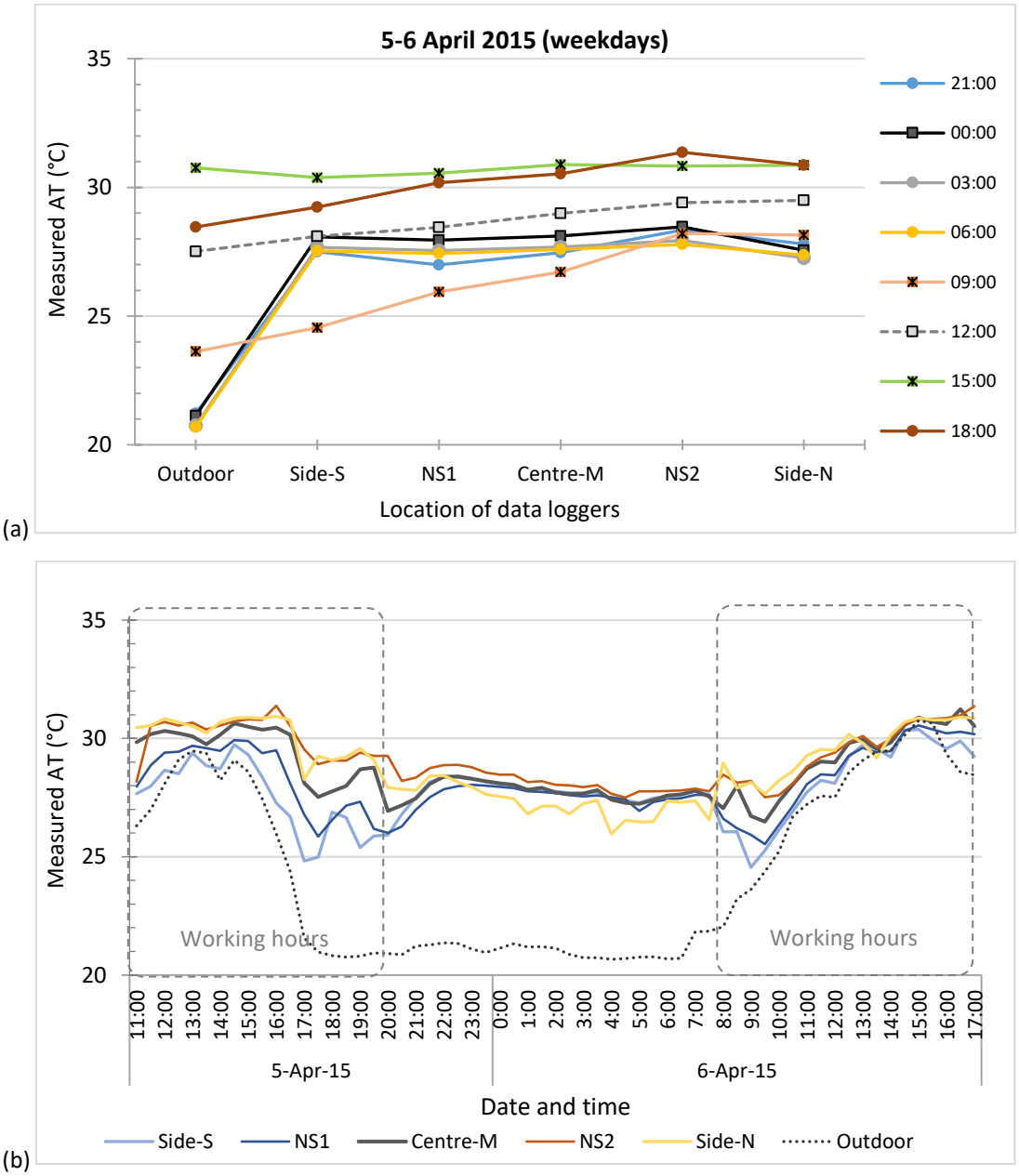


Figure 7-29: Measured AT profile recorded along the south to north axis of 1st floor during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

Both Figure 7-28 and Figure 7-29 indicate that the indoor AT values at the EW1, EW2 and NS2 positions of the floor plate remained with high temperature compared with all the zones near facades, both during day and night time.

7.6.3. Warm-humid season

Figure 7-30 reveals that the CS, SS and FS showed similar AT profiles with a maximum value of 34.8°C during peak working hours (12:00-16:00). However, during the weekend and non-working hours, deviations of AT values among the production spaces were found, these ranging up to 1.5°C. It can be observed that during the night time the difference in AT values between the CS and outdoor of up to 3.5°C were recorded. There were no significant deviations in measured RH values between production sections, with the exception of the CS, which exhibited the RH levels of up to 86%.

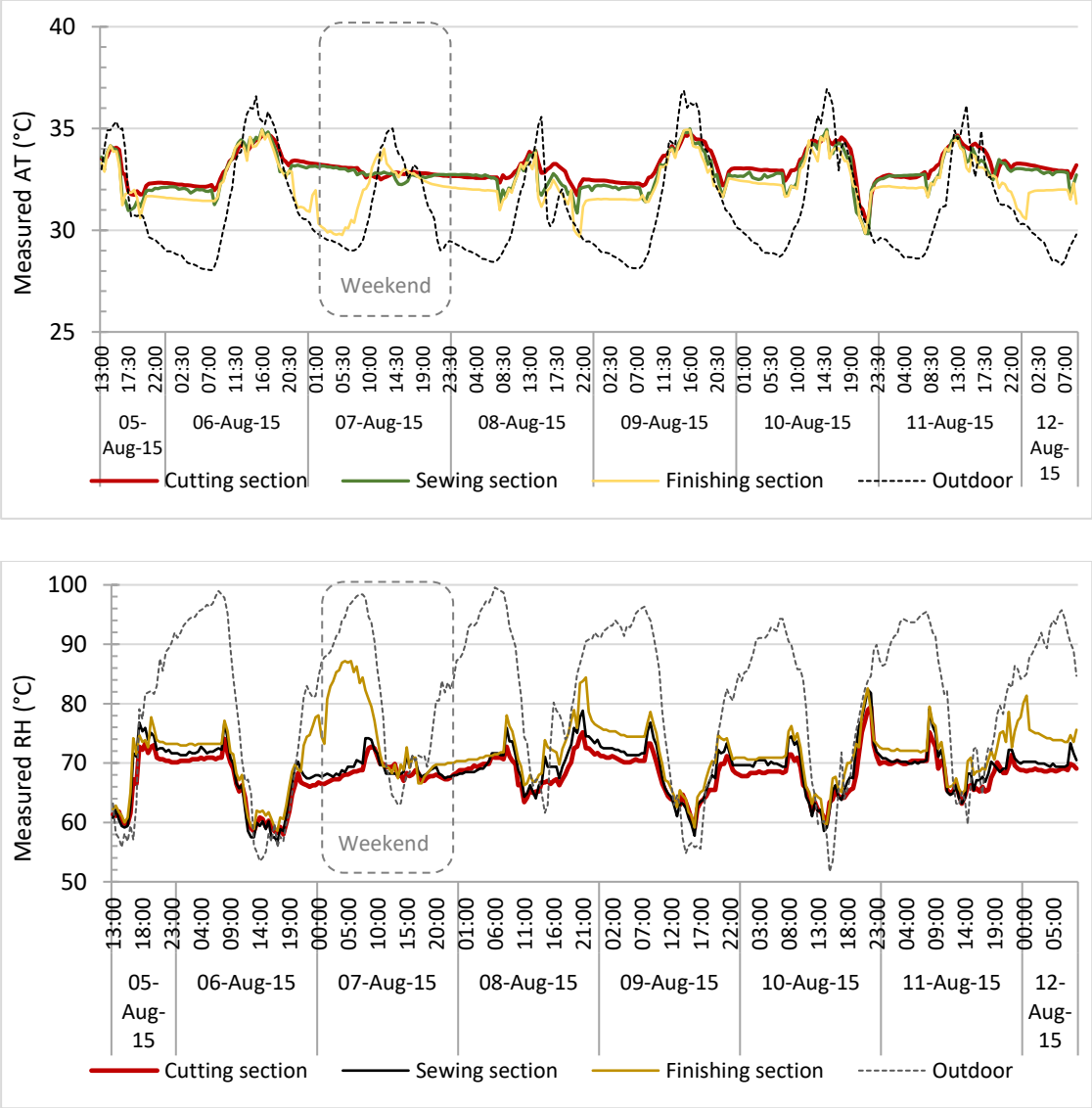
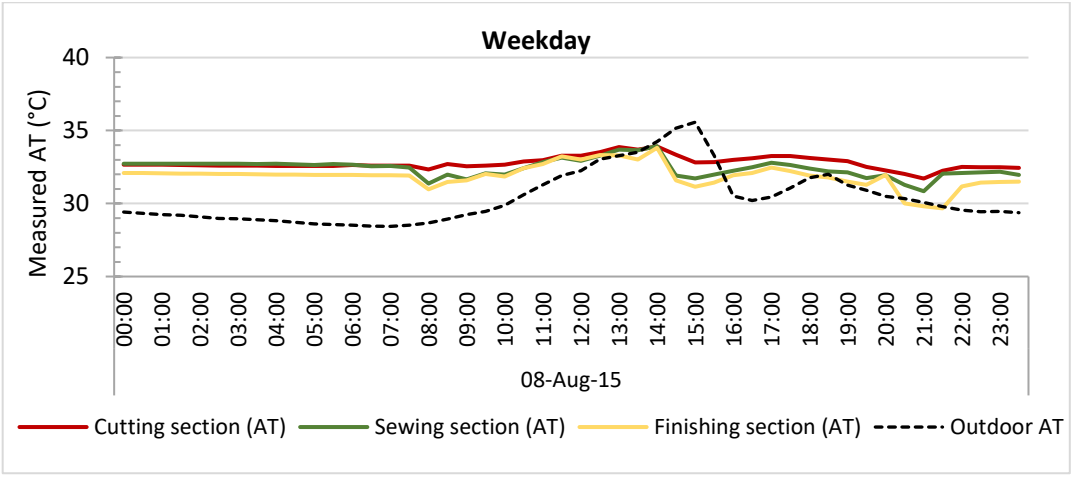


Figure 7-30: Measured AT and RH for production spaces during the warm-humid season (source: field study, year 2015)

Similar to previous two sections, continuously measured AT values for different production spaces recorded during a typical weekday and a weekend are compared in Figure 7-31. Figure 7-31(a) and Figure 7-31(b) indicate that the indoor ATs for all production floors increased from 32°C to 34°C during the working hours of a weekday. When subject to a similar outdoor temperature profile, the indoor AT values in the CS and SS were relatively constant (within the range of 32.5-33°C) during the weekend. What these data explicitly illustrates is that even with a diurnal variation of outdoor AT of 6.5°C (minimum 28.5°C at 06:00, maximum of 35°C at 14:00), the indoor AT did not drop below 32°C during night time. Similar to the analyses of the two other seasons, this indicates that indoor production spaces lack adequate ventilation and infiltration to reduce the indoor AT to the low values of outdoor AT prevailing during night time.

(a)



(b)

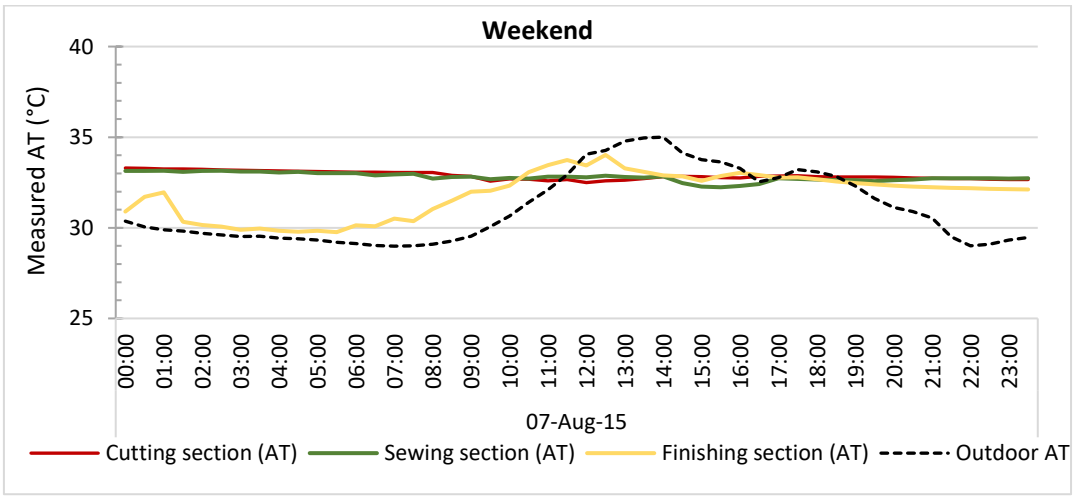


Figure 7-31: Measured AT for a typical weekday and weekend during the warm-humid season (source: field study, year 2015)

Data logging sensors were also placed in all the positions shown in Figure 5-10 to explore the horizontal dissemination of indoor AT. Figure 7-32(a) reveals that the AT values recorded at EW4 and Side-E positions on the 1st floor were at least 1°C higher than other positions of the production floor and reached their peak at noon deviating by 1°C from the outdoor AT. Figure 7-32(b) reveals that outdoor AT values at Side-W position reached their highest value (36.2°C) at 17:00 as a result of incident solar radiation on the west façade and its glazing.

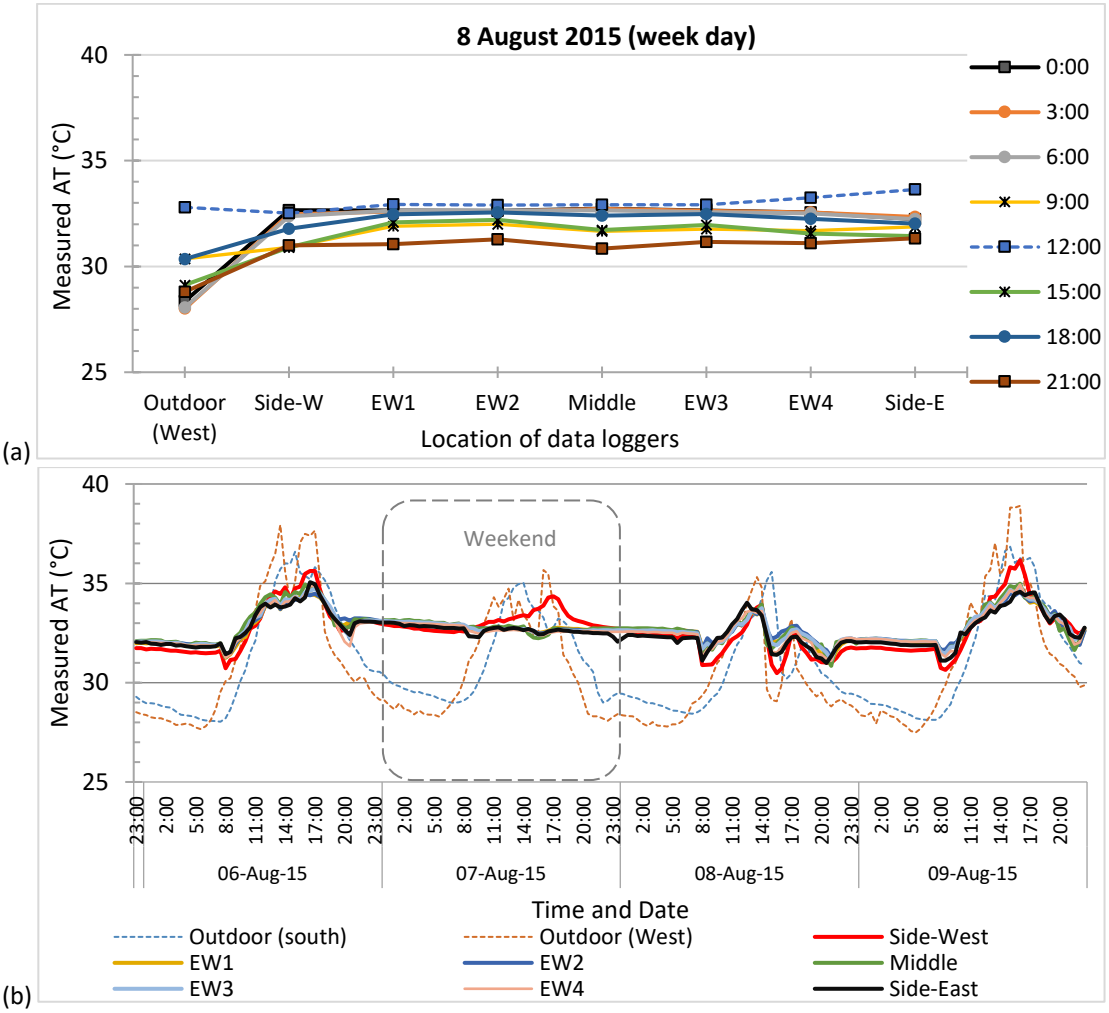


Figure 7-32: Measured AT profile recorded along the west to east axis of the 1st floor during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

Similarly, Figure 7-33(a) illustrates that the AT values at NS2 and Side- N positions were found to be at least 1-1.5°C higher than those observed near south side of the production floor. Figure 7-33(b) also shows that the measured AT values at NS2 and Side-N positions of the floor deviated by up to 5°C from the side-S of the floor during working hours (08:00-20:00). The deviations were lower during the weekend.

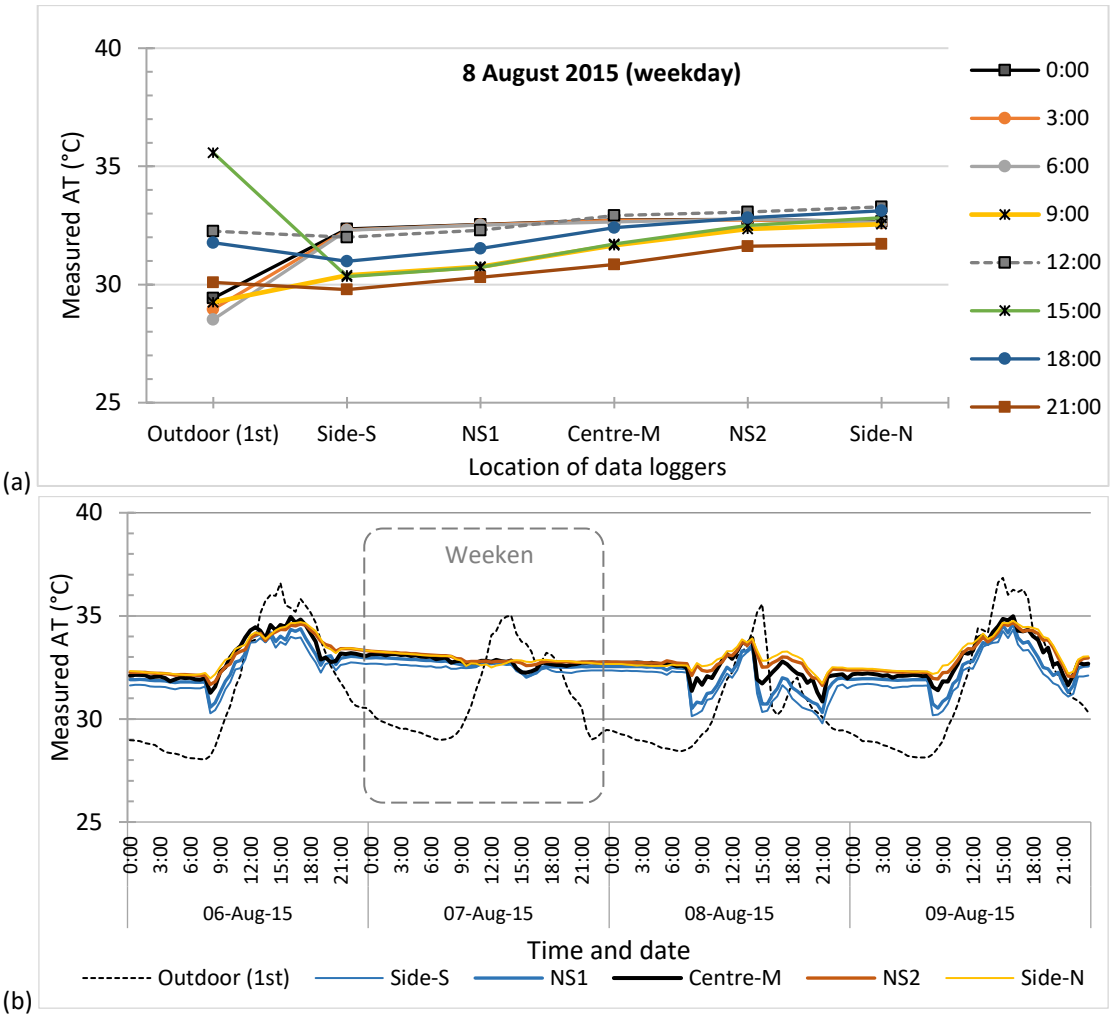


Figure 7-33: Measured AT profile recorded along the south to north axis of the 1st floor during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

Both Figure 7-32 and Figure 7-33 suggest that the indoor AT values at the EW4, Side-E, Side-W, NS2 and Side- N positions of the floor plate remained with high temperature compared with other zones of the floor both during day and night time.

7.6.4. Key learning from monitored data

The continuous field data confirmed a few of the preliminary assumptions stated in Section 7.5. The building responded as heavy-weight building and the indoor AT of the workspaces kept constant during night time while the outdoor AT fluctuated during all seasons. The impact of conductive heat gain through the west facades were visible within the horizontal distribution of AT. The SS and FS also exhibited high indoor AT during all seasons. The warm-humid season can be considered to be the 'worst-case' condition for maintaining occupant comfort due to having presence of high AT as well as high RH compared to other seasons (Figures 7-22, 7-26 and 7-30). It would be a key

challenge to provide comfort to the workers by bringing cooler air from outdoor micro-climate and simultaneously keeping the RH level below 65% (Section 2.5.2). Further discussions on these issues are presented in Section 7.9.

7.7. Spot Measurements and Predicted PMV

7.7.1. Assessment based on assumed thermal comfort

A summary of the thermal conditions (i.e. average spot measurements recorded at all workspaces during working hours) of *RMG factory 1* building are presented in Table 7-4. These may be used with Fanger's heat balance equations to estimate expected comfort (Halawa et al., 2014). The impact of seasonal variations can be observed in the AT and RH values for this case study building. For example, the mean values of indoor AT were 26.7°C, 30°C and 32.5°C while the mean values of outdoor AT were recorded 23.2°C, 29°C and 33.6°C during the cool-dry, hot-dry and warm-humid seasons respectively. Similar situations can be observed for the values of RH. Mean values of WBGT, MRT and OT were also calculated and are presented in Table 7-4. There may be assumed to be better reflect the actual thermal conditions of workspaces impacting workers' thermal comfort.

Table 7-4: Seasonal variations of the spot measured data* for the *RMG factory 1*

Season	Value type	AT (°C)	GT (°C)	RH (%)	Air speed (m/s)	WBGT (°C)	MRT (°C)	OT (°C)**	AT_{out} (°C)	RH_{out} (%)
Cool-dry	Mean	26.7	26.8	52.2	0.5	21.8	27.1	26.8	23.2	55.4
	SD	1.9	1.2	7.0	0.7	1.4	1.8	1.3	2.5	10.7
Hot-dry	Mean	30.0	29.9	66.0	0.5	26.3	29.8	29.9	29.0	66.3
	SD	1.7	1.7	6.5	0.2	1.3	1.9	1.7	3.9	14.3
Warm-humid	Mean	32.5	33.9	72.8	0.4	30.0	35.6	33.6	33.6	69.0
	SD	0.7	1.5	3.4	0.2	0.7	2.6	1.3	1.6	8.8

**During working hours only (i.e. from 08:00 to 20:00)*

***Operative temperature (OT) was only considered for those 'workstation cases' where the workers have the flexibility to operate window and/or fans, their Met value was between 1.0 to 1.3 in either working or resting condition and they have freedom to change their clothes within the Clo values of 0.5 - 1.0.*

****Unless mentioned as '_out' (e.g. AT_{out}), all the data are in the indoor environment.*

Figure 7-34 represents the frequency of average AT, RH and average air speed recorded at workers' personal workstations in the production sections during the questionnaire surveys. These data were considered to more accurately reflect workers' thermal comfort since OT and MRT directly depend on AT, RH and air speed.

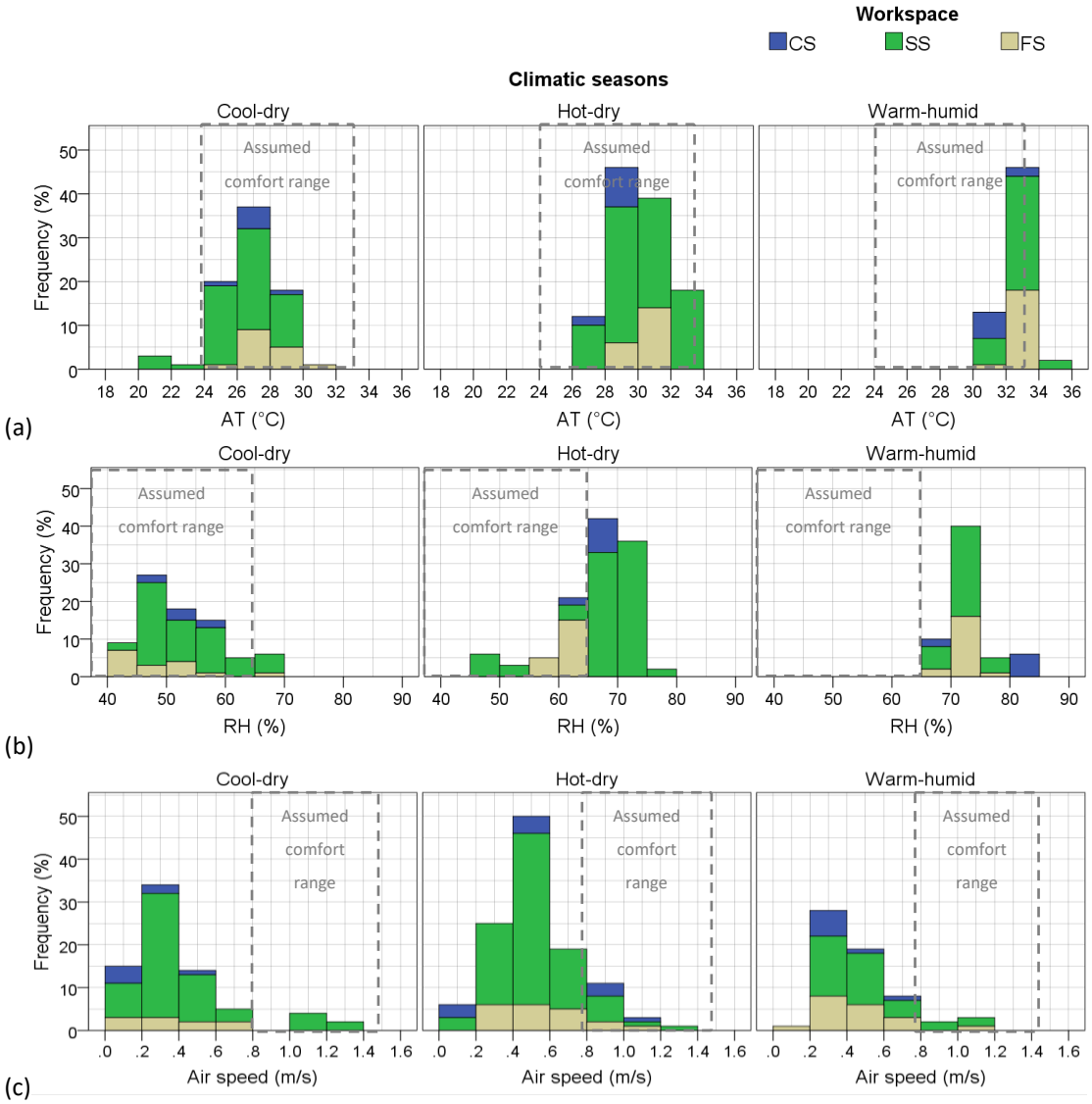


Figure 7-34: Frequency of spot measured AT, RH and average air speed and assumed thermal comfort ranges at workers' personal workstation in *RMG factory 1* (source: field studies, year 2015)

Figure 7-34(a) illustrates that the AT ranges of 24-28°C, 28-32°C and 32-34°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Among these data range the SS and FS tended to exhibit higher AT range during all seasons. During the hot-dry and warm-humid seasons, the measured AT ranges also exceeded the comfortable AT range (general and moderated), as assumed in Section 2.5.2. The data also indicates that workers in these working areas would feel

uncomfortable during these two seasons. Moreover, if the air speed is below 0.2m/s, the working areas, assumed to be within the comfortable range (i.e. 24-33°C), would not actually meet the general comfort target (i.e. 24-28.5°C).

Figure 7-34(b) shows that the RH ranges of 45-60%, 60-75% and 65-75% were found to occur with high in frequency during the cool-dry, hot-dry and warm-humid seasons respectively. Apart from the FS during the hot-dry season, all production sections tended to have high RH range during all seasons. During the hot-dry and warm-humid seasons, the measured RH ranges exceeded the comfortable RH limit (<65%) described in Section 2.5.2. This implies that workers in these production areas would feel uncomfortable during these two seasons.

Figure 7-34(c) reveals that the approximate air speeds ranging 0-0.4m/s, 0.2-0.8m/s and 0.2-0.8 m/s were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Apart from the CS which tended to have a low air speed range, workers in the SS and FS tended to experience high air speed range during all seasons. Of all the air speed ranges measured during the surveys, only around 25% of the workers experienced the target air speed range of 0.8-1.5m/s (Section 2.5.2) at their workstations. By implication, this suggests that the workers in the rest of the production spaces were more likely to experience an uncomfortable thermal environment throughout the year due to the low air velocity.

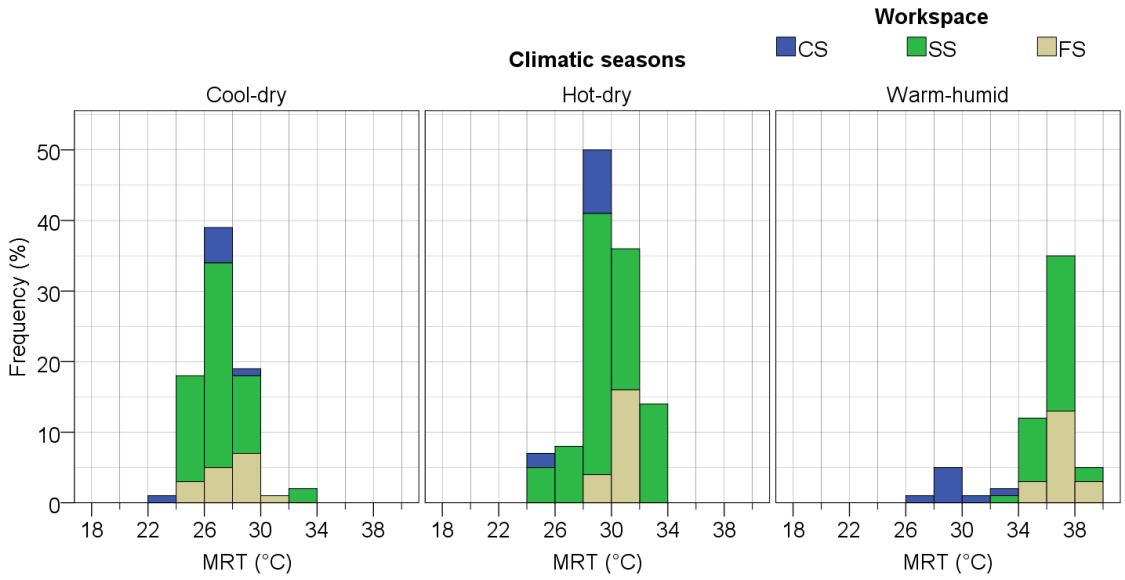


Figure 7-35: Frequency of spot measured MRT at workstations in *RMG factory 1* (source: field studies, year 2015)

From Figure 7-35, it can also be found that the estimated MRT ranges of 26-28°C, 28-30°C and 36-38°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Apart from the CS during the cool-dry season, workers in the SS and FS tended to experience higher MRT range during all seasons. Since MRT is the combined effect AT, RH and air speed (Equation 5-6), Table 7-4 and Figure 7-35 suggest that it would the major challenge to ensure thermal comfort at their workstations during the warm-humid season due to simultaneously high AT and high RH.

7.7.2. Prediction of PMV

All the indoor spot measured data (total of 256 readings in SI unit) were plotted in the psychrometric chart using 'CBE thermal comfort tool'. Figure 7-36 provides a visualisation of these data and shows the distinct regions where the data for the different climatic seasons sit. The results indicate that 218 of workstations studied (i.e. 85% of the total 256 working locations) were outside of ASHRAE comfort zone with an average PMV of 1.20 over the three field studies (i.e. three climatic seasons). In particular, 63.8% of 80 measurements fell outside the ASHRAE comfort zone (PMV: 0.42) during the cool-dry season with the weighted average exceedance intervals: 0.25. Of the 115 measurements made during the hot-dry season 92% fell outside the ASHRAE comfort zone (PMV: 1.11, weighted average exceedance intervals: 0.64) and

100% of 61 measurements taken during the warm-humid season (PMV: 2.39, weighted average exceedance intervals: 1.89) were found to lie outside of the ASHRAE comfort zone.

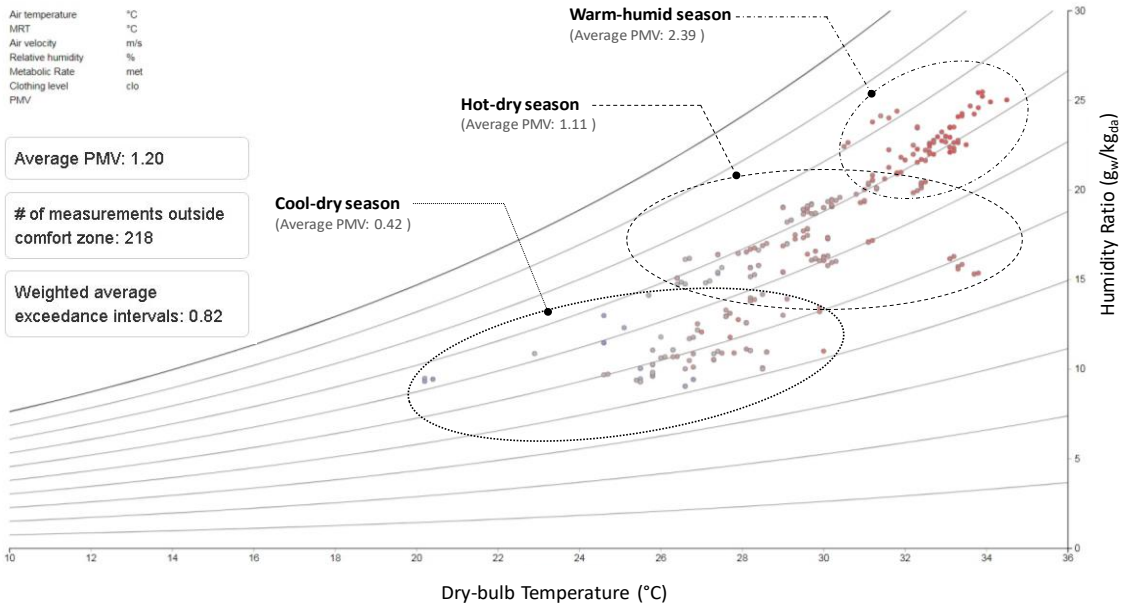


Figure 7-36: Prediction of thermal comfort vote and visualisation of measured data using a psychrometric chart (source: CBE thermal comfort tool 2013)

This practice of predicting thermal comfort vote based on the ASHRAE comfort model may not be directly applicable to evaluate the existing thermal conditions for the population. However, the results of this section are useful in serving as a reference for comparison with the actual comfort vote (Sections 7.8.1 and 10.4.1).

7.8. Workers' Subjective Feedback

7.8.1. Results from questionnaire surveys

Figure 7-37 provides histograms (frequency of ASHRAE 7-scale votes in percentage) of workers' vote on their existing thermal environment in terms of thermal sensation, humidity, airflow and freshness of air. Figure 7-37(a) reveals that approximately 54%, 43% and 23% of the workers responded with a 'neutral' vote for thermal sensation at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. These percentages also indicate that the rest of the workers during these three seasons (46.2%, 57.4% and 77% of the workers respectively) voted that they either experience conditions that are hot or cold in terms of thermal sensation. The majority of the

discomfort responses indicate workers were too warm and occurred in the hot-dry or warm-humid seasons. Workers in the CS were more likely to be neutral about their thermal environment during all seasons, while workers in the SS were more inclined toward warm sensation.

Figure 7-37(b) reveals that 90%, 87% and 6.6% of the workers provided a 'perfect' response in addition to their sensation toward humidity for existing temperatures at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. These percentages also indicate that rest of the workers experienced dissatisfaction with the prevailing levels of humidity. During the warm-humid season, 86.8% of the votes indicates that workers felt the conditions at their workstations were slightly humid or humid.

Figure 7-37(c) shows that 56.2%, 44.3% and 18% of the workers experienced 'perfect' air flow or speed at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. These percentages also indicate that rest of the workers were dissatisfied. During the warm humid season, 64% of the participants felt the air sped was low or slightly low at their workstations which indicates that these workspaces needed improvement by elevating the air speed and/or decreasing the AT.

Figure 7-37(d) provides a histogram of votes (Bedford scale) focusing on IAQ and reveals that only 7.5% and 5.2% participants felt the air was slightly stale to absolutely stale air during the cool-dry and hot dry season. This picture changed significantly during the warm-humid season when 55.7% votes found the air to be slightly stale to absolute stale during the warm-humid season. This indicates these representative percentage workers felt the air quality was poor.

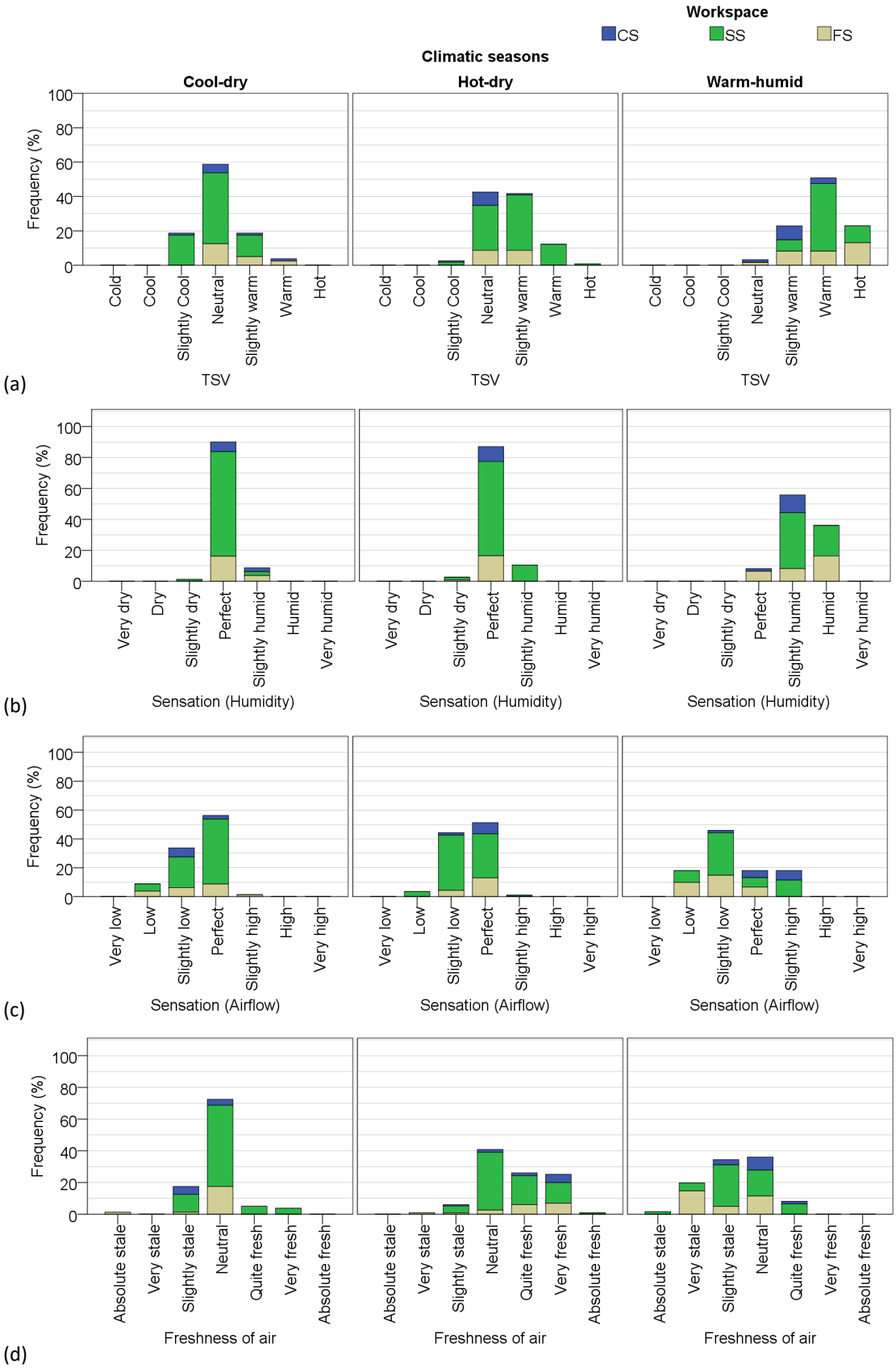


Figure 7-37: Histogram of workers' 7-scale votes on (a) Thermal sensation, (b) Humidity, (c) Airflow and (d) Freshness of air at their workstations during various seasons (source: field studies in *RMG factory 1*, year 2015)

Figure 7-38 shows workers' feedback on AT, humidity and air speed they preferred at their existing workstations. Figure 7-38(a) reveals that during the cool-dry and hot-dry seasons 71.2% and 49.6% of workers were more satisfied with the thermal environment since they voted for 'no change'. However, only 1.6% votes for 'no change' were received during the warm-humid season, while the rest of the votes (98.4%), including those collected in the CS, were seeking change to make the environment 'much cooler' or 'slightly cooler'. The results also indicate that during the warm-humid season, workstations needed major improvement to reduce the high temperature. The comfort of the workers depends on the combined effects of AT, RH and AV. However, looking at the pattern of responses for each in isolation suggests that the combined effect remains are of discomfort.

From Figure 7-38(b), it can be observed that 93.8%, 93.9% and 21.7% of the participants prefer 'no changes' to the humidity of the indoor air during the cool-dry, hot-dry and warm-humid seasons respectively. This also implies that excessive RH is an issue of concern in all workspaces during the warm-humid season.

In terms of preference on air flow, Figure 7-38(c) shows that 55.7% and 48.7% of the participants were happy with the existing air flow or speed at their workstations during the cool-dry and warm-humid seasons respectively. However, only 7.7% of the workers were satisfied with airflow votes were found during the warm-humid season. The rest of the votes were cast for 'much more airflow' and 'a bit more airflow'. These preference votes on airflow also resemble with the votes for temperature and humidity and indicates that the majority of workspaces would benefit from improvements, particularly to improve the comfort during the warm-humid season.

Among the participants in the questionnaire survey, 88.9%, 60.4% and 8.3% indicated that comfort conditions were acceptable at their workstation, during the cool-dry, hot-dry and warm-humid seasons respectively (Figure 7-39). However, to provide comfort adequately for the users of a building, 80% -90% of occupants should accept the environment as comfortable (Section 2.5.1.1). This level of acceptance was not met in the workspaces of *RMG factory 1* during the hot-dry and warm-humid seasons. Looking at the responses in a different way, the acceptability rate should be around the central three scales (vote -1, 0 and +1) of ASHREA seven-point TSV scales (-3 to +3). From

Figure 7-37(a), it can be found that 96.3%, 86.1% and 24.6% of workers' votes fell within the central three scales (-1, 0 and +1) of TSV votes during the coo-dry, hot-dry and warm-humid seasons. Comparing this with Figure 7-39, it clearly indicates all the workspaces did not meet the standard acceptability requirement (80-90%).

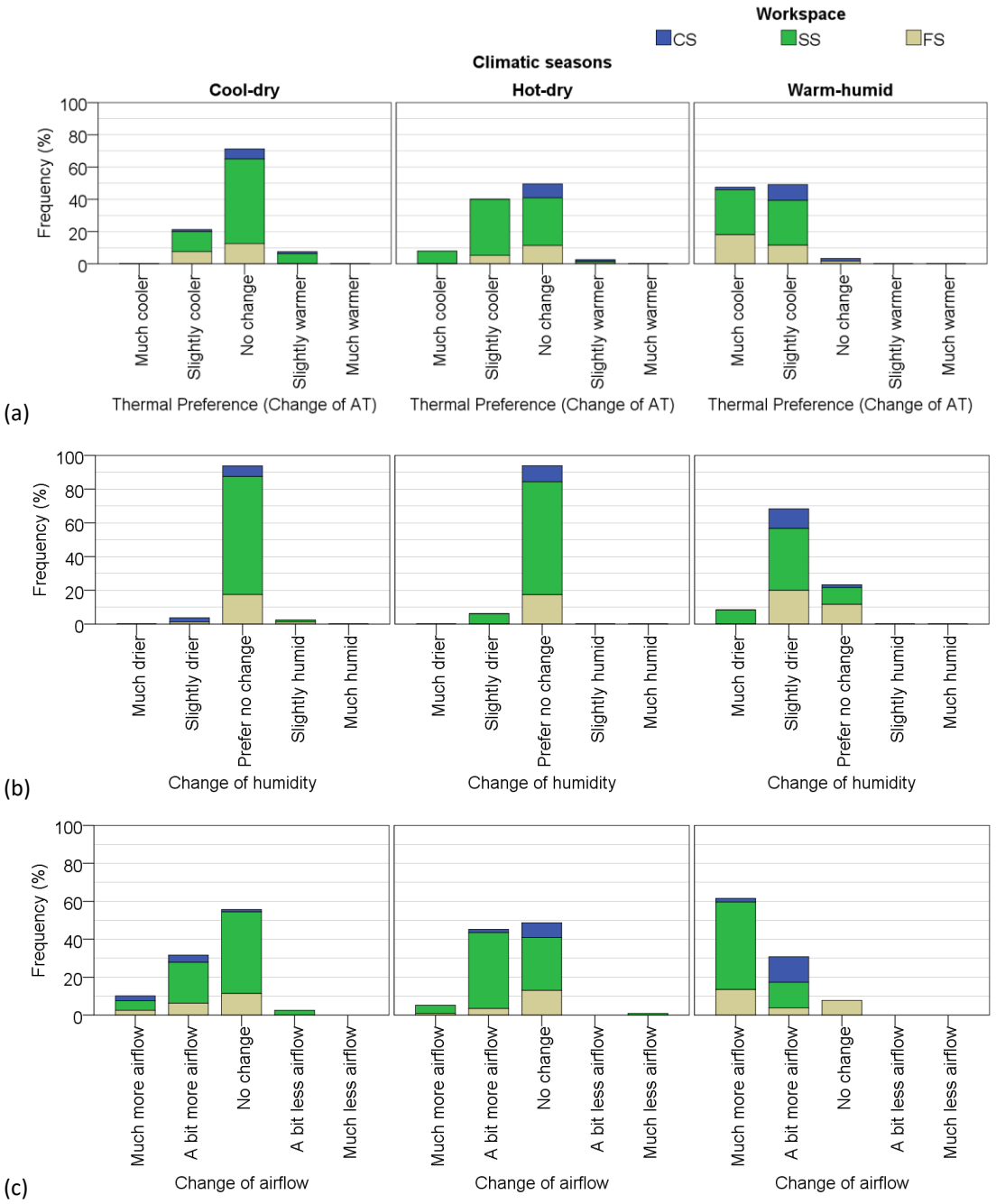


Figure 7-38: Histogram of workers' 5-scale votes on preferences to changes of (a) Temperature, (b) Humidity and (c) Air flow at their workstations during various seasons (source: field studies in *RMG factory 1*, year 2015)

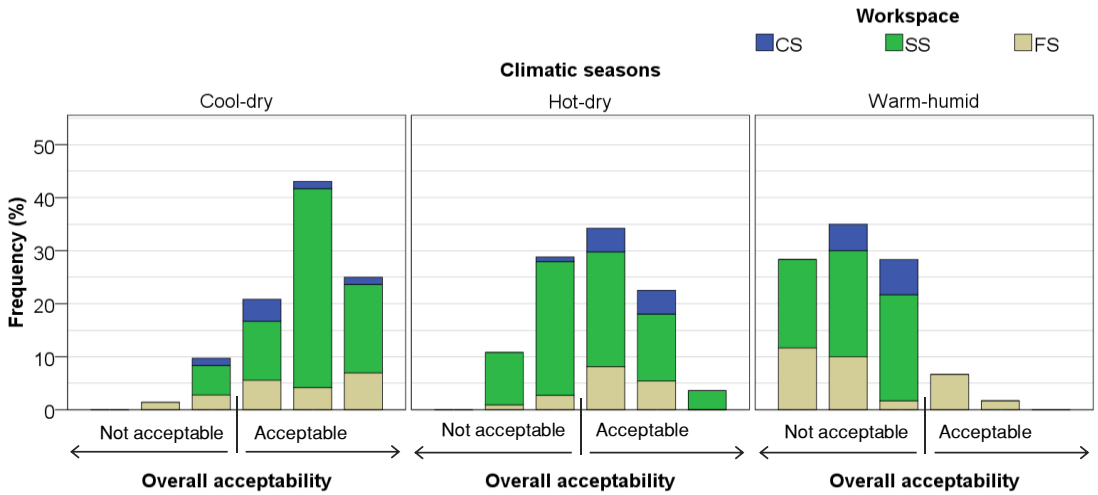


Figure 7-39: Histogram of workers' votes on overall acceptability of their existing thermal environment during various seasons (source: field studies in *RMG factory 1*, year 2015)

Comparing workers' quantitative votes on their thermal environment with spot measurements (Table 7-4 and Figure 7-35), it can be observed that high indoor MRT is the main issue during the hot-dry and warm-humid seasons (mean MRTs were 29.8°C and 35.6°C respectively). However, the actual comfort votes from workers did not completely match the comfort ranges estimated using ASHRAE scale. For example, Figure 7-34(c) shows that the majority of measured air speeds were outside of the assumed air speed during the cool-dry season. However, 55.7% of the workers were found to be happy with the existing airflow and 88.9% deemed that the working environment was acceptable. On the other hand, predicted comfort ranges were overestimated suggesting that 63.8%, 72.2% and 100% of the votes should likely to lie outside of the comfort range during the three seasons respectively. The TVS votes from the survey show that only 46.2%, 57.4% and 77% of the votes lay outside the 'neutral' band. These mismatches suggest workers may be habituated to their thermal environment and their comfort response including adaptive behaviour may not be effectively represented by existing comfort models. Chapter 10 will consider this holistically and quantitatively revaluate the 'assumed thermal comfort ranges' comparing with the actual votes from the workers of *RMG factory 1*.

7.8.2. Results from focus group discussions

Tables 7-5 and 7-6 provides summary of workers' feedback from two focus group discussions in *RMG factory 1*. The workers from both groups suffer from thermal

discomfort, particularly inside the SS and FS, during the hot-dry and warm-humid seasons. During the cool-dry season, direct flow of cold air on the workers next to the window was highlighted as an issue. However, during the same period workers in the middle part of the floor plate suffered from thermal discomfort due to high temperature. Discussions confirmed a preference amongst workers for workstations located next to the windows where speed is high, as opposed to workstations in the middle of the floor plate where perceived air speed was negligible. They recommended providing more flexibility in operating the windows, even during the rainy seasons, and more personal control over the operation of the extract fans.

Both questionnaire surveys (Section 7.8.1) and focus group discussions provided common feedback on improving working environment during the hot-dry and warm-humid seasons. Moreover, the discussions also revealed a range of realistic suggestions from the workers as to how their existing working environment might be modified to meet their comfort expectations.

Table 7-5: Summary of the workers' perception and adaptive measures from two focus groups

Season	Group	Perception and issues within their existing ventilation strategy and thermal experience	Adaptive measures to resolve the issues and ensure their thermal comfort
Cool-dry	one	- They feel slightly cold during 8am-11am and after 4pm due to running extract fans. The person in the ironing section never feel cold. - Ceiling fans remain switched off until 11am. They start feeling cold from 11am to 4pm due to running the ceiling fans.	- When they feel cold, they shut windows and ask the floor manager to turn off extract fans. - They use group opinions to regulate ceiling fans. Personal pedestal fan are provided in the ironing workstations.
	two	- They face issues to switch on the ceiling fans due to diverse opinions within groups resulting discomfort. - No provision of control on windows make them considering the comfort of the workers near windows and compromising with existing thermal experience. - From 10am till 5pm they feel hot (high near lunch time).	- Going to fresh room to splash water on their body and drinking water are the common adaptive measures. - They take a break to stand beside the windows and change their cloths.
Hot dry	one	- They feel hot most of the time after 9am even the windows are open, and fans are running. - The workers in the ironing section always feel very hot and humid. However, workers in the CS have no issue. - They experience very hot environment around lunch time.	- Going to fresh room to splash water on their body, drinking water, taking a quick break and just sitting on their seat are common adaptive behaviours.
	two	- Walking to the factory limit their thermal comfort to only 30 minutes in the morning. They feel uncomfortable rest of the time. - They experience tiredness, headache and dehydration due to high AT, especially after lunch time. - Airflow from ceiling fans increases their thermal discomfort. - During storm, they feel very hot and stuffy.	- Drinking a lot of cold water, splashing water on their body, taking a break from their work and standing near windows are the common adaptive measures.
Warm humid	one	- Workers always feel very hot and humid apart from during the rain. - They feel tired, dehydrated and very sleepy hampering their work efficiency. - Limited run of ceiling fans during certain activities in the CS cause thermal discomfort.	- They always keep the fans on and windows open. - They drink cold lemon and saline water to avoid their tiredness.
	two	- The fans are unable to escalate their thermal comfort. - They feel very hot and humid all the time. - Sweating disrupts their workflow.	- Drinking cold and saline water, standing near windows, splashing water on their body and taking shower during lunch break are their common measures.

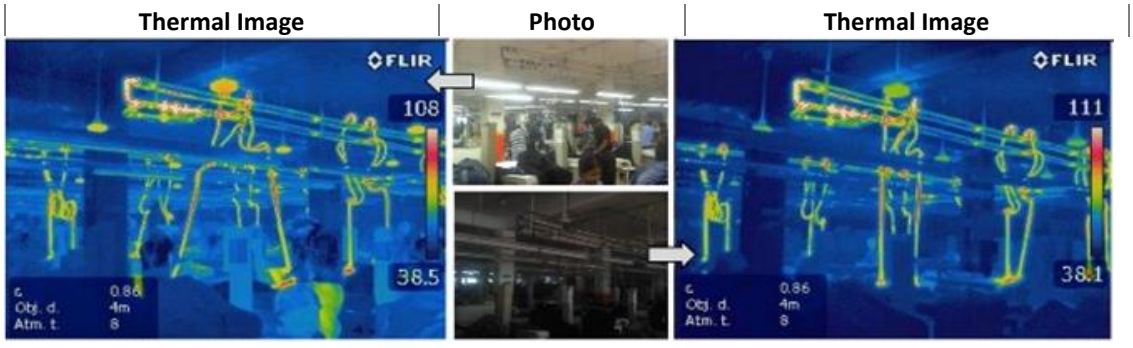
Table 7-6: Workers' overall feedback on expected improvement

Group one	Group two
- Draughts cause thermal discomfort during the cool-dry season. It also hampers workers' workflow in the SS. They tend to close the window as a solution. - Workers in the ironing section prefer their workstations located near windows. - More flexibility in window opening and closing could help them to personalise their thermal environment.	- They prefer their workstations near windows (apart from during the cool-dry season). - They expect personal controls on all fans. They prefer different air speeds and control strategies for different work types for comfort. - They also prefer daylight for their work since bright artificial lights produce heat and cause discomfort.

7.9. Existing Issues and Proposed Improvements

7.9.1. Ventilation strategy during unoccupied hours

Results from the data logging (Section 7.6) reveal that during the cool-dry and hot-dry seasons, peak outdoor AT occurs between 11:00 – 16:00 tracking the presence strong solar radiation. During the reminder of the day, the outdoor AT was cooler dropping by up to 10°C at night (Figure 7-22). During the warm-humid season, this deviation in AT between indoors and outdoors within the day was up to 3.5°C. It was also found that at night, when the external AT was sufficiently low to provide passive cooling of the building fabric, the windows were closed, and the fans remained switched off. Indoor Temperatures remained high and relatively station due probably to the release of heat stored during the daytime in the building fabric. This evidence triggered a need for further investigation presented here, of the thermal performance of these spaces during occupied and unoccupied hours.



Before lunch break (at 12:40 on 8 Aug 2015) During lunch break (at 13:40 on 8 Aug 2015)

Figure 7-40: Surface temperature profile of the FS (*RMG factory 1)* before and during a lunch break

Thermal images, such as those shown in Figure 7-40, indicated that the surface temperatures inside the production floors either increased or remained within the same range in the absence of the active ventilation during unoccupied hours (i.e. lunch breaks). Equipment and the indoor building fabric had limited provision to release heat with the help of ventilation during this period. For instance, the recorded surface temperatures of the workstations and machinery in the FS of *RMG factory 1* building recorded a maximum of 111°C during the unoccupied hours and 108°C during occupied hours at the daytime. Heat transfer between the room internal surfaces and the room air through convection and radiation has the potentials to limit some of these temperature rise created by the response of heat generating equipment. This effect will depend on the extending area of the exposed building fabric and the heat transfer coefficient of the surfaces, which for these exposed concrete buildings is likely to be 5.9 – 10 W/m^2K (Artmann et al., 2008). Moreover, currently the extract fans do not operate, and ventilation do not take place in these workspaces during the unoccupied hours (i.e. night time and in the weekend). Section 7.6 indicates the potential of ventilation for an extended period to reduce the high AT. In particular, night cooling strategy (Section 3.7.1) may be a more effective way to flush out the unwanted heat and remove stored heat from the thermal mass at night. Therefore, it can be suggested that the application of a night-time ventilation strategy utilising thermal mass of the building can potentially improve the thermal conditions in the building during daytime.

7.9.2. Effect of size and operation of the inlet-windows

Figure 7-15 illustrated a combination of sliding windows acting as ventilation inlets on one side of the floor plate and providing opening for extract fans on the opposite side. This combination of ventilation inlets and outlets was common to all CS, SS and FS workspaces. In addition to limiting the effective opening area and hence ventilation rates, this choice of window type generates an undesirable air flow pattern and exposed to direct solar radiation for those sitting close by, as witnessed by user interventions such as the use of hardboard baffles to reduce draughts and use of thick curtains to reduce direct penetration of the sun (Figure 7-41). According to the workers' feedback (Table 7-5 in Section 7.8.2), workstations located close to windows were perceived as thermally comfortable. However, they also experienced draughts,

which cause disruptions to their work, for example, marking out fabrics, sorting and sewing small pieces of fabrics. This reduces ventilation rates and presents a potential issue of high temperature. Previous field studies have indicated that the window opening behaviour can reduce the peak indoor temperatures by up to 4.6°C (Rijal et al., 2007).

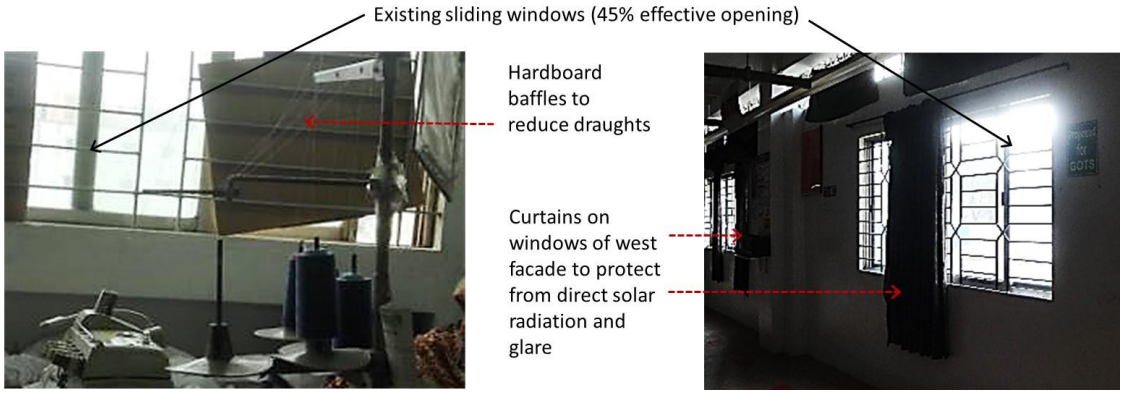


Figure 7-41: Sliding windows at ventilation inlets with hardboard baffles and curtains to protect workers from direct air flow and solar radiations

To explore the impact of changing the effective area of the inlet windows on the indoor AT profiles, an onsite field experiment was conducted in *RMG factory 1*. The extract fan speed was held as constant and the opening area of the windows was adjusted to vary ventilation rate. The study was conducted during the warm-humid season as this was considered the most challenging period of the year to provide comfort (Section 7.8.1). Measurements were conducted simultaneously on two floors (SS) using data loggers and anemometers placed 1m and 10m away from the ventilation inlets. Factory owners agreed to a 30 minutes period over which the experiment could be conducted in order to minimise disturbance to workers and impact on their production.

Figure 7-42 and Table 7-7 show the results from the experiment and illustrates that changing the effective opening area from 45% to 0% increased internal AT by approximately 1°C and exhibits time lags of around 2-3 minutes. Increasing the window opening area caused reduction of indoor AT, the temperature taking longer to respond to the change. It is probable that these lag effects are in part related to the temperature sensor response. The conditions monitored deeper inside the space showed similar, but, more heavily damped response to change in window opening

area.

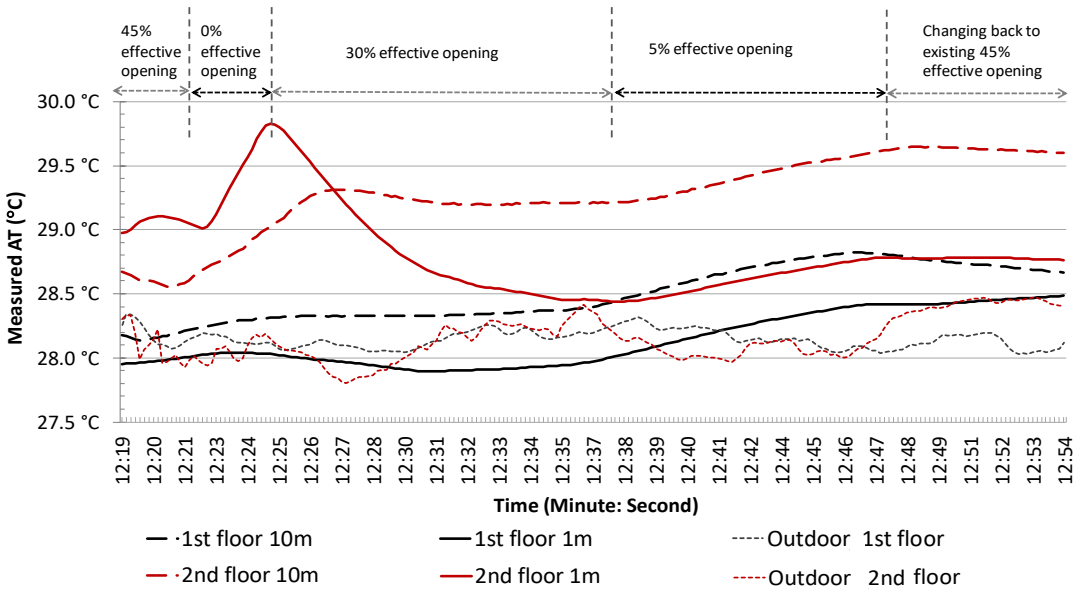
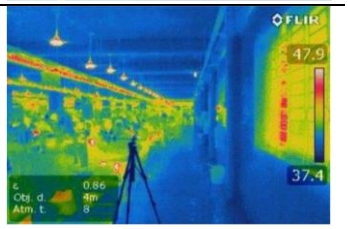
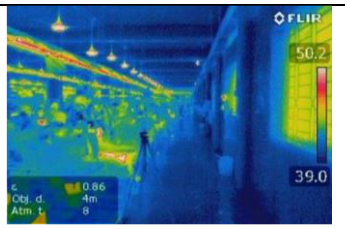


Figure 7-42: Effect of the inlet window-opening area on indoor air temperature (source: field experiment on the 1st September 2015)

Indoor surface temperatures determined from thermal images indicated an increase of between 0.7 and 3°C when the windows were closed (Table 7-7) and that surface temperature dropped in response to reopening the windows.

In addition to measuring the thermal performance, the workers were consulted on their views on the internal environment. When opening areas were reduced workers both near and far from the inlets complained of being uncomfortable and requested the researcher to open the windows as quickly as possible. This indicated a spontaneous response to changes in indoor AT and air velocity within the workstation caused by changes to the ventilation inlet windows. Although only AT and surface temperature profiles were recorded in the case study building, it can be safely assumed that changes in the air speed and direction were also occurred when opening areas were reduced. When combined with the increase in AT and ST this would force up the SET, this being reflected in the additional thermal discomfort expressed by the workers.

Table 7-7: Effect of changing inlet area on surface temperature (source: field experiment on 1 September 2015)

Time	Effective inlet size	Range of surface temperature (°C)		Deviation from the first state with 45% open (°C)		Photo	Thermal image
		Min	Max	Min	Max		
12:20	45%	37.8	47.7	-	-		
12:24	0%	38.5	51.7	0.7	3		
12:30	30%	37.4	47.9	-0.4	0.2		
12:45	5%	39.0	50.2	1.2	2.5		

As referred in the Section 3.7.2, the ventilation efficiency in workspaces also depends on window design and operation. Therefore, there was scope to explore the design configuration of inlet-windows (including measures to increase the effective opening size) of this case study building to make the exiting ventilation system more efficient and the air flow pattern more useful towards improving thermal comfort.

7.9.3. Efficiency of equipment and passive ventilation

The daily electrical energy demand in production spaces of *RMG factory 1* (shown in Appendix G) reveals that up to 2202 KWh, 794 KWh, 872 KWh and 12285 KWh of the electrical energy were consumed per day by existing lights, extract fans, ceiling fans and other production equipment respectively. The ceiling and extract fans are mainly

used to provide ventilation and air circulation helping to address the thermal comfort needs of the workers. However, ceiling fans will also act as sources of internal heat gain. When combined with the high internal heat gain from the equipment in this case study building (Section 7.4.3), there is a case for exploring whether increasing equipment efficiency can reduce the high temperature issue as part of a strategy combined with extended ventilation time (Section 7.9.1). In effect this is a strategy that combines reduced gains with increased ventilation loss as a means of tackling high temperature.

As shown in Sections 3.7.3 and 6.7, passive ventilation could be another strategy to flush out the indoor hot air as well as save electrical energy by avoiding use of fans. From Section 7.6, it was found that for all seasons, particularly during unoccupied hours, outdoor ATs were 3.5-11°C lower than indoor AT of production spaces. Hence, stack induced ventilation is considered to be applicable as a workable natural convective cooling strategy, particularly during night time, by introducing the ventilation shafts into the production spaces without the need of using mechanical extract fans. Since the location of the SS and FS are in the lower floors of the case study building, the stack height of the proposed ventilation shafts may be sufficiently large to ensure high air flow rates as shown in Section 6.7.2.

7.9.4. Functional layout and segmentation

From spot measurements, it was found that the highest AT and lowest air speed were mainly experienced in the SS and FS during all seasons. The location of the spots with low air speed and high AT were investigated by the researcher and were found near the 'ironing work-zone' of the SS and FS, which locally increased the AT due to high heat output of the equipment (Section 7.4.3). The localised hot air generated from the ironing work-zone is easily distributed across the other workspaces due to the downward air speed of the ceiling fans. Appendix H-1 shows the zones categorised by the researcher to show that these hot zones with its functional layout were not considered while designing the ventilation system from inlets of the building to outlet. It can easily be assumed that the low heated area will be affected by the immediate high heat generating equipment and would benefit from segmentation with a different ventilation system (Section 3.7.3) to improve workers' thermal comfort.

Figure 7-43 provides onsite evidence showing how workers spontaneously use hardboard baffles to protect themselves from high heat radiating equipment near them. Hence, the function layout should be rearranged and segmentation of spaces should be provided respecting both production flow as well as workers' thermal experience.

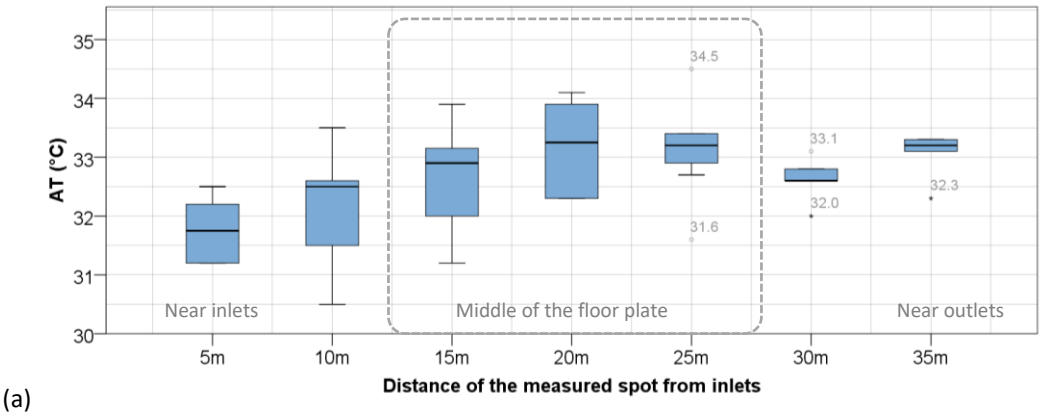


Figure 7-43: Workstations with hardboard baffles to protect workers from heat radiating equipment

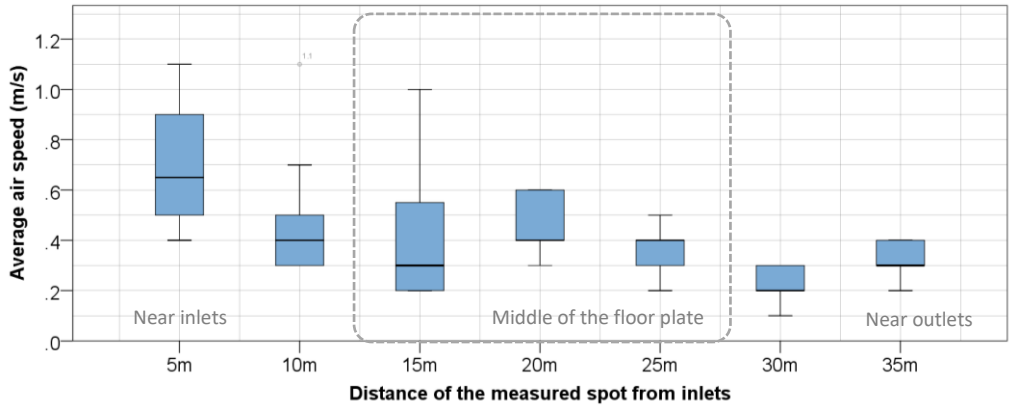
7.9.5. Personalised control for occupants

From focus group discussions (Section 7.8.2), it was found that workers prefer personalised control over the air velocity at their workstations. Workers near windows had a degree of flexibility to control air flow by operating the nearby windows. However, workers in the middle zone should have additional extended airflow from the side and personal control strategy.

Figure 7-44 reveals that the workstations in the middle part of the floor (i.e. workstations located around 15m to 25m away from the inlet windows) were subject to high (up to 34°C) AT and were unlikely to get airflow above 0.8m/s. These results suggest that enhancing the airflows to the workstations by installing more personal fans and extending workers' personalised control over the ventilation and comfort strategy might improve the overall thermal comfort of the workers, especially for those located far from the inlets.



(a)



(b)

Figure 7-44: Ranges of spot measured (a) air temperature and (b) average air speed in terms of the distance of the spot from inlets (source: field study during the warm-humid season, year 2015)

7.9.6. Construction materials and thermal mass

The results from Section 7.3 indicated that all the façades and the roof of the case study building were subject to incident solar radiation. However, Table 7-2 reveals that the estimated U-values of the existing external walls and roof were 2.25 and 4.65 W/m^{2}K. Increasing the thickness of the external walls and roof could decrease the U-value and control conductive gain. Since night ventilation is more effective with high thermal mass (Sections 3.5.2 and 3.7.1), increasing thermal mass of existing materials of the building, such as external walls (75.5 KJ/m^{2}K), internal floor/ceiling (186.6 KJ/m^{2}K), by increasing thickness, refurbishing the existing materials with higher thermal mass could enhance the night ventilation strategy and provide additional cooling for building during working hours. Changing existing glazing to materials with low U-values and extending the shading elements could also reduce solar gains through the windows.

7.10. Summary

This chapter aimed to present field investigation including environmental conditions of workspaces and issues related to workers' thermal comfort of an existing case study building (*RMG factory 1*) and to propose a range of design solutions to improve these issues. The key findings of this chapter are as follows:

- The outdoor AT measured at all the building facades and roof top indicated high amount of heat gain during the sunshine hours and the presence of these hot air might also affect the indoor ventilation and thermal performance of the building during working hours. However, measured outdoor thermal data evidenced the presence of relatively low ranges of outdoor AT during night time of all seasons.
- Due to constrained active ventilation and operation of windows bounded to working hours, the indoor air and surface temperature of workstations, for instance middle part of the CS, SS and FS, remained hot during unoccupied hours in all three climatic seasons.
- Results from on-site spot measurement as well as the workers' response study suggested that it would be a major challenge to ensure thermal comfort at their workstations during the warm-humid season due to simultaneous presence of high AT and high RH.
- Full day ventilation including operation during night time and weekends was proposed as one of the design strategies to improve existing working environment of *RMG factory 1*.
- Sliding windows restricted outdoor air to flow in the workspaces and had a direct impact on increasing indoor AT causing a maximum deviation up to 2.5°C.
- Changing the factory's existing equipment with lower heat generating models would not only improve the indoor thermal environment but also save annual expenditure on energy.
- Passive stack ventilation could couple with the existing ventilation strategy, particularly during night time, when the outdoor AT is lower than indoor AT.
- Field measurements and workers' response, including the results from questionnaire study and focus group discussions, confirmed that workers

having their workstations located remotely from the ventilation inlets suffer from discomfort due to simultaneously high AT and low air speed.

- Changing the existing functional layout and enhancing the personalised control over the ventilation strategy could improve the comfort condition for the workers.
- There were provisions to reduce external conductive heat gain during day time and accentuate night time cooling by refurbishing the existing building materials to materials with low U-values and high thermal masses.

The next two chapter (Chapters 8 and 9) will provide results from the field studies of *RMG factory-2* and *RMG factory-3*.

CHAPTER 8. FIELD STUDIES: *RMG FACTORY 2*

This chapter presents the results from the field studies conducted in the second case study building, *RMG factory 2*. Similar to previous chapter, exiting issues of thermal environment and a number of improvement strategies are proposed at the end of the chapter.

CHAPTER 8. FIELD STUDIES: *RMG FACTORY 2*

8.1. Introduction

Similar to previous chapter (Chapter 7) this chapter focuses on the second case study building RMG *factory 2*, one of the three case study buildings of this research (Section 5.5.2).

8.2. Chapter Aim and Scope

The aim and scope of the chapter are same as shown in Section 7.2. Based on the methodologies applied for the field studies (Section 5.5), the preliminary observations, assumptions and field results are provided in the Sections 8.3 – 8.9.

8.3. Site and Micro-climate Study

RMG factory 2 is a 4 storey building located within the Chittagong region, 5km away from the Chittagong meteorological weather station. The total site area is 2400m^2 and the building footprint is 1600m^2. Figure 8-1 shows the footprint of the case study building with its site and surroundings.



Figure 8-1: The case study building: *RMG factory 2* within its site area (source: Google Map)

The meteorological data of the Chittagong region (years: 2008-2015) reveal the same climatic seasons as described in Section 7.3. The warm-humid season has an extreme

mean RH of 96.6% (Meteorological Department of Chittagong, 2016). The mean AT of this region varies from 24.2°C to 35.0°C during all seasons. Figure 8-2 shows the annual AT and RH ranges of Chittagong region.

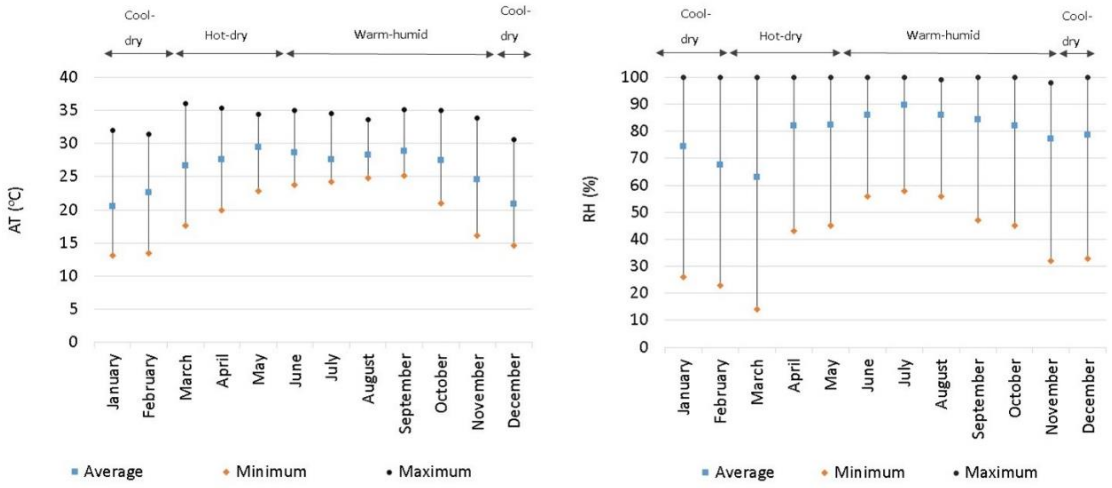


Figure 8-2: Measured AT and RH ranges in the Chittagong region (source: Meteorological data - year 2015)

Figure 8-2 illustrates the outdoor AT and RH recorded during the three field studies. It can be observed that the outdoor ATs varied by season ranging 13-27°C, 21-36°C and 25-33°C during the cool-dry, hot dry and warm-humid seasons respectively. Outdoor RHs also varied ranging 48-100%, 40-100% and 75-100% during the cool-dry, hot dry and warm-humid seasons respectively. Comparing data set presented in Figures 8-2 and 8-3, it can be observed that the data recorded from the field and the meteorological department are similar. Figure 8-3 reveals that there are diurnal variations of 12°C, 11°C and 7°C during the cool-dry, hot-dry and warm-humid seasons. The other external factors, such as the presence of waterbody next to the building, might have affected the local outdoor AT and RH.

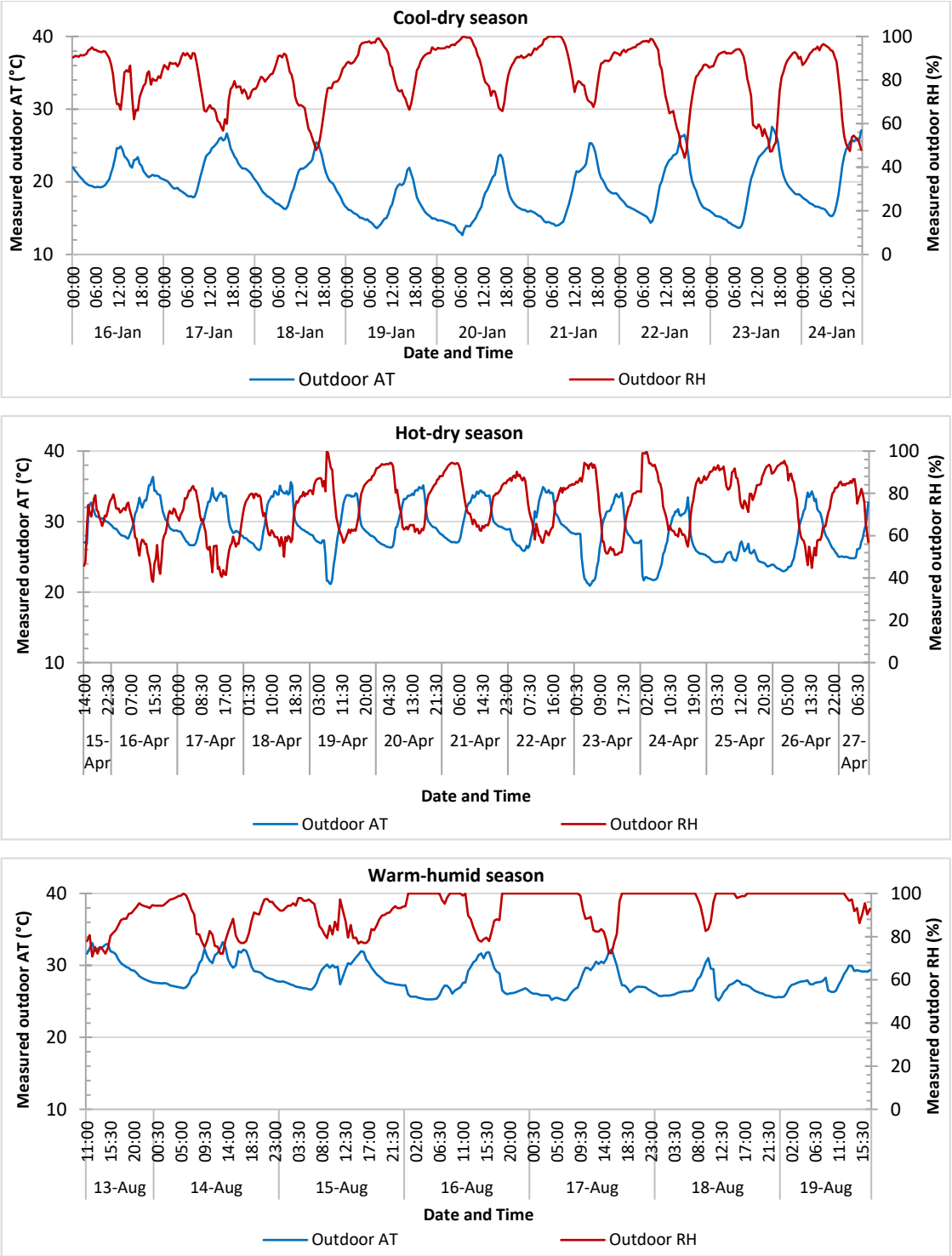


Figure 8-3: Micro-climate data representing days during each season (Source: field study in 2015)

Figure 8-4 reveals that the north building facades remain mostly shaded over the course of a year and that the south, east and west facades are exposed to sun for longer periods of a year. This figure also indicates that the winter winds from the north or north-west direction and summer winds from the south-east represent the sources of prevailing wind for the building.

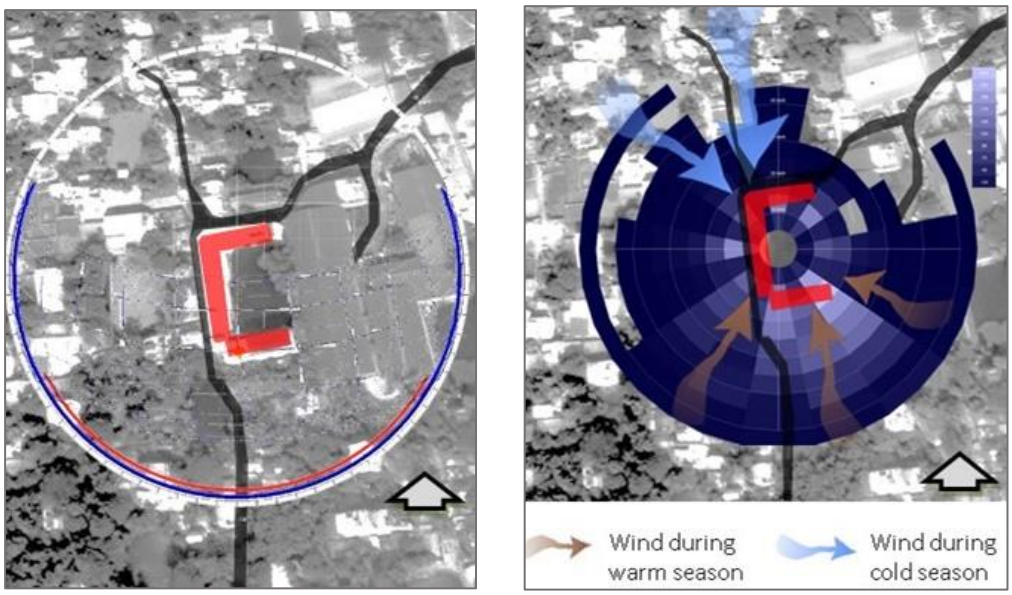


Figure 8-4: Sun-path diagram and wind-rose (source: Google Maps, author's 3D modelling and Ecotect Analysis 2011)

Figure 8-5 shows the shadow pattern at different times of day for the summer solstice, equinox and winter solstice. The north side of the building subjects to self-shading during the cool-dry and hot-dry season. The south and west façades are subject to incident solar radiation.

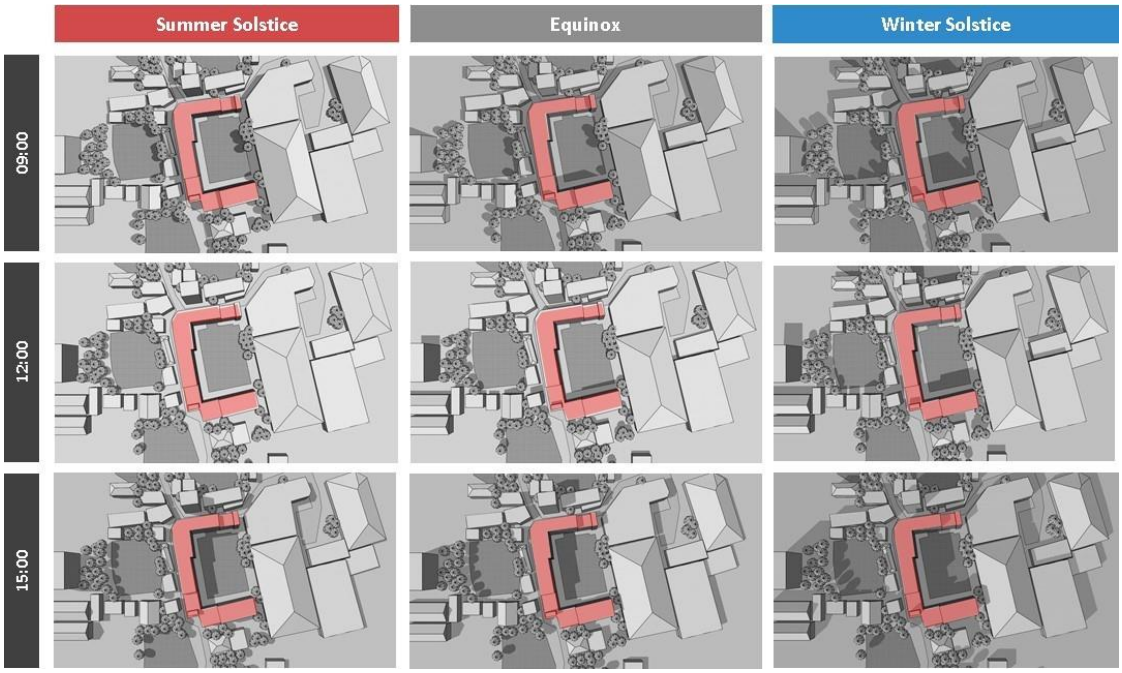


Figure 8-5: Shadow analysis of *RMG factory 2* (source: Google Maps, author's 3D modelling and Ecotect analysis 2011)

Figure 8-6 represents the morphological context of *RMG factory 2*. The building is sited in a semi-urban environment where adjacent buildings are a mixture of residential and industrial. This figure indicates that prevailing winds should experience major obstruction from north and south sides of the building. Facades facing towards waterbody may get the prevailing winds. Hence, the major issue is the incident solar radiations on and round the building (Section 3.4.1).



Figure 8-6: Morphological context views from the case study building (source: author-generated 3D models and photographs)

Figures 8-7, 8-8 and 8-9 show estimated distribution of incident solar radiation and field measured surface temperature on all façades on a same day of the year 2015. Figure 8-7 reveals that roof gets the highest incident solar radiation (5.7KWh/m^2) on the day, while the south and west sides receives up to 4KWh/m^2 radiation. It indicates that the workspaces facing the west-south and located on the top floor likely to receive solar and conductive heat gain. Figures 8-8 and 8-9 reveal that west façade reached

maximum surface temperature of up to 43.6°C after 3pm on 17 August 2015. Glazing on all façades affected the temperature profile.

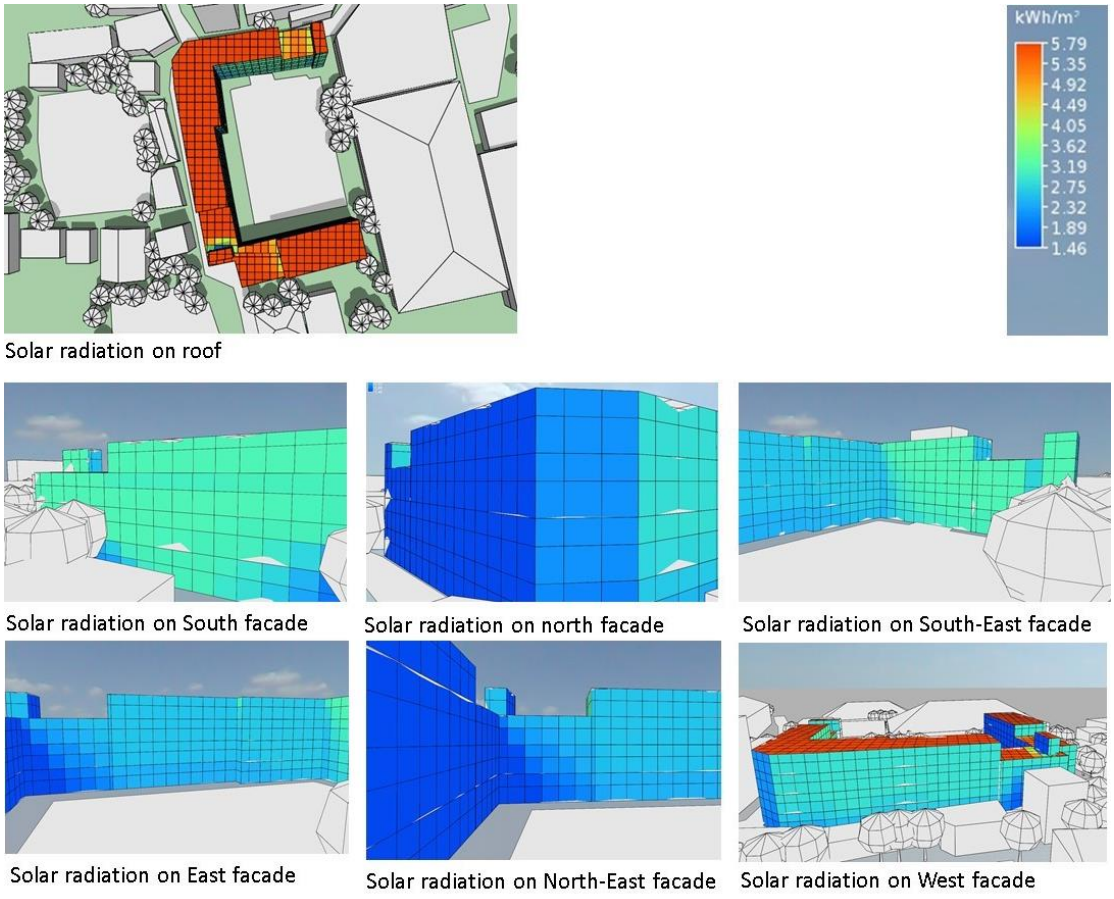


Figure 8-7: Distribution of Incident Solar Radiation on a partly sunny day of the year (source: Ecotect analysis on 17 August 2015)

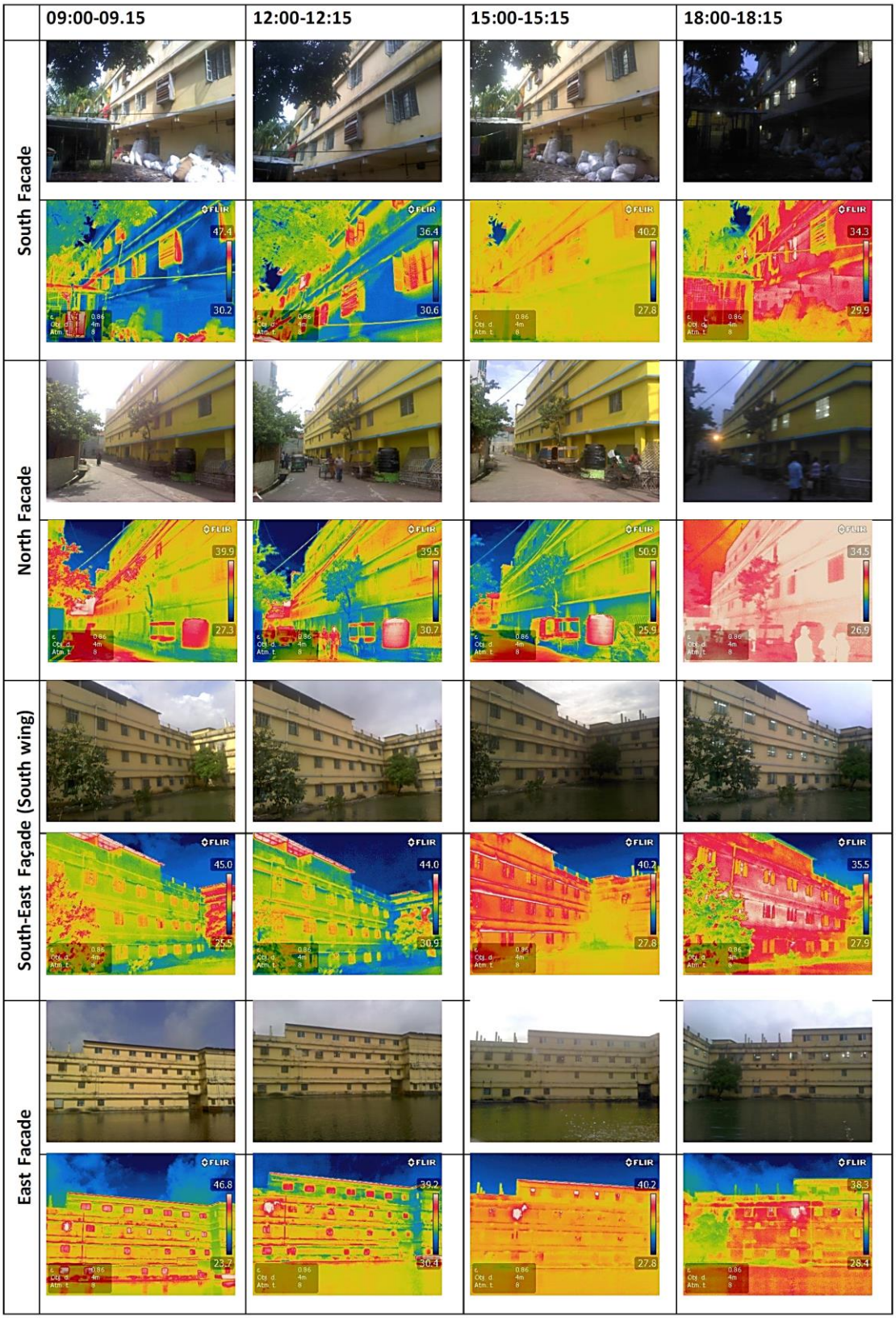


Figure 8-8: Surface temperature profile (not in same temperature scale) of south, north, north-east and east façades of *RMG factory 2* (source: field study on a partly sunny day, 17 August 2015)

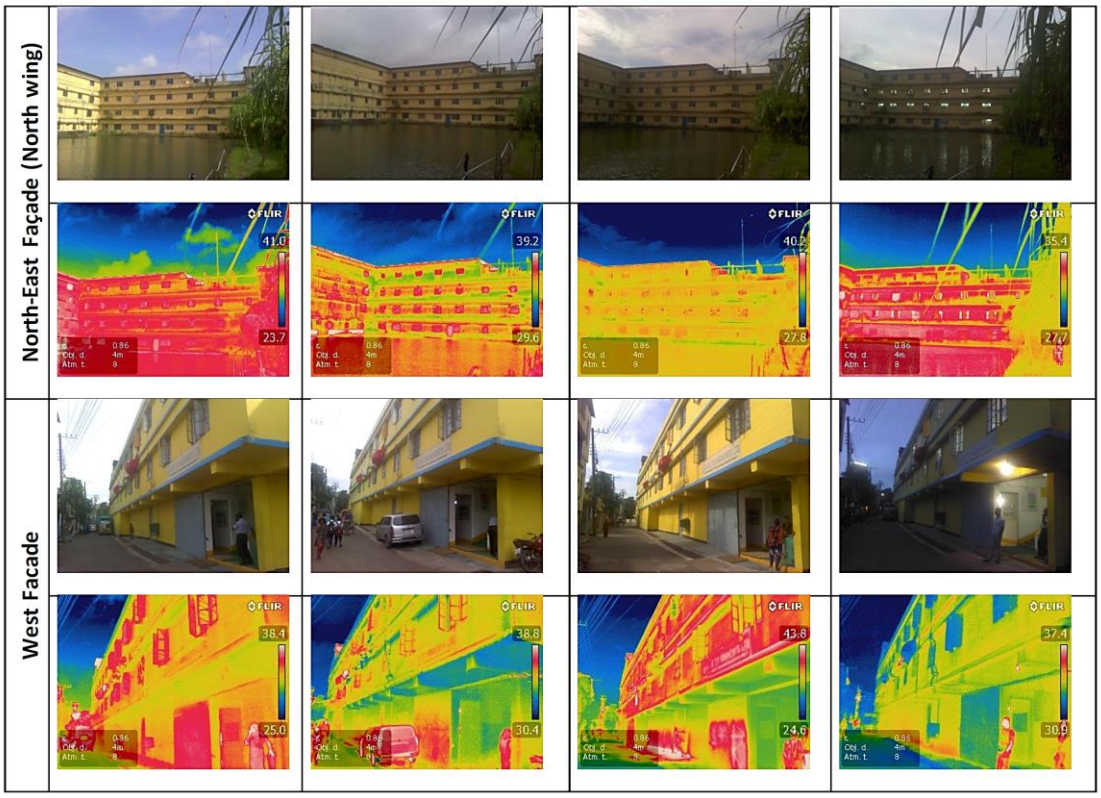


Figure 8-9: Surface temperature profile (not in same temperature scale) of south-east and west façades of *RMG factory 2* (source: field study on a partly sunny day, 17 August 2015)

Figure 8-10 provides a section through the building indicating the prevailing winds and position of the sun relative to the north and south facades.

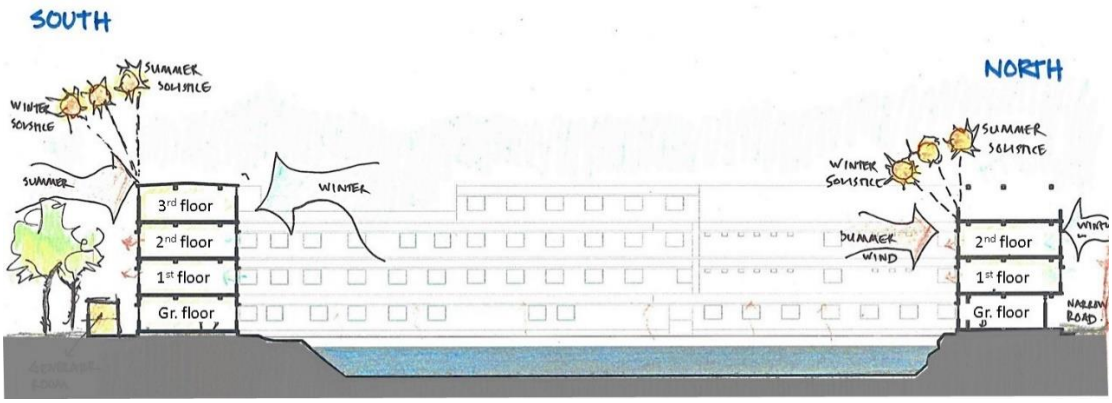


Figure 8-10: Observation of microclimate on a building section (source: author's schematic drawings)

Initial observation on the building morphology, solar exposure and predicted air flow regime indicate that west and south sides of the building, including the external walls, roof and glazing elements are vulnerable to incident solar radiation and solar control should be considered as a strategy to reduce external conductive heat gain.

8.4. Building Observation

8.4.1. Functional layouts and workspaces

The main production floors are located on the ground, 1st and 2nd floors (as shown in Figure 8-11). The entries are located on the west side (road side) of the building. Other spaces are mainly for storage, administration and dining (workflows are shown in Figure 8-11).

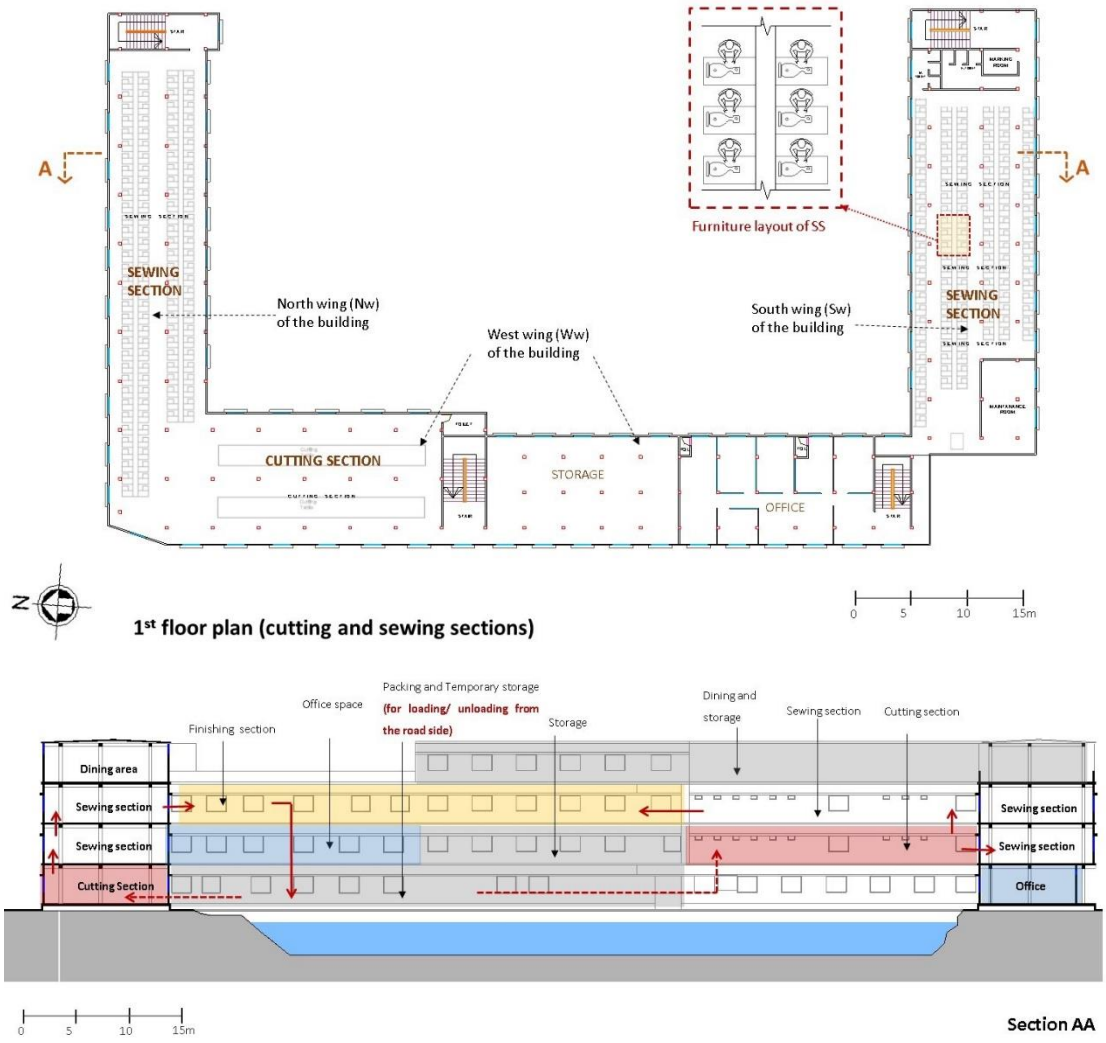
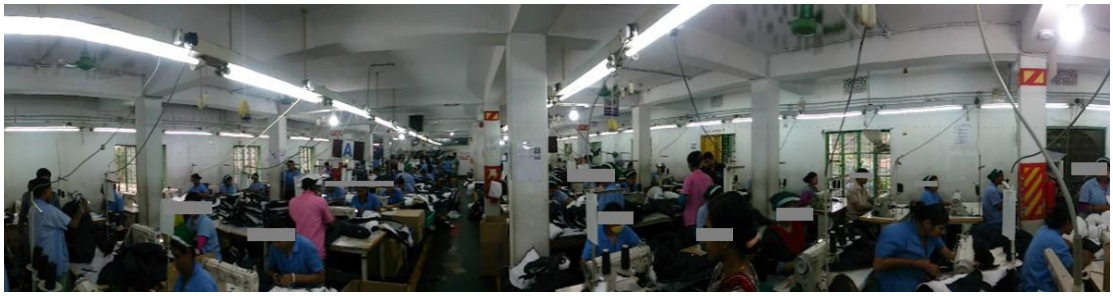


Figure 8-11: Location of the production spaces and activity flow in *RMG factory 2*

Panoramic views shown in Figure 8-12 represent that the density of workers is less in the CS and very high in the SS and FS. Figure 8-13 illustrates estimated density of workers per floor. Total of 37, 693, 113 workers work in the CS, SS and FS respectively. On average there are 285 workers per production floor excluding the office spaces.



(a) CS (1st floor-Ww*)



(b) SS (1st floor-Sw*)



(c) FS (2nd floor-Ww*)

**Here, Sw and Ww refer as the South-wing and West-wing of the building respectively*

Figure 8-12: Panoramic views of (a) Cutting, (b) Sewing and (c) finishing sections of *RMG factory 2*

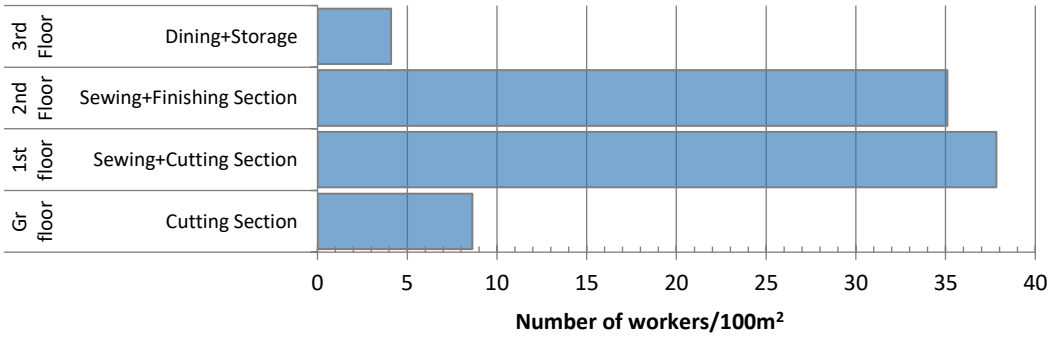


Figure 8-13: Estimated density of the workers in *RMG factory 2*

8.4.2. Existing ventilation strategy

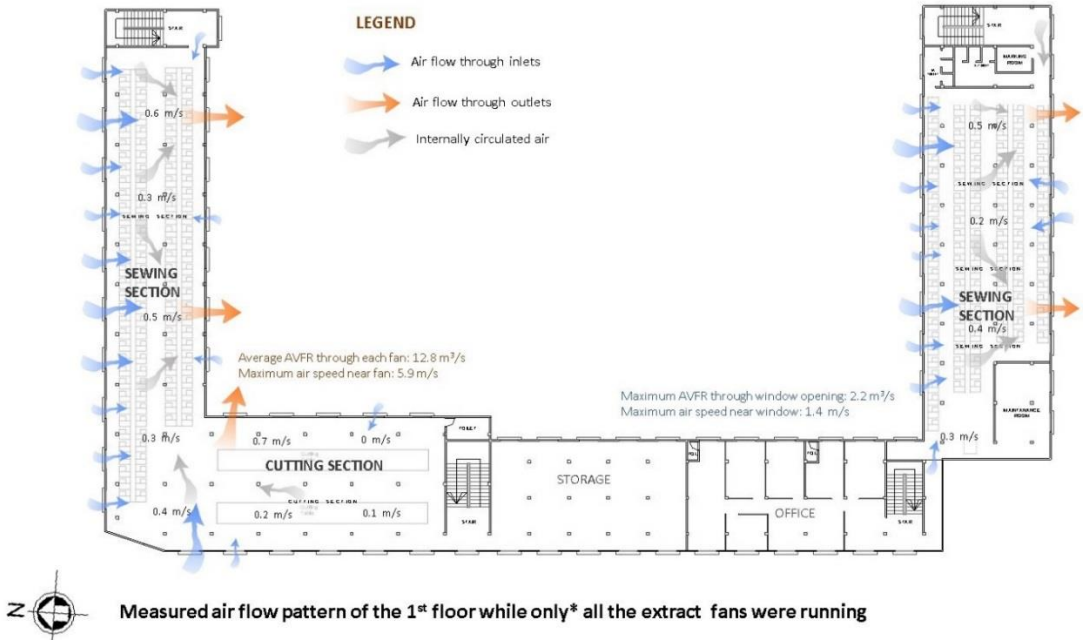
The case study building is ventilated mainly by total 12 large (1.4m diameter) mechanically controlled extract fans placed on the south and east facades of the building. The width of the floor is 10m and the ceiling height to floor-plate width ratio (1:3.5). Hence, natural cross ventilation seemed to be viable within the production

floors (Section 3.5.1). However, scientific evidence could not be collected. Figure 8-14 shows a production floor (1st floor) with inlets and outlets respectively. Ceiling fans were also available as a provision of providing additional cooling for workers in the production spaces during working hours. Worker have full control on the extract fans as well as ceiling fans. Hence, there is no fixed schedule of active ventilation could be retrieved. However, there is no NTV strategy and windows are kept closed during unoccupied hours including the weekends.



Figure 8-14: Existing production floors with two types of inlets, outlets (extract fans) and ceiling fans

Figure 8-15 shows the 1st floor plan and the typical horizontal air flow pattern at work plane level. Each extract fan was found to be capable of extracting air by 12.8 m^3/s volume flow rate (Section 5.4.5). Maximum air speed near these fans was measured 5.9 m/s. However, this pattern usually varies affected by air flows from the ceiling fans.



Measured air flow pattern of the 1st floor while only* all the extract fans were running

**Ceiling fans were not operation during the field study to understand the horizontal air flow pattern solely for the extract fans*

Figure 8-15: Measured air flow pattern of 1st floor of *RMG factory 2* with active ventilation (source: field studies in 2015)

8.4.3. Impact of internal heat gains

Similar to Section 7.4.3, Table 8-1 provides an overview of the sources of high gain and their STs during working hours measured on a typical day during the hot-dry season. The highest ST was observed in ironing workstations located both in the FS and SS. Given that the number of sewing machines (all types) are relatively high in the production sections (1st and 2nd floors), a significant amount of heat could be generated in the SS resulting in environment with high AT (Appendix H-2).

Table 8-1: Sources of internal heat gain in *RMG factory 2* with their surface temperatures (source: field studies)



Thermal images of three production spaces (CS, SS and FS) are presented in Figure 8-16. The figure reveals that surface temperature ranges of 31-39°C, 33-43°C and 32-54°C were recorded in the CS, SS and FS respectively. This would have an effect on indoor AT and RH during working hours and might cause high temperature (Section 3.4.3).

Figure 8-17 shows internal heat gains that were for different floors of the building excluding the services and office areas (Sections 5.4.5 and 5.5.5). It reveals that the 1st and 2nd floor had the high internal heat gains up to 295 W/m^2.

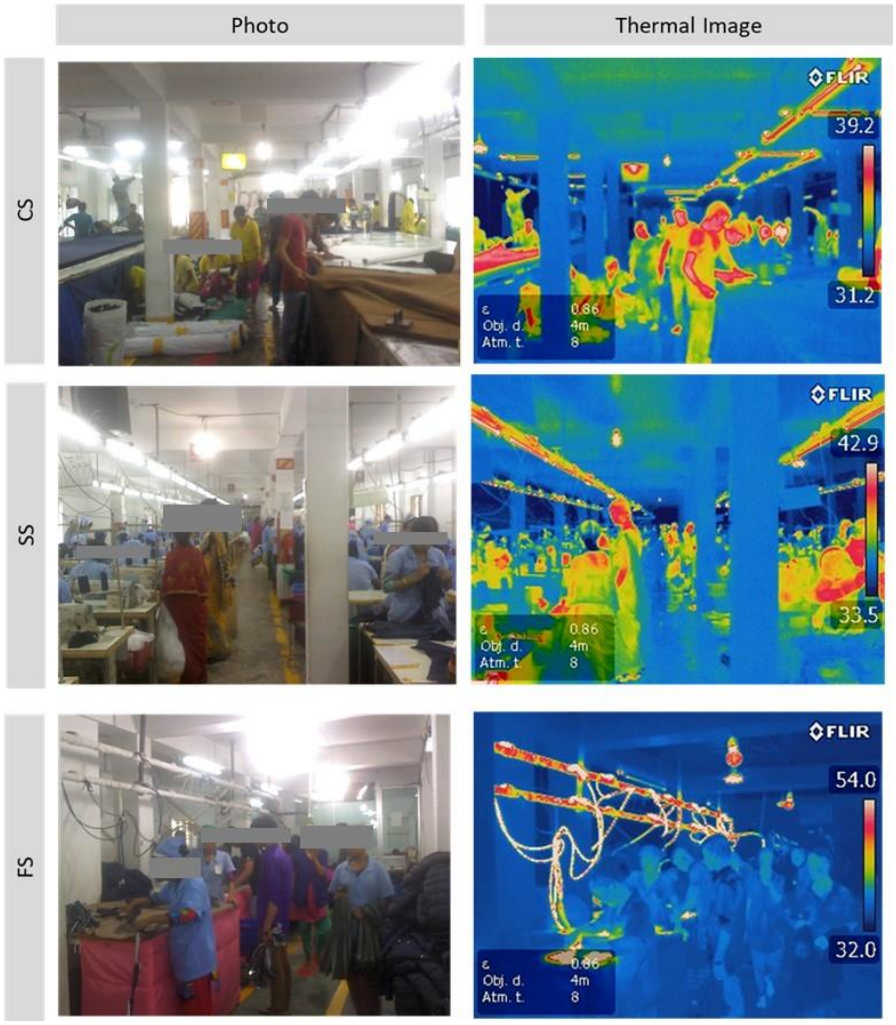
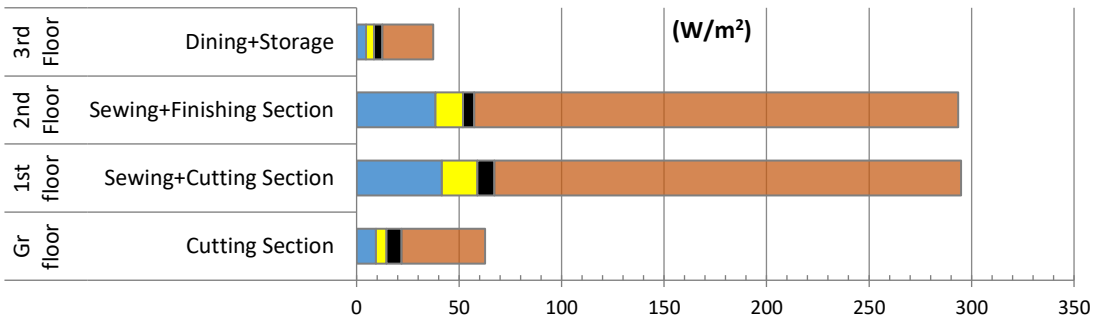


Figure 8-16: thermal images of key production sections in *RMG factory 2*



	Gr floor	1st floor	2nd Floor	3rd Floor
	Cutting Section	Sewing+Cutting Section	Sewing+Finishing Section	Dining+Storage
Occupant heat gain (W/m2)	9.5	41.6	38.5	4.5
Heat gain from lights (W/m2)	5.1	17.4	13.4	4.0
Heat gain from fans (W/m2)	7.4	8.3	5.4	4.0
Heat gain from Equipment (W/m2)	40.8	227.7	236.2	24.8

Figure 8-17: Estimated internal heat gain (in W/m^2) of *RMG factory 2* building

Field evidence from the thermal images and estimates of internal heat gain profile suggest that there is a risk high indoor temperature unless a subsistence amount of air changes are provided.

8.4.4. Material and construction

The main construction type is RC beam-column structure with concrete floor plates and 125mm thick external brick walls. Both sliding and horizontal swing windows with single glazing panes are located on all facades all of which have same sill height (1.3m). The sliding and swing windows have maximum effective opening 45% and 80% respectively. The effective WFR is 1:18 which is adequate for natural ventilation (Sections 2.7 and 3.5.1).

Figure 8-18 and Table 8-2 provide an overview of the main construction materials of the case study building and reveal that it may act as a heavy weight building. The extensive area of glazing materials and 125mm external wall indicate that the building would be subject to conduction heat transfer through the building envelop including roof slab (U-value of 4.65W/m^2K), external walls (U-value of 2.31 W/m^2K) and glazing materials. It might result in significant external solar gain through the building envelope which could also cause high temperature inside workspace during day time.

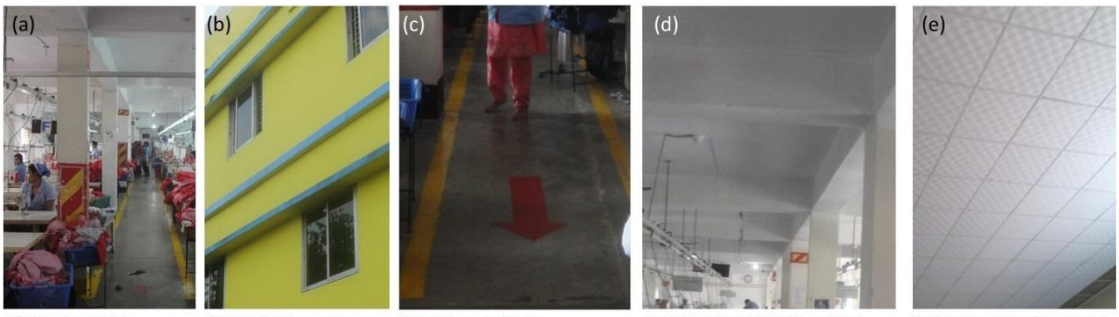


Figure 8-18: Various construction elements of *RMG factory 2*

Table 8-2: Main construction elements of *RMG factory 2* (source: author-generated based on field study)

Main construction elements	Description	Total Thickness (mm)	U-value (W/m^2K)	Thermal mass ($KJ/m^2 K$)	Specific heat capacity J/ (kg K)
Ground floor slab	0.100m thick concrete floor with 10mm cement mortar (floor), 8mm ceramic floor tiles, 0.6m brick soling and sand filling underneath	378 *(including sand fill above the ground)*	1.81	310.0	800 (tiles) 800 (mortar on floor) 840 (concrete) 837 (brick soling) 1550 (Sand filling)
Suspended floor slab (floor/ ceiling)	0.15m thick reinforced concrete floor with 12mm thick light plaster (ceiling), 10mm cement mortar (floor) and 10mm cement finished floor.	170	2.54	176.2	800 (tiles) 800 (mortar on floor) 1000 (RCC) 1000 (Fired clay)
External walls	0.1m brick work with 10mm medium weight plaster each side with paint	120	2.31	72.1	800 (brick work) 1000 (plaster)
Glazing with frames (sliding windows)	Clear float 6mm glass, single glazed (G-value: 0.82, transmittance 0.78) with aluminium frames and recessed local shade	6mm	5.17 (including frame) 5.69 (glass)	-	-
Local shading element (west and south sides)	0.15m thick reinforced concrete floor with 12mm thick light plaster (ceiling), 10mm cement mortar (floor)	177	2.42	186.1	1000 (cement coating) 800 (mortar on floor) 1000 (RCC) 1000 (Fired clay)
Roof slab	0.15m thick RCC with 5mm cement coating	155mm	4.65	178.25	1000 (cement coating) 1000 (RCC)

8.5. Preliminary Assumptions

Based on the preliminary observations of the case study building, its operation and temporal varieties of its micro-climate (Sections 8.3 - 8.4), the following assumptions can be made for further investigation in addition to assumptions shown in Section 7.5:

- Incident solar radiations on the south, east and west façades, preheated outdoor air, moisture from the waterbody may affect the indoor spaces.
- Thermal comfort may be enhanced by utilising the narrow floor plate and flexibility in controlling the airflow at workstations.

The physical measurements and subjective field data, presented in Sections 8.6 - 8.8, will be tested considering these assumptions.

8.6. Continuously Monitored AT and RH

A comprehensive summary of continuously recorded AT and RH of the *RMG factory 2* buildings is presented in Table 8-3 in respect to the immediate outdoor thermal environment. The SDs of indoor conditions did not show any significant fluctuation of AT (0.9 - 2°C) and RH (4.2 - 6.3%) compared with the variations observed in the outdoor condition. As the above observations only represent data collected over a week during each field study, this can be more explicitly visualised in Sections 8.6.1- 8.6.3.

Table 8-3: Descriptive statistics of the continuously recorded indoor and outdoor environmental data (i.e. TA and RH)* in all seasons (source: three field studies in 2015)

Season	Work section	Avg. AT_{in} (°C)		Avg. AT_{out} (°C)		Avg. RH_{in} (%)		Avg. RH_{out} (%)	
		Min - Max	Mean (SD)	Min-Max	Mean (SD)	Min - Max	Mean (SD)	Min - Max	Mean (SD)
Cool-dry	CS	22.9 - 27.7	25.0 (1.1)	12.7 - 28.7	19.3 (3.7)	43.6 - 68.0	56.2 (4.5)	43.9 – 96.1	73.6 (13.9)
	SS	23.1 - 31.6	26.9 (1.8)			41.3 - 69.6	52.3 (4.8)		
	FS	20.3 - 30.0	24.5 (2.0)			43.0 - 73.9	60.5 (5.2)		
Hot-dry	CS	25.8 - 32.8	30.0 (1.5)	20.9 - 36.3	28.8 (3.5)	46.5 - 78.7	67.2 (6.0)	38.2 - 99.9	74.0 (13.8)
	SS	26.2 - 33.7	31.1 (1.7)			43.4 - 85.8	63.4 (5.9)		
	FS	25.6 - 34.9	31.2 (2.1)			43.3 - 81.5	62.9 (6.5)		
Warm-humid	CS	27.1 - 32.0	29.5 (0.9)	25.1 - 33.2	28.1 (2.0)	70.4 - 90.4	79.8 (4.2)	70.8 - 100	92.8 (8.5)
	SS	28.9 - 33.3	30.9 (1.1)			67.1 - 88.1	74.5 (4.6)		
	FS	28.3 - 34.3	30.9 (1.5)			65.6 - 89.9	75.2 (6.3)		

**Same as Table 7-3* Figure 7-3*, ** Same as Table 7-3.*

Similar to Section 7.6, the data set will be analysed for individual production sections. The recorded data from the 1st floor–Sw (SS) will then be assessed further, focusing on the horizontal and vertical profile of AT and RH produced by the different data logger sensors, the position of which are shown in Figure 5-11.

8.6.1. Cool-dry season

Figure 8-19 reveals that the CS (ground floor-Sw) had a relatively low AT profile (ranging 24-28°C) while the SS had higher range (up to 31°C) probably due to the high internal heat gain (Figure 8-17) from the sewing machines. As predicted in Section 8.5, the building acts as a heavy-weight building and indoor spaces exhibit limited diurnal variations of AT compared with those recorded in outdoor. During the weekend and

non-working hours deviations in AT that correspond to the pattern of use of the building can also be observed. Though the building has enough provisions of natural cooling though cross-ventilation, the indoor ATs are unable to correspond with outdoor AT during night time. This is due to the fact that windows are kept closed during night time. The SS and FS within the 2nd floor tended to exhibit fluctuation of AT with the outdoor temperature.

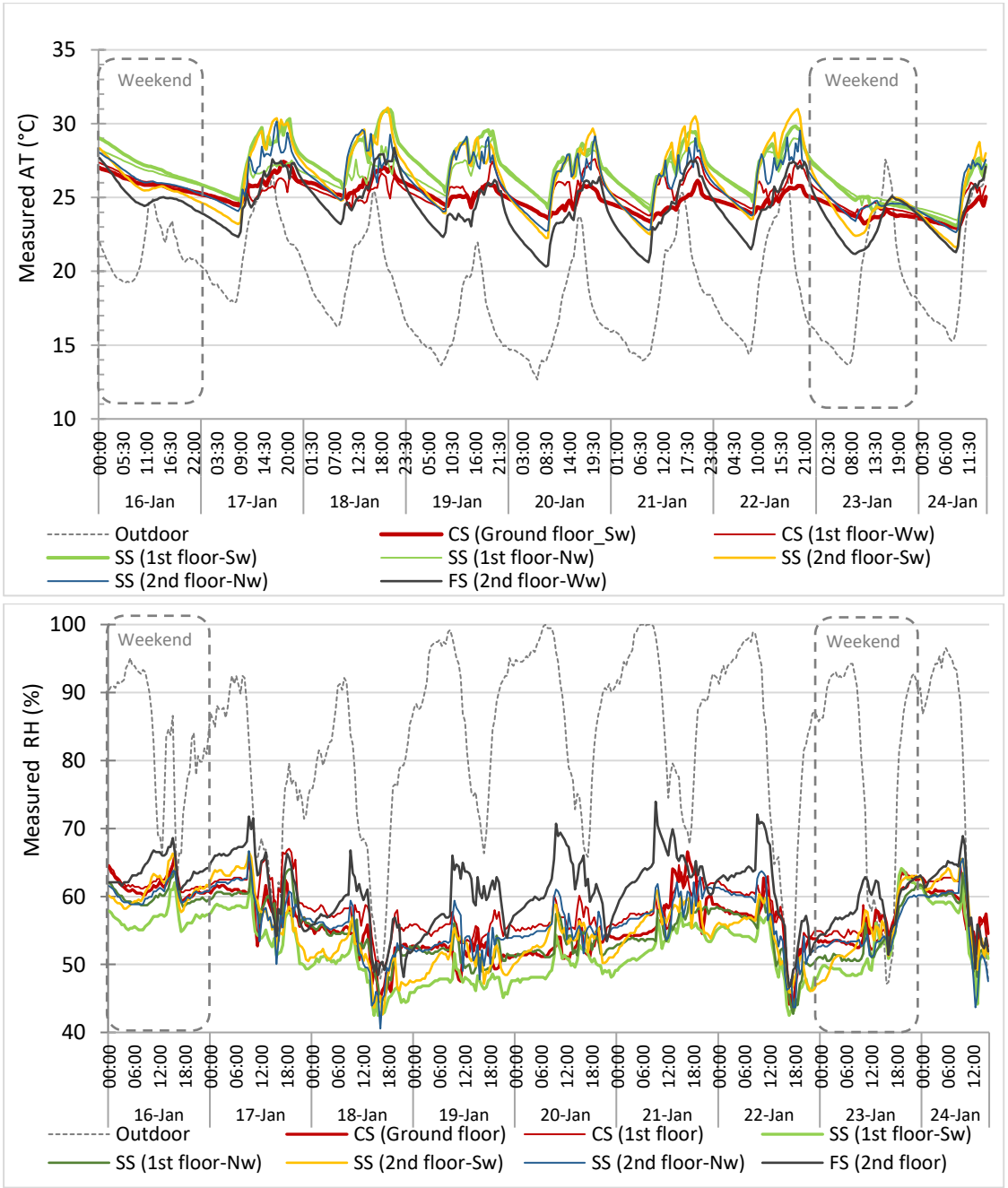
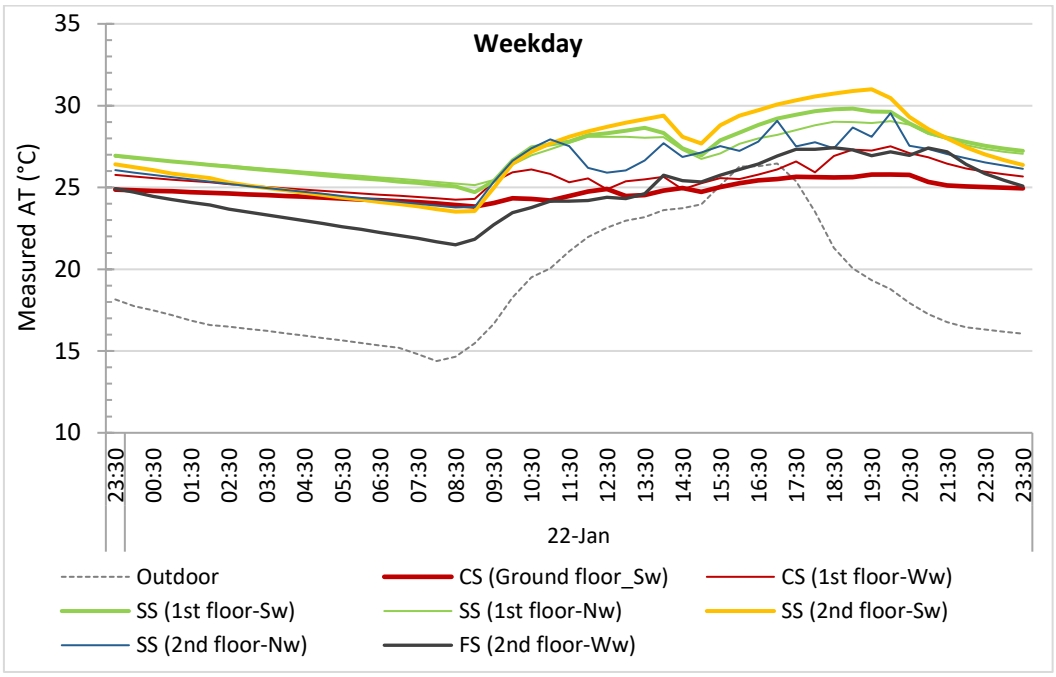
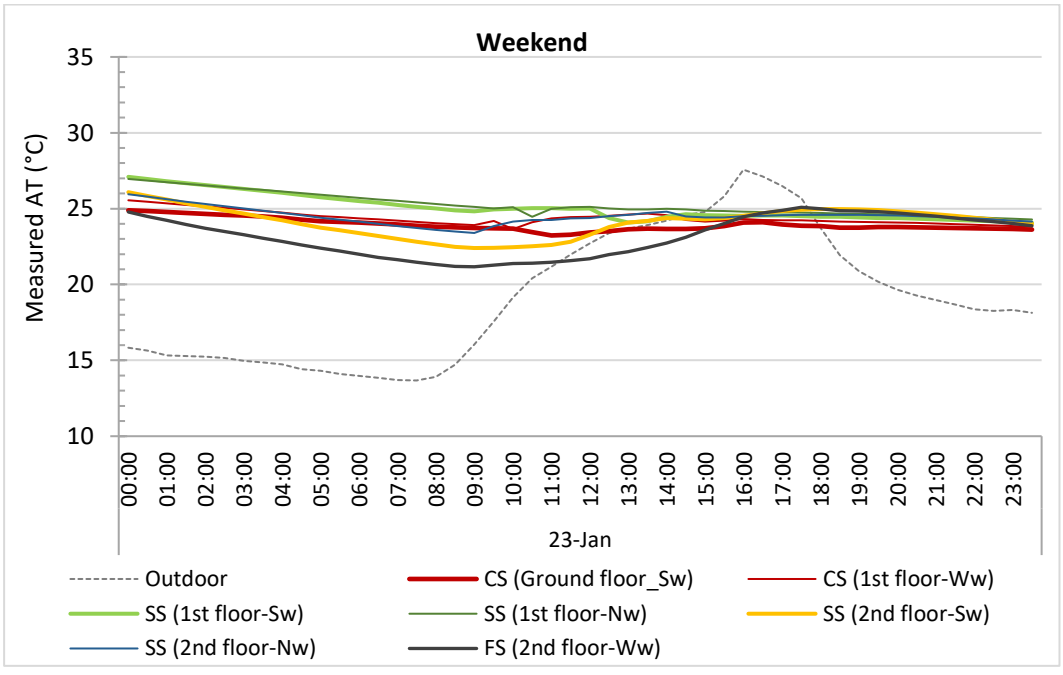


Figure 8-19: Measured AT and RH for production spaces during the cool-dry season (source: field study, year 2015)

Figure 8-20 reveals that due to the internal heat gains the indoor AT was elevated from 25°C to 30°C for the weekday while in similar outdoor temperature conditions, the indoor AT was steady (21-25°C) during the weekend. This indicates that the natural infiltration rate might be inadequate to cool down the indoor fabric including machinery and reduce the indoor AT to match low night time outdoor AT.



(a)

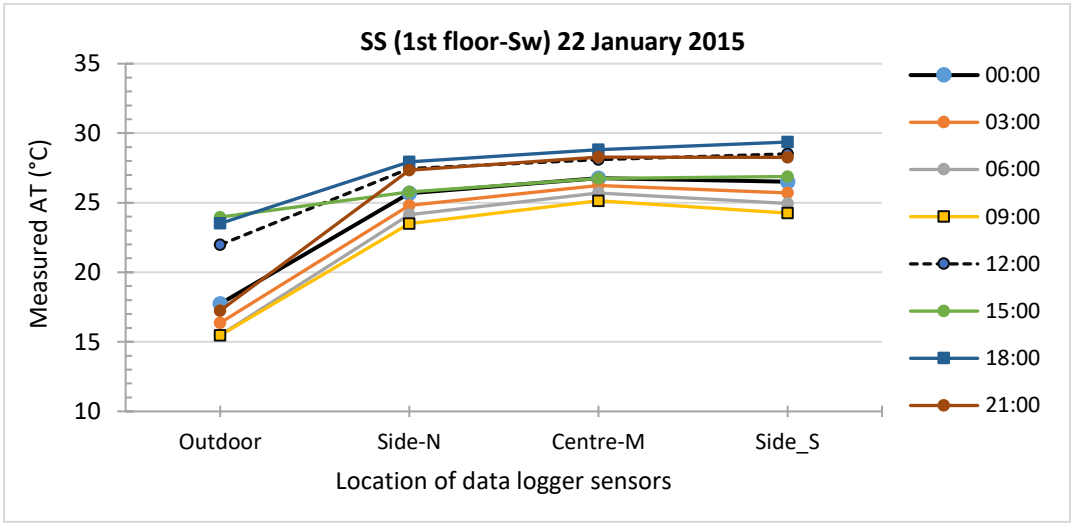


(b)

Figure 8-20: Measured AT for a typical weekday and weekend during the cool-dry season (source: field study, year 2015)

Data logging sensors were also placed in all the positions shown in Figure 5-11 to explore the horizontal dissemination of indoor AT. Figure 8-21 reveals that AT values at Centre-M and Side-S positions on the floor were at least 1-2°C higher than those near the north sides of the production reaching a peak between 18:00 and 21:00 of the day and exhibited a minimum deviation of 5°C from the outdoor AT (at 18:00). This indicates the impact of incident solar radiation on the south façade and adjacent indoor space during the cool dry season.

(a)



(b)

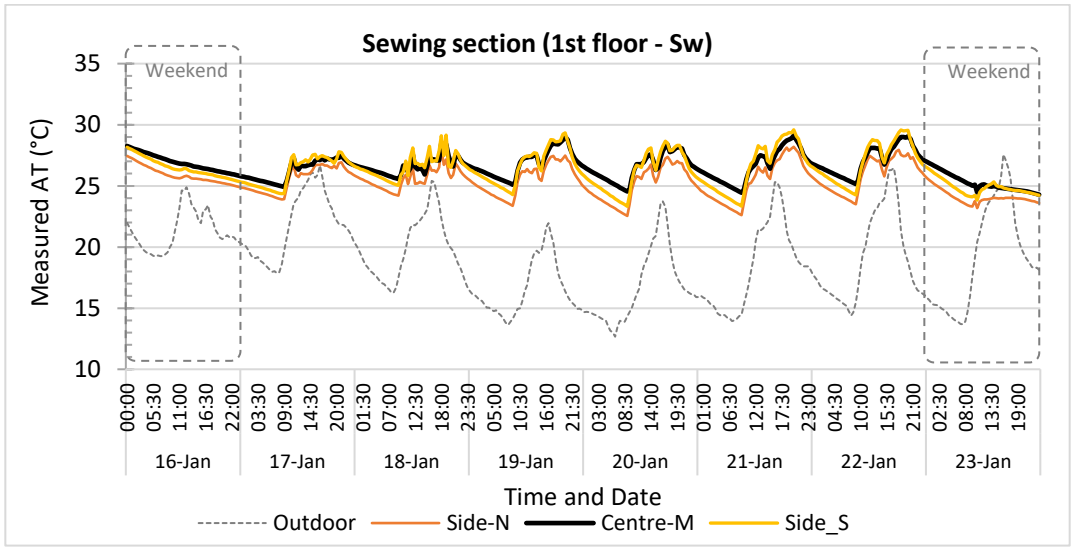


Figure 8-21: Measured AT profile recorded along the north to south axis of the SS (1st floor-Sw) during the cool-dry season - (a) data for different times of day and (b) continuously recorded data

8.6.2. Hot-dry season

Figure 8-22 illustrates that the CS had relatively low AT profile (maximum 33.2°C) while the SS and FS had 2°C higher values (35°C) during peak hours (12:00-16:00) probably

due to the high internal and external heat gains. However, during the weekend and non-working hours, these deviations were found to vary by up to 3°C, particularly at the 2nd floor as an effect of only external heat gains.

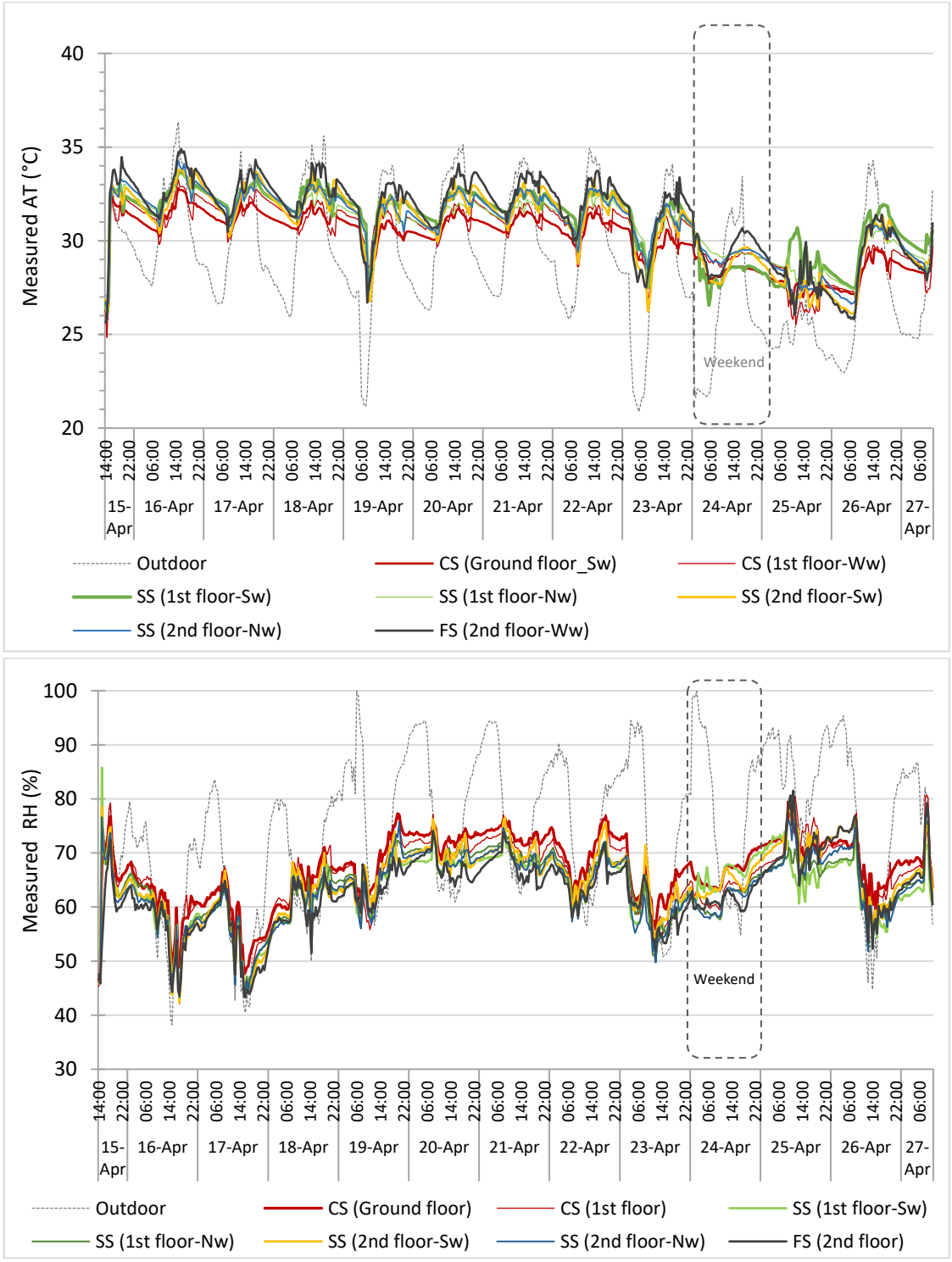


Figure 8-22: Measured AT and RH for production spaces during the hot-dry season (source: field study, year 2015)

Similar to Section 8.6.1, continuously measured AT values in different production spaces of a typical weekday and a weekend were compared in Figure 8-23. Like the cool-dry season, this figure clearly indicates the response as heavy-weight building and the natural infiltration rate might be inadequate to cool down the indoor fabric including machinery and reduce the indoor AT to match low night time outdoor AT.

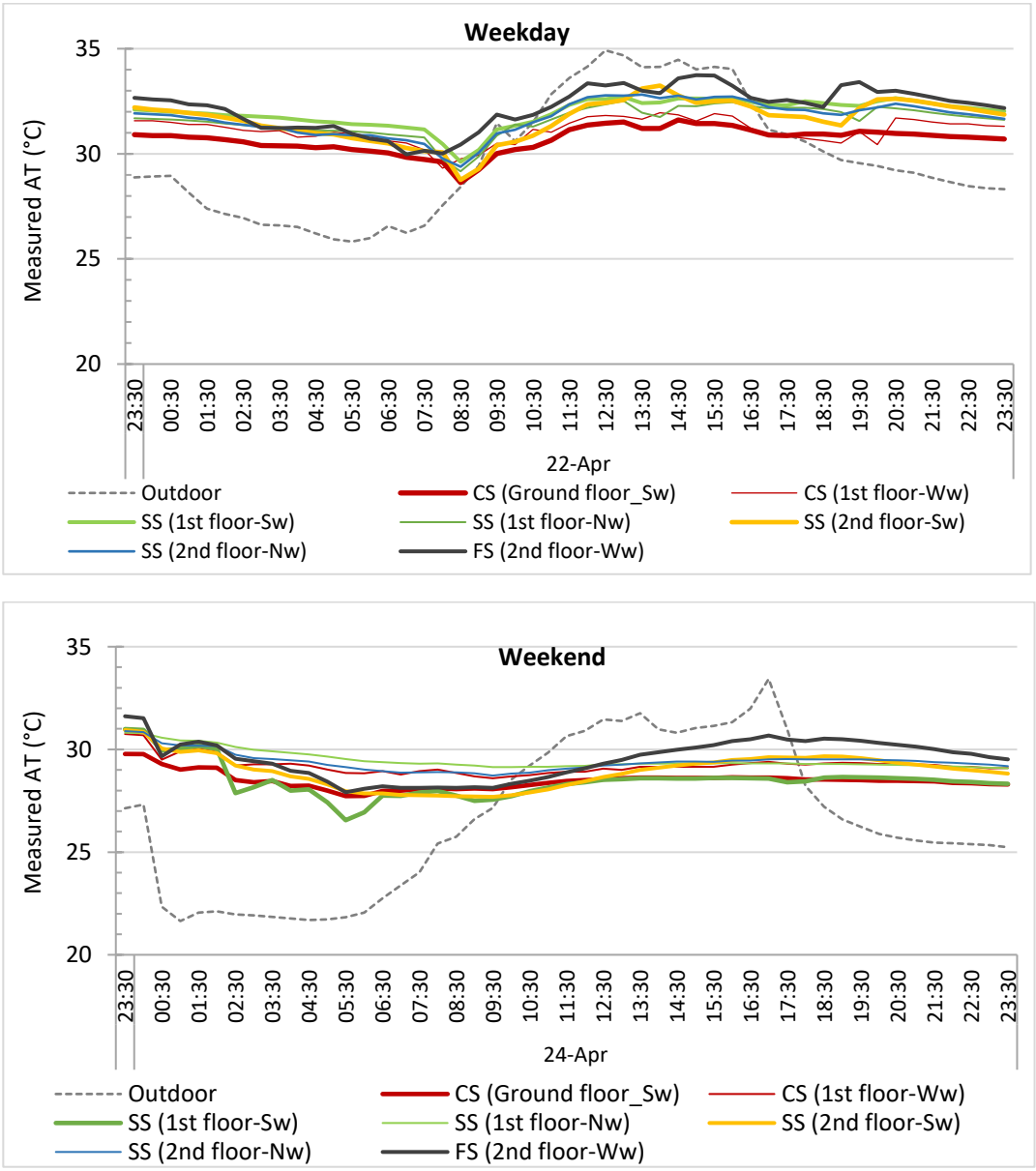


Figure 8-23: Measured AT for a typical weekday and weekend during the hot-dry season (source: field study, year 2015)

Figure 8-24 reveals that the AT profile recorded along the west to east axis of the production space was relatively uniform. In contrast, Figure 8-25 shows that AT values recorded near the North facade were relatively low (30°C at 09:00). Both figures shows

that indoor AT values at all the positions of the floor plate remained with high temperature compared with outdoor AT during night time (20:00 – 07:00).

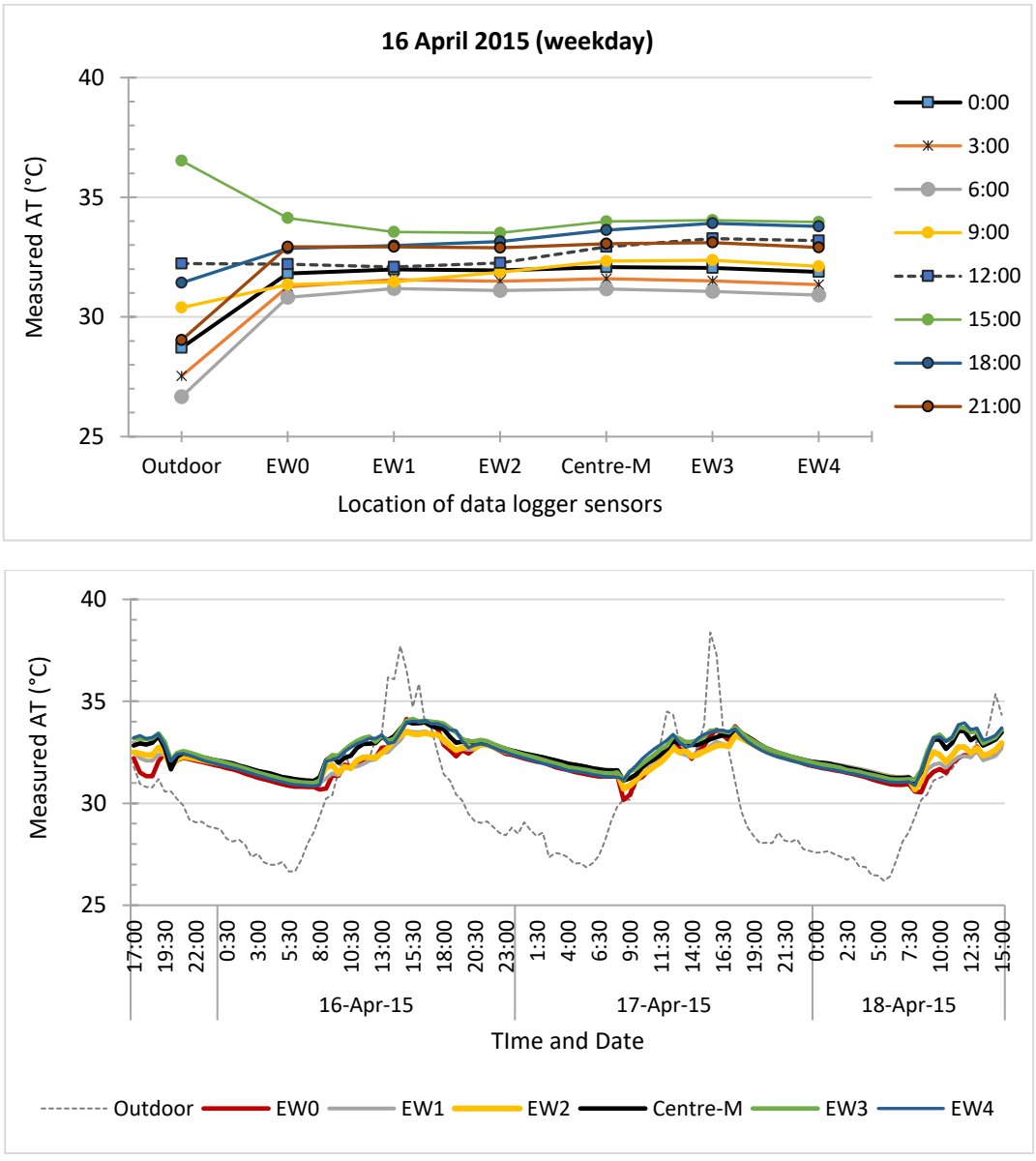


Figure 8-24: Measured AT profile recorded along the west to east axis of the SS (1st floor-Sw) during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

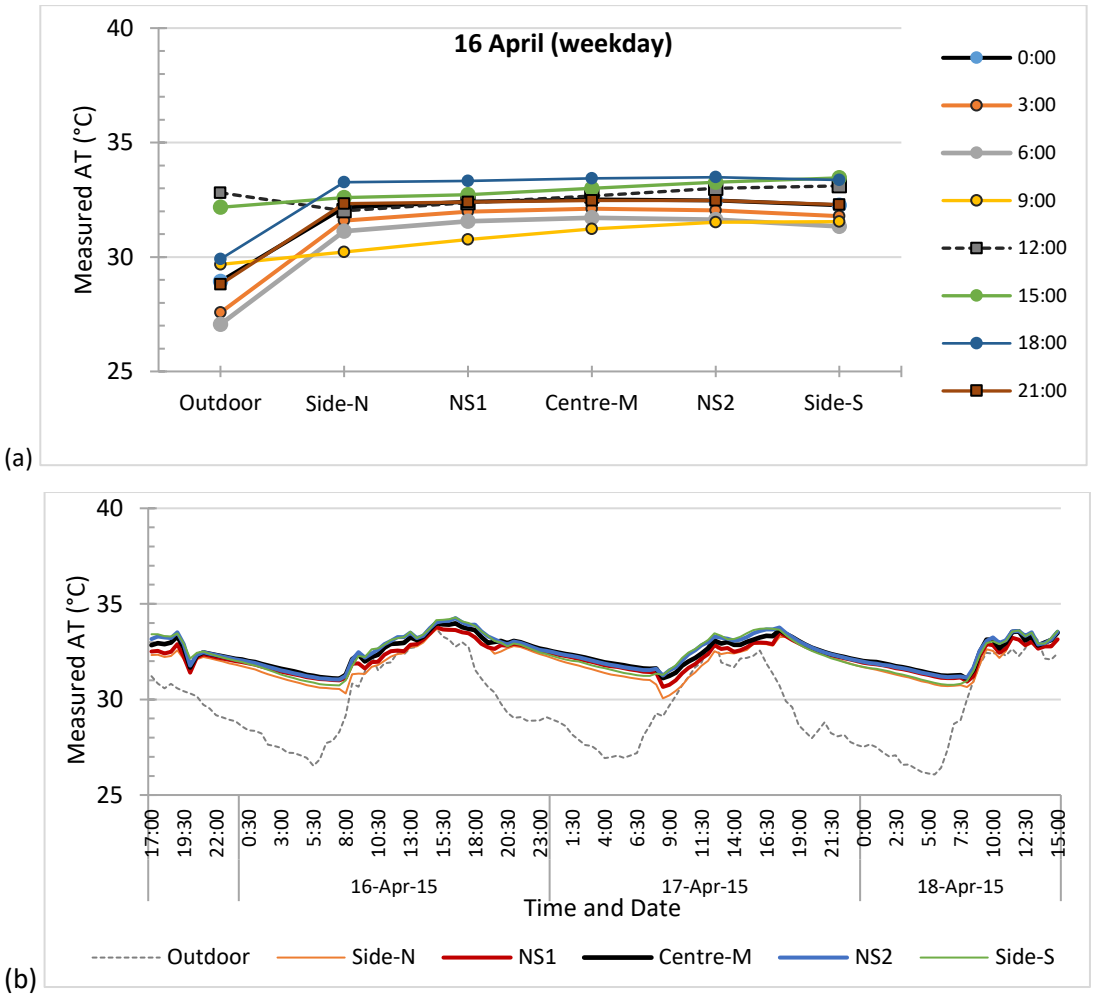


Figure 8-25: Measured AT profile recorded along the north to south axis of the SS (1st floor-Sw) during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

8.6.3. Warm-humid season

Figure 8-26 reveals that the CS exhibited at least 1°C low AT profiles compared to other production spaces with a maximum value of 33.5°C during peak working hours (12:00-16:00). It can be observed that during the night time the difference in AT values between the production spaces and outdoor of up to 3°C were recorded. There were significant deviations in measured RH values between production sections, particularly at the CS, SS (1st floor-Sw), SS (2nd floor-Sw) and FS (2nd floor), which exhibited the RH levels of up to 92%.

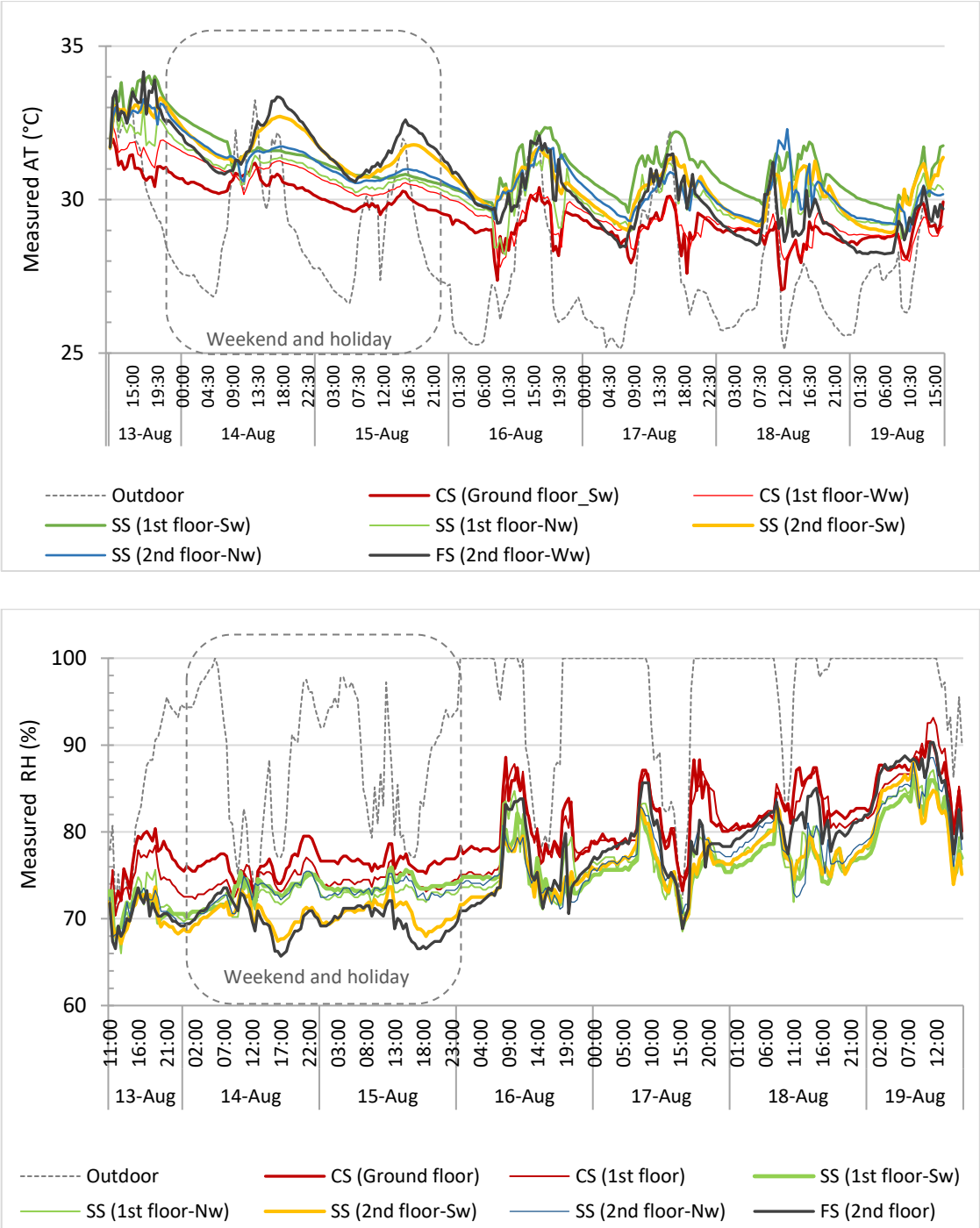


Figure 8-26: Measured AT and RH for production spaces during the warm-humid season (source: field study, year 2015)

Similar to previous two sections (Sections 8.6.1 and 8.6.2), Figure 8-27 reveals that the indoor ATs for all production floors increased from 27.5°C to 32°C during the working hours of a weekday. When subject to a similar outdoor temperature profile, the indoor AT values in the CS and SS were relatively constant (within the range of 29.5 -32.5°C) during the weekend.

What these data explicitly illustrates is that even with a diurnal variation of outdoor AT of 5°C (minimum 26.5°C at 06:00, maximum of 32°C at 16:00), the indoor AT did not drop below 29°C during night time. Similar to the analyses of the two other seasons, this indicates that indoor production spaces lack adequate ventilation and infiltration to reduce the indoor AT to the low values of outdoor AT prevailing during night time.

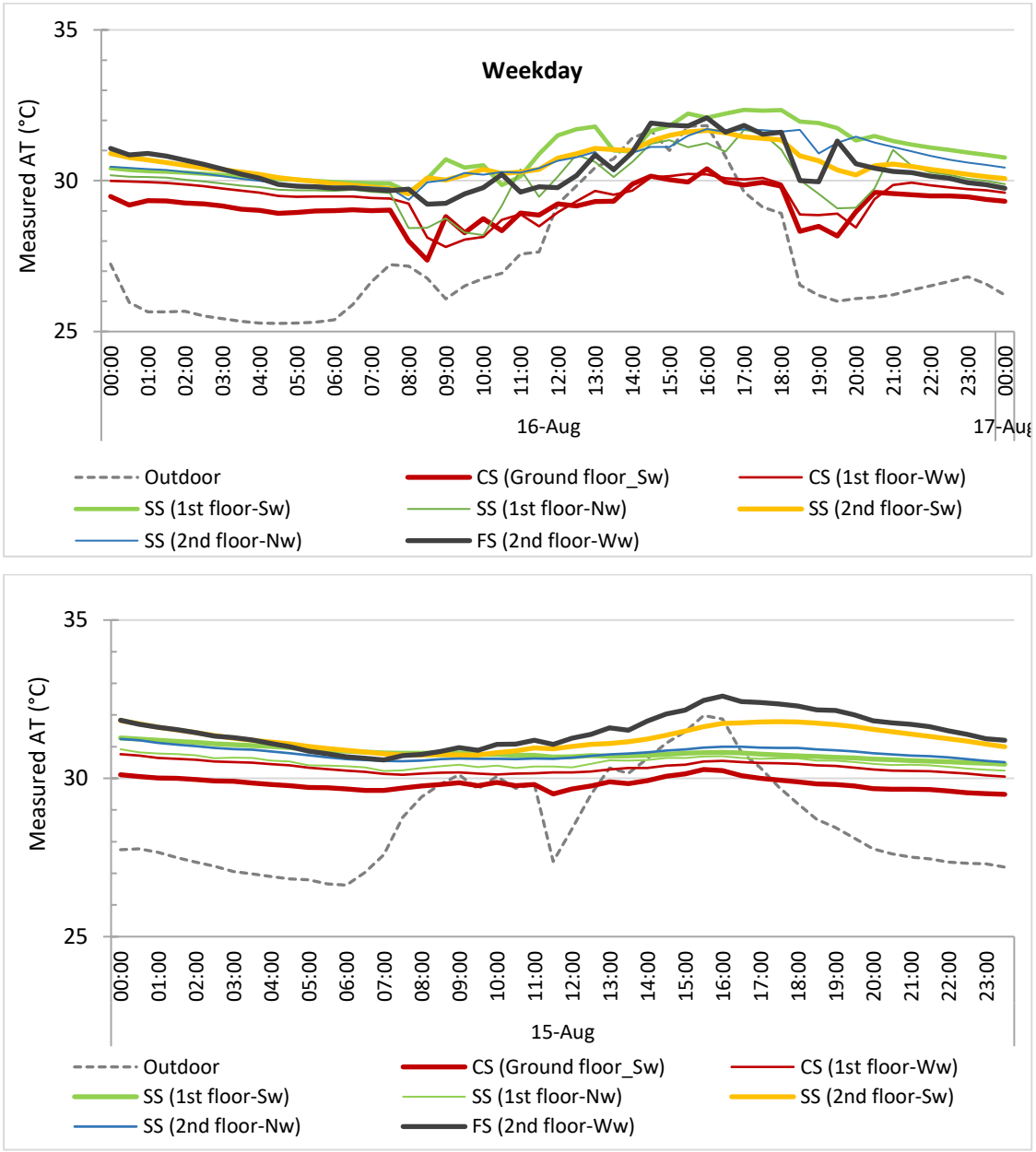
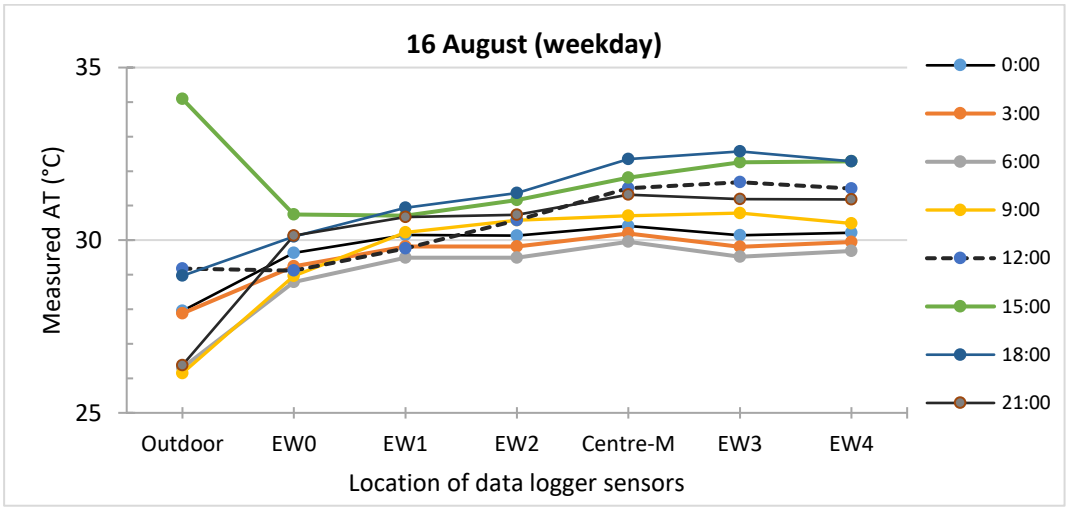


Figure 8-27: Measured AT for a typical weekday and weekend during the warm-humid season (source: field study, year 2015)

Figures 8-28 and 8-29 reveal that the AT values recorded at the EW0 (near west façade) and Side-N (near north façade) positions corresponded with the outdoor AT values. Further investigation was made, and it was found that to avoid dampness caused by

the rainy days a few windows at the North-west side were kept open and night cooling took place.

(a)



(b)

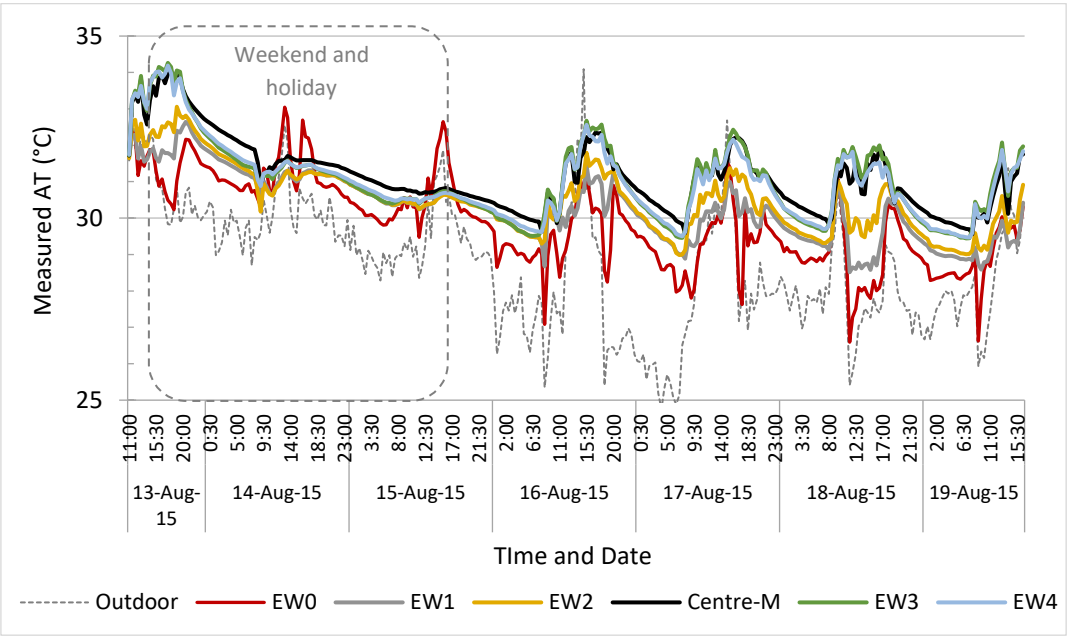


Figure 8-28: Measured AT profile recorded along the west to east axis of the SS (1st floor-Sw) during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

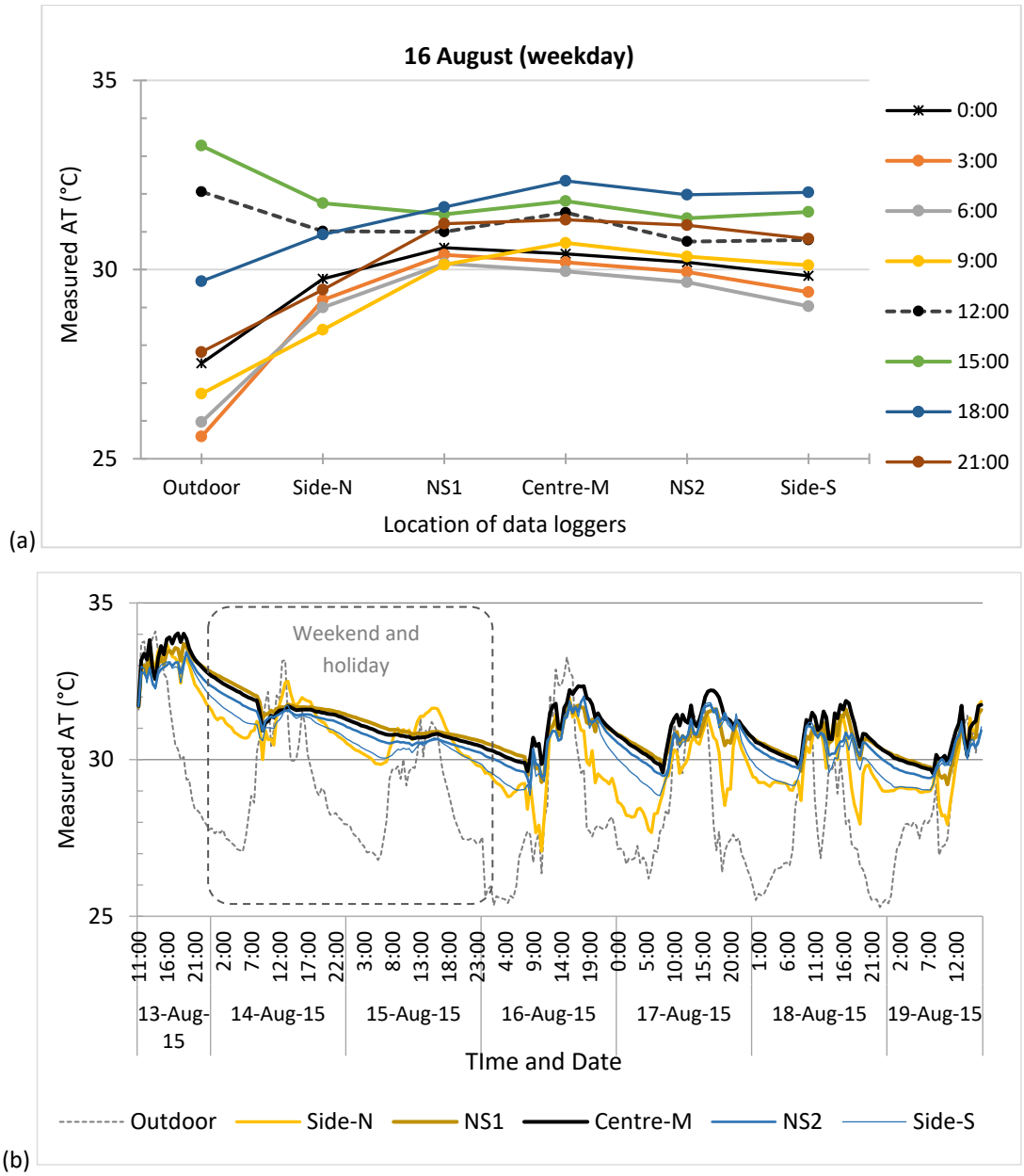


Figure 8-29: Measured AT profile recorded along the north to south axis of the SS (1st floor-Sw) during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

8.6.4. Key learning from monitored data

The continuous field data helped confirming a few of the preliminary assumptions stated in Section 8.5. The building responded as heavy-weight building and the workspaces exhibited constant AT profiles during the night time while the outdoor AT fluctuated during all seasons. The impact of external heat gain through the south and west facades were visible within the horizontal distribution of AT. The SS (at the 1st and 2nd floors) and FS exhibited high indoor AT during all seasons. Since the values of outdoor RH is relatively high during the warm-humid season (up to 100%), it would be

a key challenge to provide comfort to the workers by bringing cooler air from outdoor micro-climate and simultaneously keeping the RH level below 65% (Section 2.5.2). An evidence of natural ventilation was found at the north-west zone of the building (Section 8.6.3). However, this was not fully utilised as a strategy of building cooling during all season.

8.7. Spot Measurements and Predicted PMV

8.7.1. Assessment of data based on assumed thermal comfort

The impact of seasonal variations can be explicitly observed in AT and RH values of this case study building (Table 8-4). For example, mean value of indoor AT were 27°C, 32°C and 30.4°C while the mean values of outdoor AT were recorded 20.8°C, 32.9 and 28.6°C during the cool-dry, hot-dry and warm-humid seasons respectively. Mean values of MRT are high (32.7°C) during the hot-dry and warm-humid season.

Table 8-4: Seasonal variations of the spot measured data* for the *RMG factory 2*

Season	Value type	AT (°C)	GT (°C)	RH (%)	Air speed (m/s)	WBGT (°C)	MRT (°C)	OT (°C)**	AT_{out} (°C)	RH_{out} (%)
Cool-dry	Mean	27.0	26.8	60.0	0.3	23.1	26.7	26.9	20.8	73.5
	SD	1.4	1.6	5.6	0.3	2.2	2.0	1.6	3.6	13.0
Hot-dry	Mean	32.0	32.0	64.9	0.3	28.1	31.9	32.0	32.9	60.2
	SD	1.0	1.0	5.8	0.3	1.0	1.1	1.0	1.8	6.4
Warm-humid	Mean	30.4	31.6	79.6	0.3	28.7	32.7	31.3	28.6	91.3
	SD	0.7	1.4	3.4	0.1	0.6	2.2	1.2	1.9	9.3

**During working hours only (i.e. from 08:00 to 19:00); **same as Table 7-4; ***same as Table 7-4*

Figure 8-30 represents the frequency of average AT, RH and average air speed recorded at workers' personal workstations in the production sections during the questionnaire surveys. From this figure, it can be observed that the AT ranges of 26-28°C, 31-33°C and 30-31°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Among these data range, the SS and FS tended to exhibit higher AT range during all seasons. During the hot-dry and warm-humid seasons, the measured AT and RH ranges also slightly exceeded the comfortable AT and RH ranges (general and moderated), as assumed in Section 2.5.2.

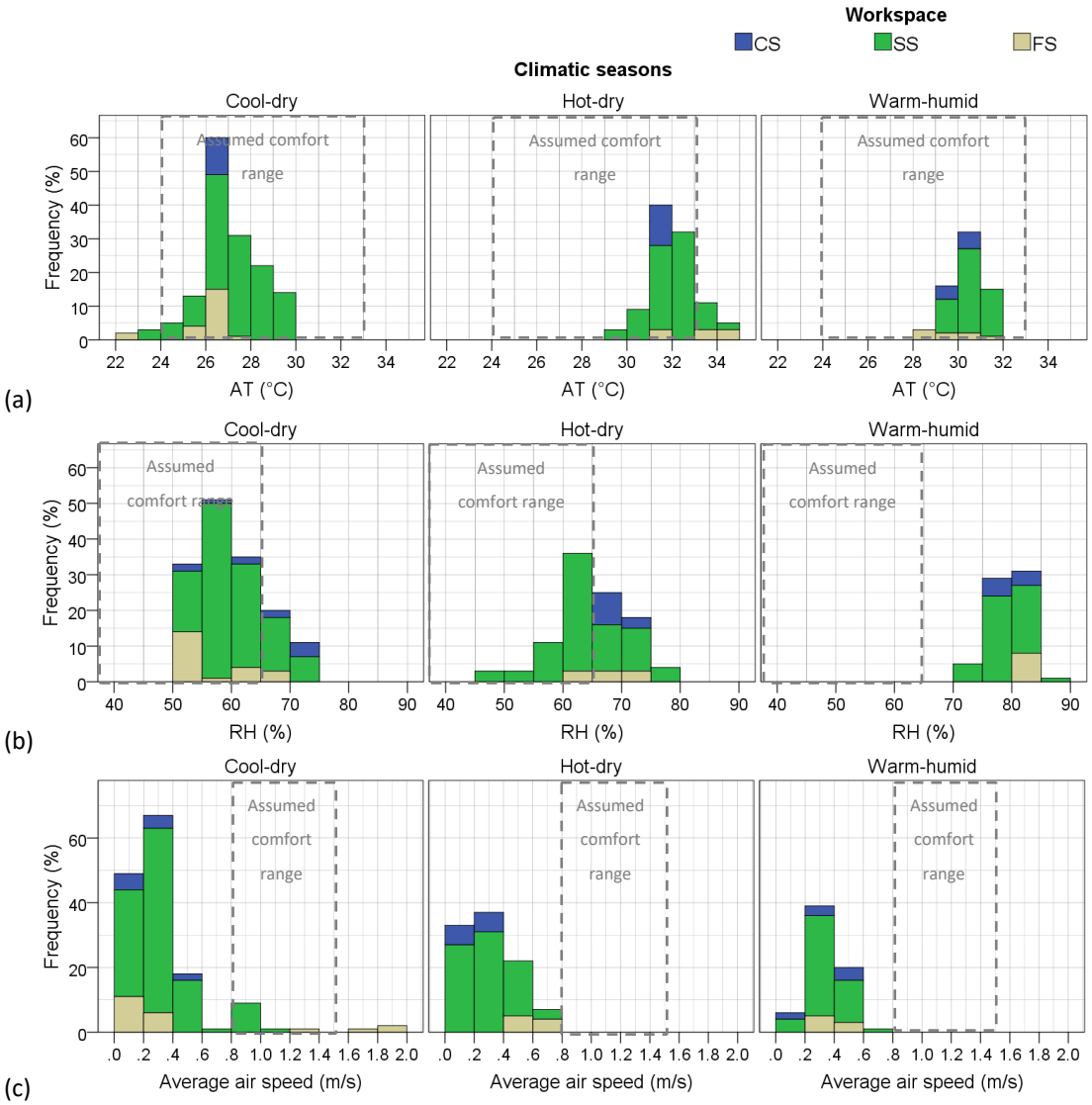


Figure 8-30: Frequency of spot measured AT, RH and average air speed and assumed thermal comfort ranges at workers' personal workstation in *RMG factory 2* (source: field studies, year 2015)

Figure 8-30(c) reveals that the approximate air speeds ranging of 0-0.4 m/s, 0-0.6 m/s and 0.2-0.6 m/s were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Only less than 10% of air speeds in the SS were within the comfort range and this suggests that the workers in the rest of the production spaces were more likely to experience an uncomfortable thermal environment throughout the year due to the low air speed. This can be prevented by ensuring comfortable range of AT and increasing air speed.

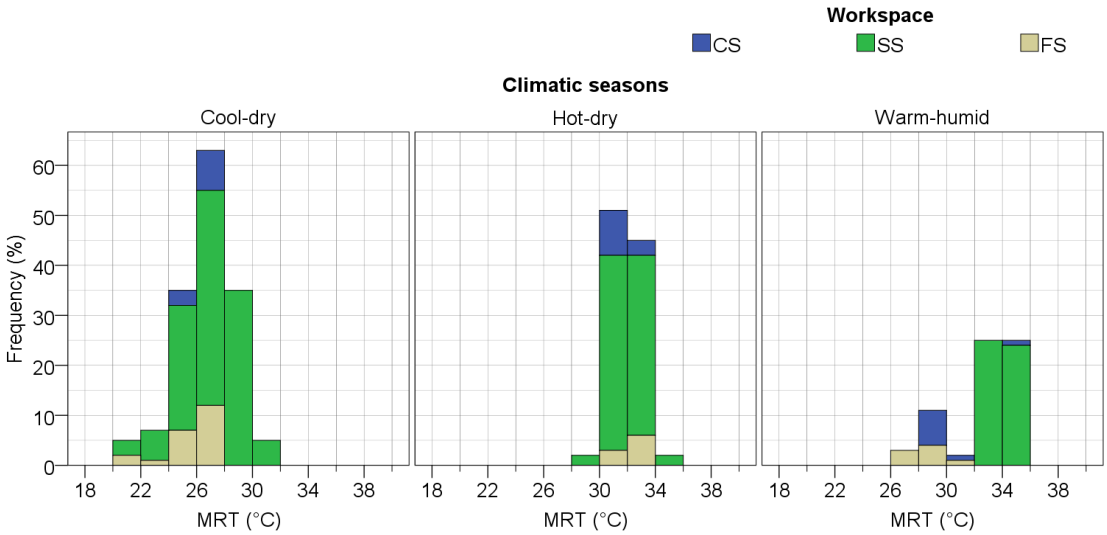


Figure 8-31: Frequency of spot measured MRT at workstations in *RMG factory 2* (source: field studies, year 2015)

Figure 8-31 shows that the estimated MRT ranges of 26-28°C, 30-34°C and 32-36°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Apart from the CS during the cool dry season, workers in the SS and FS tended to experience higher MRT range during all seasons. Table 8-4 and Figure 8-31 suggest that it would the major challenge to ensure thermal comfort at their workstations during the warm-humid season due to simultaneously high RH and low air speeds.

8.7.2. Prediction of PMV

Figure 8-32 indicates that 263 of workstations studied (i.e. 83% of the total 316 working locations) were outside of ASHRAE comfort zone with an average PMV of 1.33 over the three field studies (i.e. three climatic seasons). This gives an insight into the wider ranges of thermal condition during the cool-dry and hot-dry seasons compared to those during the warm-humid season.

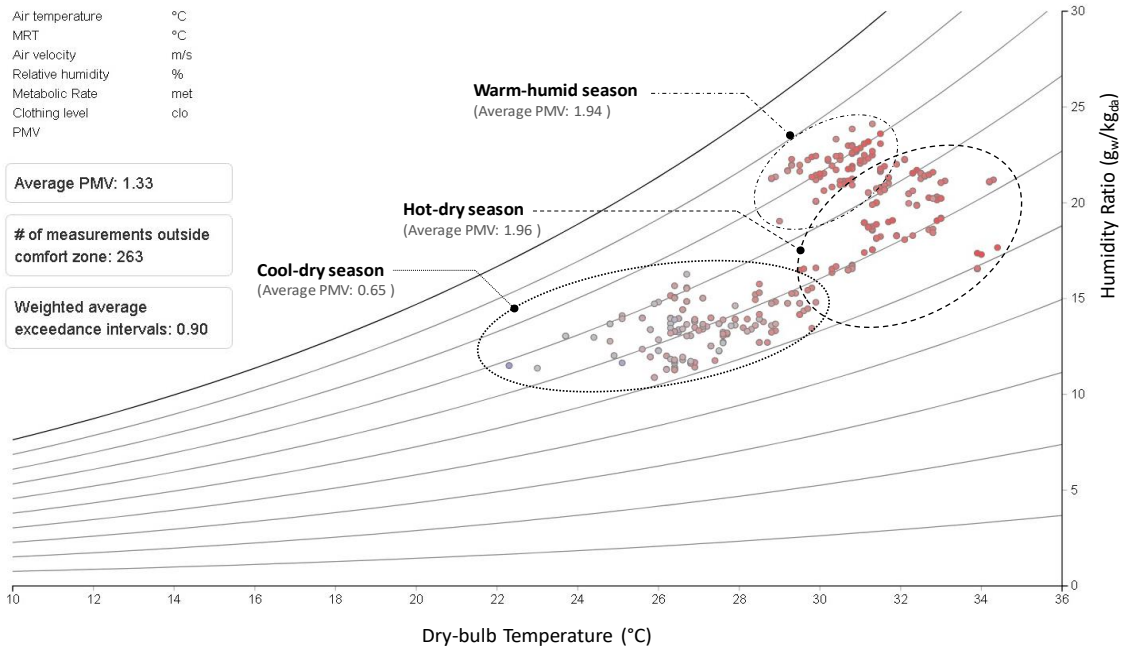


Figure 8-32: Prediction of thermal comfort vote and visualisation of measured data using a psychrometric chart (source: CBE thermal comfort tool 2013)

The results of this section are useful in serving as a reference for comparison with the actual comfort vote (Sections 8.8.1 and 10.4.1).

8.8. Workers' Subjective Feedback

8.8.1. Results from questionnaire surveys

Figure 8-33 provides histograms (frequency of ASHRAE 7-scale votes in percentage) of workers' vote on their existing thermal environment in terms of thermal sensation, humidity, airflow and freshness of air. Figure 8-33(a) reveals that 65%, 42.2% and 35.2% of the workers responded with a 'neutral' vote for thermal sensation at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. Figure 8-33(b) reveals that 90%, 83% and 86.6% of the workers provided a 'perfect' response in addition to their sensation toward humidity for existing temperature at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. Similarly, Figure 8-33(c) and (d) provide their votes for air speed and freshness of air at their workstations. This indicates these representative percentage of workers felt the airflow and air quality were either favourable or poor.

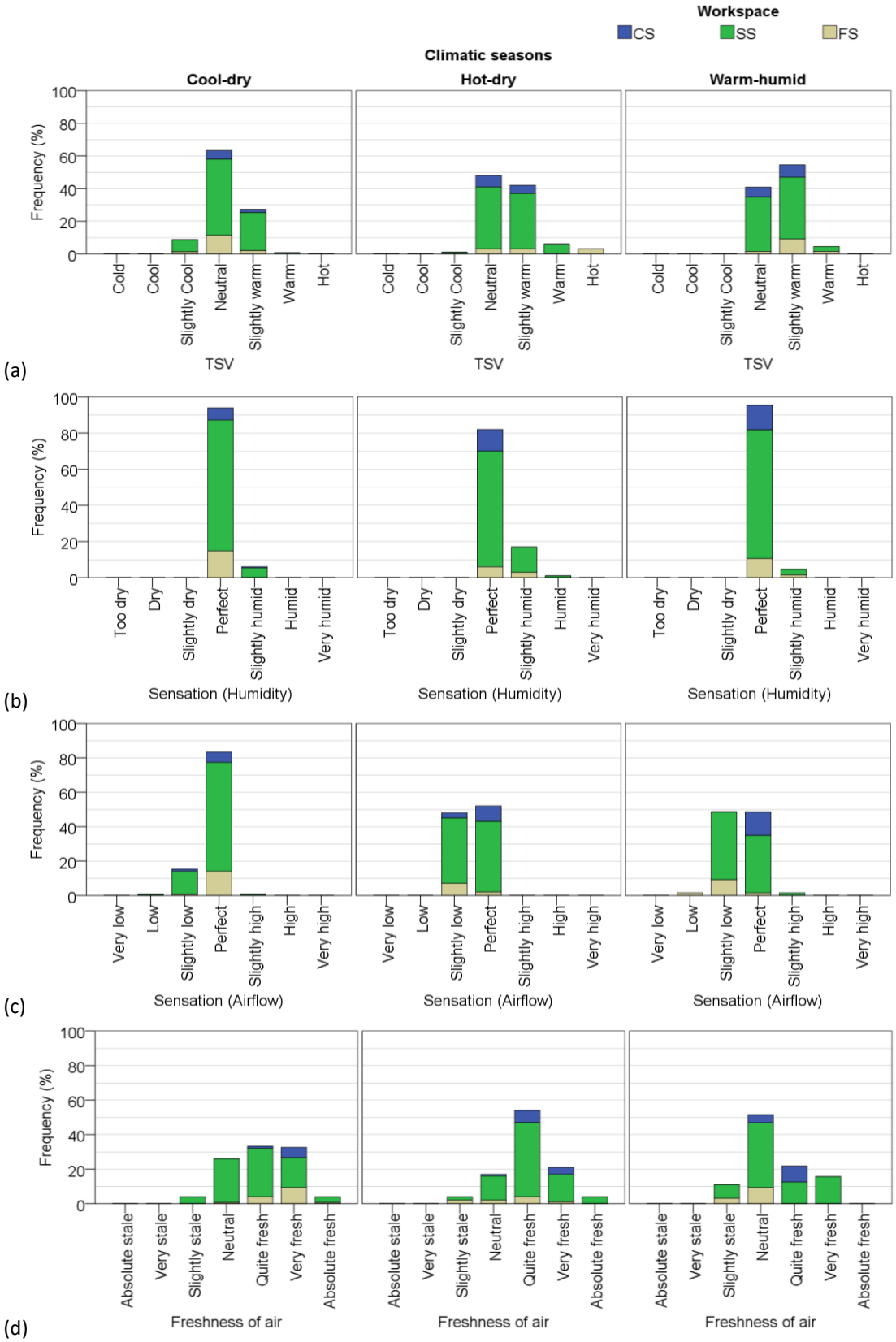


Figure 8-33: Histogram of workers' 7-scale votes on (a) Thermal sensation, (b) Humidity, (c) Airflow and (d) Freshness of air at their workstations during various seasons (source: field studies in *RMG factory 2*, year 2015)

Figure 8-34 shows workers' feedback on AT, humidity and air speed they preferred at their existing workstations. It reveals that during the cool-dry and hot-dry seasons 85% and 55.3% of workers were more satisfied with the thermal environment since they voted for 'no change'. However, only 43% votes for 'no change' were received during the warm-humid season. This also indicates that during the warm-humid season, workstations needed major improvement to reduce the high temperature. Figure 8-34(b) represents that the workers also accepted the humid environment recorded during this season (Figure 8-30). However, looking at the pattern of responses for each in isolation suggests that the combined effect remains are of discomfort. Comparing this with Figure 8-35, it clearly indicates all the workspaces did not meet the standard acceptability requirement (80-90%) during the warm-humid season.

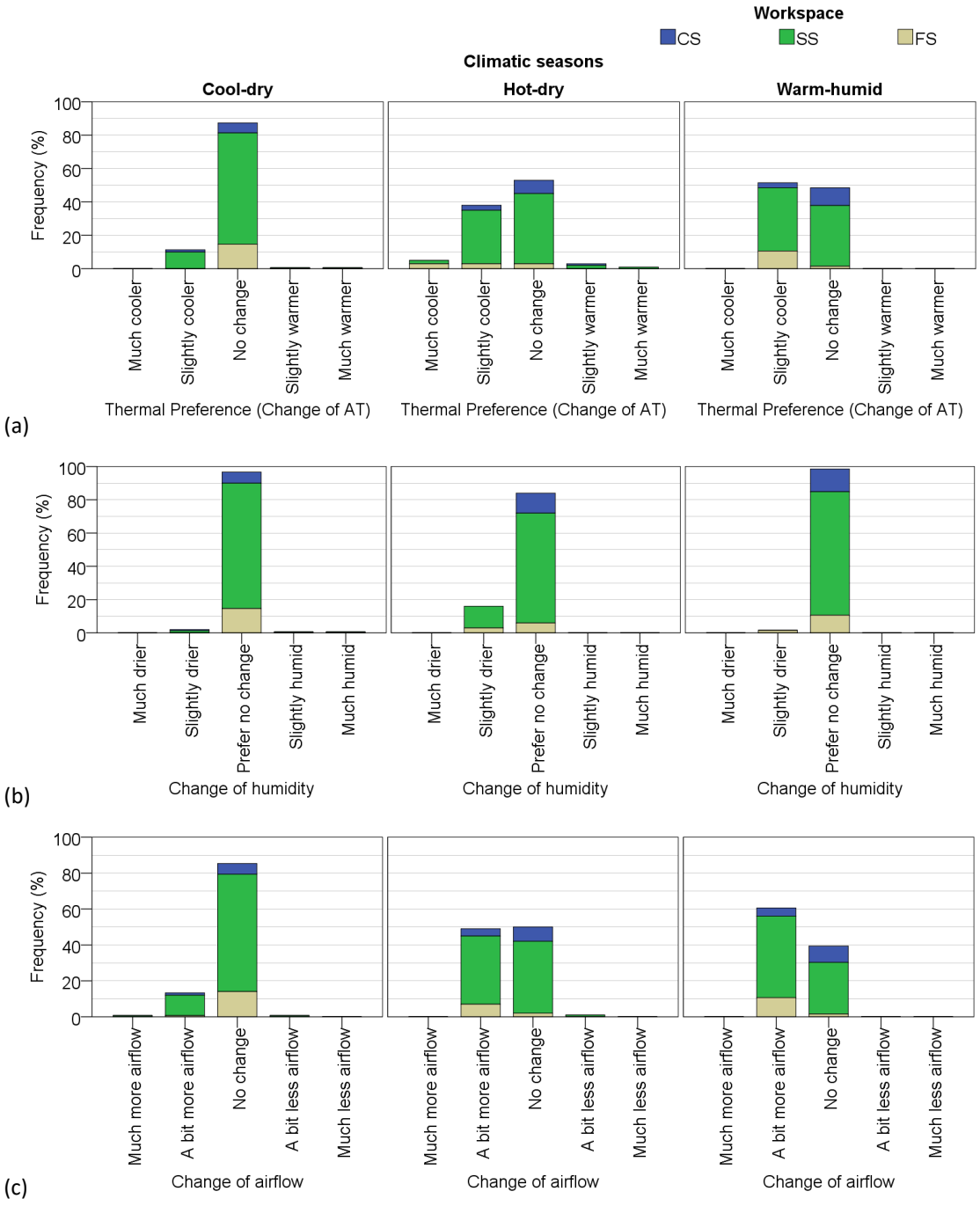


Figure 8-34: Histogram of workers' 5-scale votes on preferences to changes of (a) Temperature, (b) Humidity and (c) Air flow at their workstations during various seasons (source: field studies in *RMG factory 2*, year 2015)

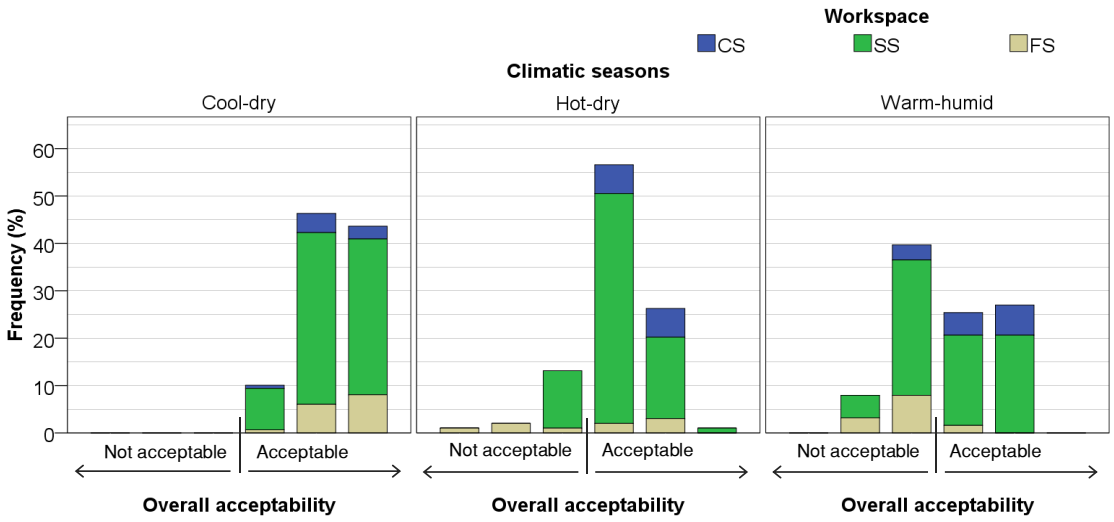


Figure 8-35: Histogram of workers' votes on overall acceptability of their existing thermal environment during various seasons (source: field studies in *RMG factory 2*, year 2015)

Comparing workers' quantitative votes on their thermal environment with spot measurements (Table 8-4 and Figure 8-31), it can be observed that high indoor MRT is the main issue during the hot-dry and warm-humid seasons (mean MRTs were 31.9°C and 32.7°C respectively). Moreover, the mismatches between predicted votes (Figure 8-32) and actual votes (Figure 8-33) suggest workers may be habituated to their thermal environment (further explained in Chapter 10).

8.8.2. Results from focus group discussions

Tables 8-5 and 8-6 provides summary of workers' feedback from two focus group discussions in *RMG factory 2*. The workers from both groups mainly suffer from thermal discomfort, particularly inside the SS and FS, during the hot-dry and warm-humid seasons. High airspeed near extract fans and direct solar radiation from the west facades were highlighted as the major issues for the workers whose workstations were located near extract fans or windows. On the other hand, workers whose workstations remote from windows preferred to be located near windows and wanted an extended control over the fans and windows.

Table 8-5: Summary of the workers' perception and adaptive measures from two focus groups

Season	Group	Perception and issues within their existing ventilation strategy and thermal experience	Adaptive measures to resolve the issues and ensure their thermal comfort
Cool-dry	one	- They feel slightly cold during 8am-10am and after 5pm if the ceiling fans are running. - Ceiling fans remain switched off and windows are kept shut until 10am. From 10am to 5pm, fans are turned on and they feel cold due to high airspeed resulting in working faster.	- When they feel cold, they shut the windows and switch of the extract fans. - They have full control on ceiling fans. - They drink water or take break if they feel hot.
	two	- They start feeling a bit warm after 10am. - Since they have the partial control on their ceiling fans, they feel overall comfortable during this season. - After lunch break, they feel hot and tired.	- Taking a break, reducing their work-speed and standing near window are the common measures. - Worker from the CS have the flexibility to change their position around a table.
Hot dry	one	- They feel hot until 10am and comfortable after 5pm. They feel uncomfortable and tired near lunch time. - They feel very hot near windows on the west façade due to the direct solar radiations and absence of curtains.	- Drinking a lot of water, going to fresh room to splash water on their body are the common adaptive behaviours. - Using curtain is a common practice for protection from direct solar radiation.
	two	- They feel comfortable in the morning. However, they feel uncomfortable during the rest of the day and during power-cuts. - They feel tired and anxious around lunch hours.	- Wearing thin cotton dresses, taking a break from their work, standing near windows, drinking saline water, splashing water on their body are the common adaptive measures.
Warm humid	one	- They always feel very hot and humid. - They feel comfortable when the window glazing are cool during the rains. They prefer swing windows than sliding windows. - Worker from the FS always feel humid and tired.	- Drinking cold and saline water, taking extra break from work and frequently splashing water on their body are the common measures.
	two	- They always feel humid. Particularly, they feel very hot and humid when they have to turn off the fans for sorting and sewing small pieces of fabrics. Body sweating also disrupt their activity. - They only feel comfortable when it rains.	- Taking a break, taking a shower, drinking cold and saline water and splashing cold water on their bodies are the common measures.

Table 8-6: Workers' overall feedback on expected improvement

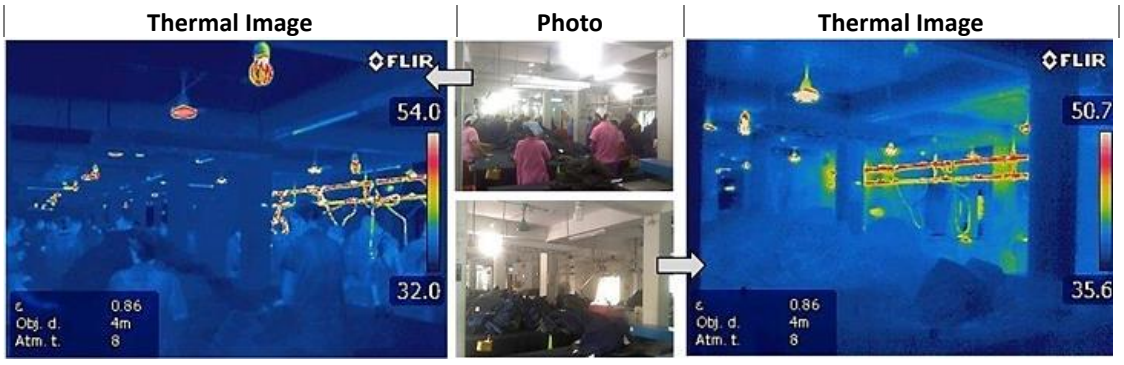
Group one	Group two
- They prefer to be located near windows. However they want to avoid the direct solar radiations in the afternoon, especially from the west side. - They support the flexibility in changing their uniforms during the hot season. - They suggested to increase extract fans in a safe distance from their workstations.	- They all prefer to have their workstations located near windows and have the full control on manoeuvring personal fans and windows.

Both questionnaire surveys (Section 8.8.1) and focus group discussions provided common feedback on improving working environment during the hot-dry and warm-humid seasons by ensuring personalised control on their airflow at their workstations.

8.9. Existing Issues and Proposed Improvements

8.9.1. Ventilation strategy during unoccupied hours

Results from the data logging (Section 8.6) reveal that the outdoor AT was cooler dropping by up to 11°C during night time (Figure 8-19). During the warm-humid season, the deviation in AT between indoors and outdoors within the day was up to 5°C. It was also found that at night, when external AT was sufficiently low to provide passive cooling of the building fabric, the windows were closed, and the fans remained switched off.



Before lunch break (at 12:00 on 17 Aug 2015) During lunch break (at 13:30 on 17 Aug 2015)

Figure 8-36: Surface temperature profile of the FS (*RMG factory 2*) before and during lunch break

Thermal images such as those shown in Figure 8-36 indicated that the surface temperatures inside the production floors either increased or remained within the same range in the absence of the active ventilation during unoccupied hours (i.e. lunch breaks). For instance, the recorded STs of the workstations and machinery in the FS of *RMG factory 2* building recorded a maximum of 50.7°C during the unoccupied hours and 54.0°C during occupied hours. The extract fans do not operate, and ventilation do not take place in these workspaces during the unoccupied hours (i.e. night time and in the weekend). Therefore, the NTV strategies, described in Section 7.9.1, can be an improvement measure.

8.9.2. Effect of size and operation of the inlet-windows

Workers reported that workstations located near windows were perceived as thermally comfortable. However, they also experienced draughts which cause disruptions to their work. They also preferred the horizontal swing windows as they have more control on manoeuvring the window panes. Whereas, for sliding window, they can only either open it or close it. Inlet-windows were also found located too close to ventilation outlets (Figure 8-37) bringing stale air. Moreover, this figure also shows that workers experience direct solar radiation through windows on the West side.

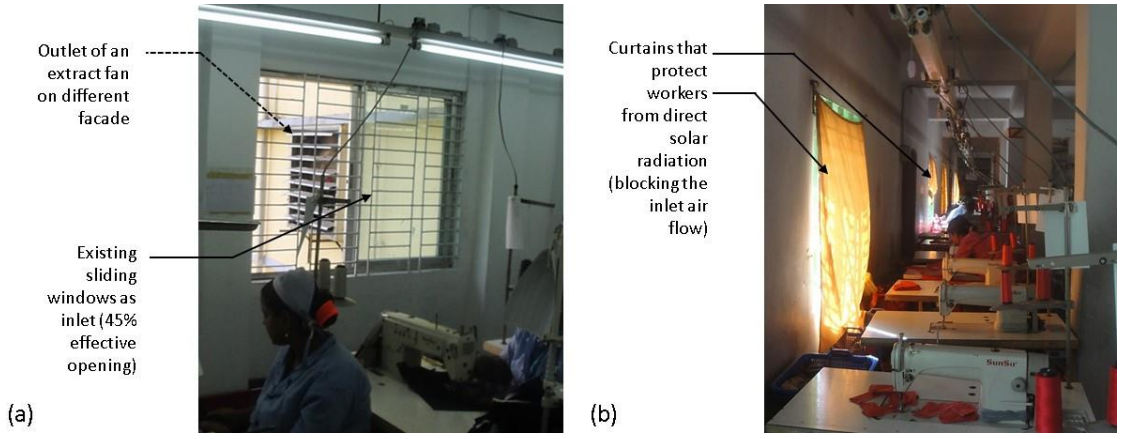


Figure 8-37: (a) Sliding windows as ventilation inlets which is too close to another outlet and (b) curtains to protect workers from direct solar radiations which also blocks air flow from outdoor

As referred in the Sections 3.7.2 and 7.9.2, there was scope to explore the design configuration and location of inlet-windows of this case study building to improve thermal comfort.

8.9.3. Efficiency of equipment and passive ventilation

The daily electrical energy demand in production spaces of *RMG factory 2* (shown in Appendix G) reveals that up to 292 KWh, 203 KWh, 114 KWh and 3807 KWh of the electrical energy are consumed per day by existing lights, extract fans, ceiling fans and other production equipment respectively. The annual expenditure for consuming electricity and running fuel-generators during power cuts are approximately US$40200 and US$15000 respectively. When combined with the high internal heat gain from the equipment in this case study building (Section 8.4.3), there is a case for exploring whether increasing equipment efficiency can reduce the high temperature issue.

Considering the 10m wide workspaces of this case study building, stack induced passive ventilation through solar chimney (Section 3.5.1) or night-time ventilation through shafts can be an intermediate intervention (Ford, 2010), without the need of using mechanical extract fans, to tackle high energy demand as well as improve indoor thermal conditions.

8.9.4. Functional layout and segmentation

From spot measurements, it was found that the highest AT was experienced in the SS and FS during all seasons. The location of the spots with low air speed and high AT were investigated by the researcher and were found near the 'ironing work-zone' of the SS and FS, which locally increased the AT due to high heat output of the equipment (Section 8.4.3). Appendix H-2 shows the zones categorised by the researcher to show that these hot zones with its functional layout were not considered while designing the ventilation system from inlets of the building to outlet.

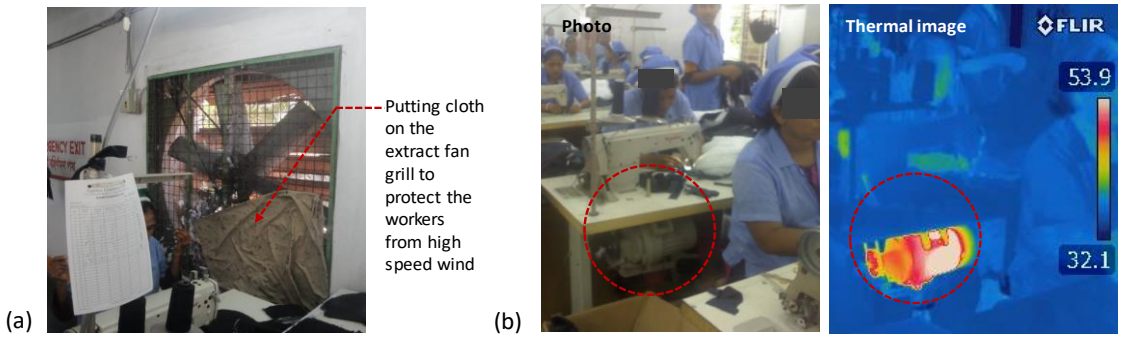


Figure 8-38: Workstations located (a) too close to extract fans and (b) next to heat radiating equipment (source: field studies in *RMG factory 2*, year 2015)

Figure 8-38 provides onsite evidence showing how workers spontaneously use fabric to protect themselves from high airspeed induced by extract fans and how they are exposed to high heat radiating equipment near them. Hence, the function layout should be rearranged and segmentation of spaces should be provided.

8.9.5. Personalised control for occupants

From focus group discussions (Section 8.8.2), it was found that workers prefer full personalised control over the air velocity at their workstations. Figure 8-39 reveals that the workstations remote from the inlets were subject to high (up to 31°C) mean AT and were unlikely to get mean airflow above 0.2m/s.

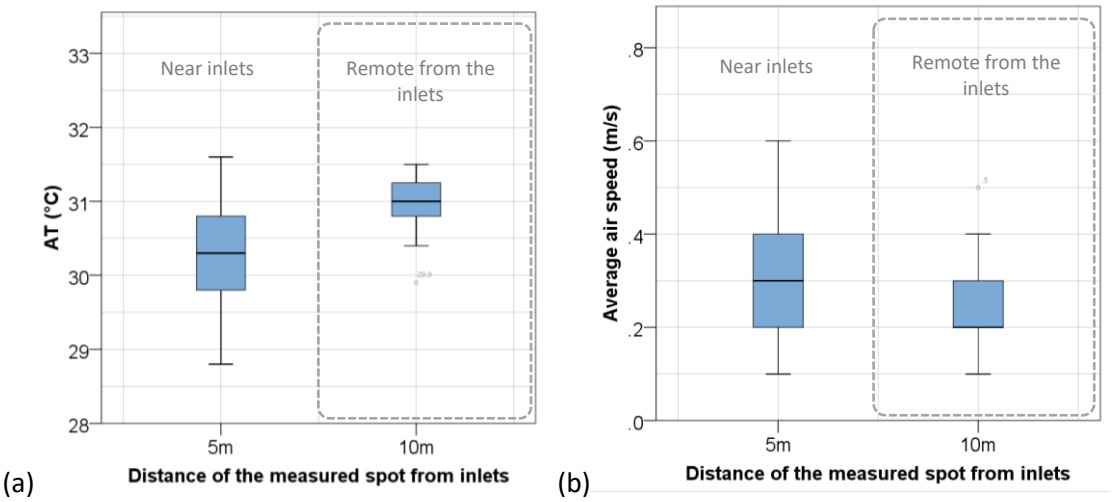


Figure 8-39: Ranges of spot measured (a) air temperature and (b) average air speed in terms of the distance of the spot from inlets (source: field study during the warm-humid season, year 2015)

These results suggest that enhancing the airflows to the workstations by installing more personal fans and extending workers' personalised control over the ventilation and comfort strategy might improve the overall thermal comfort of the workers.

8.9.6. Construction materials and thermal mass

Figure 8-40 provides an evidence of the effect of incident solar radiation on the 125mm external wall and the window located at the west façade of this building resulting in high indoor ST (up to 40.2°C).



Figure 8-40: Surface temperature ranges of existing 125mm thick external wall and a window with glass pane and metal frame as a result of incident solar radiation (source: field study, year 2015)

Considering Table 8-2, there could be provisions to make treatment to the building facades, glazing elements and roof surfaces with materials of low U-values, high thermal mass and to extend the shading elements and in so doing, the overall thermal performance of the building could be improved.

8.10. Summary

This chapter aimed to present field investigation including environmental conditions of workspaces and issues related to workers' thermal comfort of the 2nd case study building (*RMG factory 2*) and to propose a range of design solutions to improve these issues. The key findings of this chapter are as follows:

- The outdoor climate data and thermal images recorded from field studies indicated high amount of heat gain during sunshine hours and the presence of relatively low ranges of outdoor AT during nigh time of all seasons.
- Due to constrained active ventilation and operation of windows bounded to working hours, the indoor air and surface temperature of workstations remained hot during unoccupied hours in all three climatic seasons.
- Results from on-site spot measurement as well as workers' response study suggested that it would a major challenge to ensure thermal comfort at their workstations during the warm-humid season due to simultaneous presence of high AT and RH, and low air speed.
- Full day ventilation including operation during night time and weekends was proposed as a key design strategy to improve existing working.
- Configuration and location of the inlet-windows need further improvement.
- Changing the factory's existing equipment with lower heat generating models would not only improve the indoor thermal environment but also save annual expenditure on energy.
- Passive stack ventilation and solar chimney could couple with existing ventilation strategy, since the building has the potentiality of natural cross ventilation, particularly during night time.
- Changing the existing functional layout and improving personalised control over airflow at workstations could improve the overall thermal experience.
- Refurbishing the existing building materials with low U-values and high thermal masses may reduce external conductive heat gain during day time and accentuate night time cooling.

The next chapter (Chapter 9) will provide results from the field studies of *RMG factory 3*.

CHAPTER 9. FIELD STUDIES: *RMG FACTORY 3*

This chapter presents the results from the field studies conducted in the third case study building, *RMG factory 3*. Similar to previous two chapters, exiting issues of thermal environment and a number of improvement strategies are proposed at the end of the chapter.

CHAPTER 9. FIELD STUDIES: *RMG FACTORY 3*

9.1. Introduction

Similar to previous two chapters (Chapters 7 and 8), this chapter focuses on the third case study building *RMG factory 3*, one of the three case study buildings of this research (Section 5.5.2).

9.2. Chapter Aim and Scope

The aim and scope of the chapter is same as shown in Section 7.2. Based on the methodologies applied for the field studies (Section 5.5), the preliminary observations, assumptions and field results are provided in the Sections 9.3 – 9.9.

9.3. Site and Micro-climate

RMG factory 3 is a 9 storey building located within the Dhaka region, 12km away from the Dhaka meteorological weather station. The total site area is 8000m^2 and the building footprint is 2100m^2. Figure 9-1 shows the footprint of the case study building with its site and surroundings.

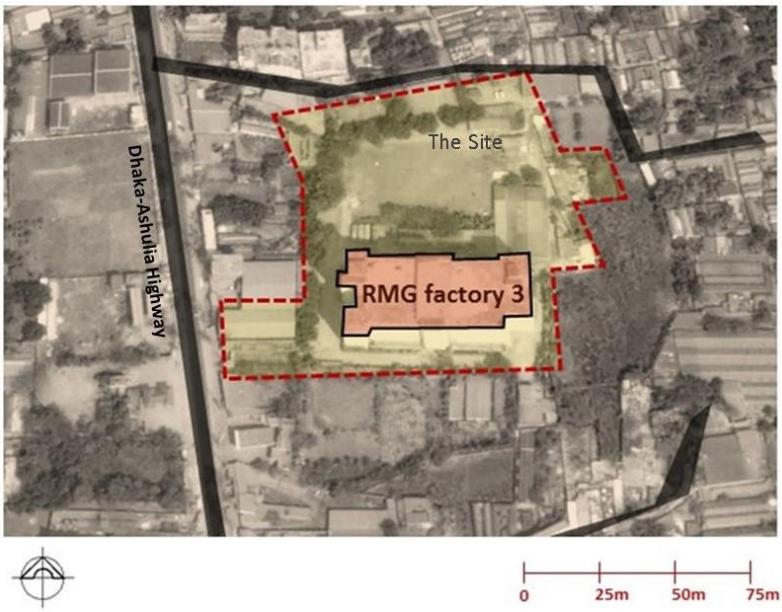


Figure 9-1: The case study building: *RMG factory 3* within its site area (source: Google Map)

The Meteorological data and relevant weather information of the Dhaka region are same as described in Section 7.3. Figure 9-2 illustrates the outdoor AT and RH during the three field studies. It can be observed that the outdoor ATs varied by season

ranging 13-33°C, 22-36°C and 25-35°C during the cool-dry, hot dry and warm-humid seasons respectively. Outdoor RHs also varied ranging 28-82%, 40-99% and 68-100% during the cool-dry, hot dry and warm-humid seasons respectively.

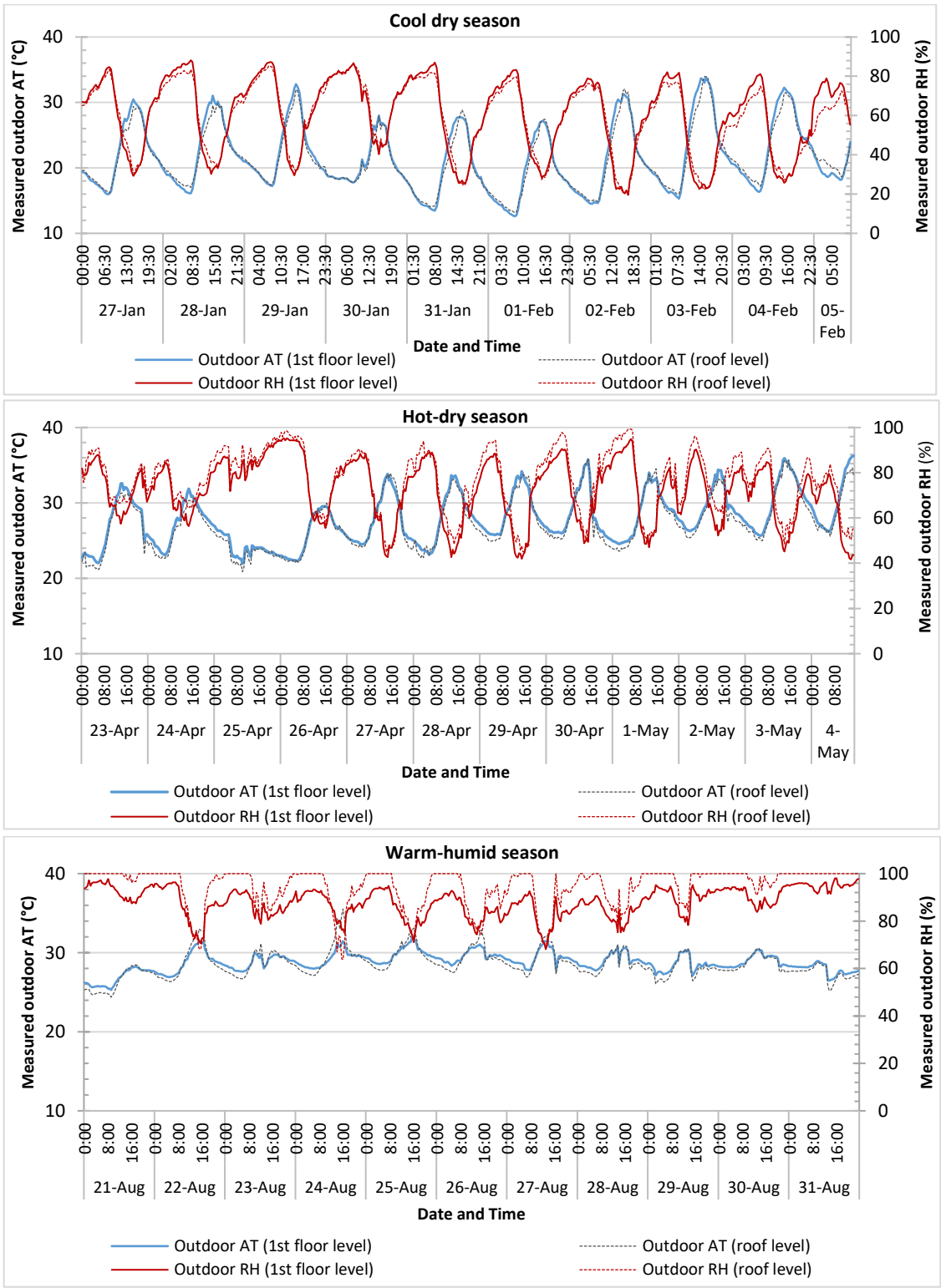


Figure 9-2: Micro-climate data representing days during each season (Source: field study, year 2015)

Comparing data set presented in Figures 7-2 and 9-2, it can be observed that the data recorded from the field and the meteorological department are similar. However the other external factors, such as open green area next to the building might have affected the local outdoor AT and RH. Figure 9-2, also reveal that there are diurnal variations of around 14°C, 11°C and 5°C during the cool-dry, hot-dry and warm-humid seasons. A difference of up to 20% in RH can be observed between outdoor RH on the 1st floor and roof level.

Figure 9-3 illustrates the annual sun-path diagrams and wind-rose shown relative to the case study building on site. It reveals that the north building façades remain mostly shaded over the year and that the south, east and west facades are exposed to sun for longer periods of a year. This figure also indicates that winter winds from the north or north-west direction and summer wind from the south and south-east represent the sources of prevailing wind for the building.

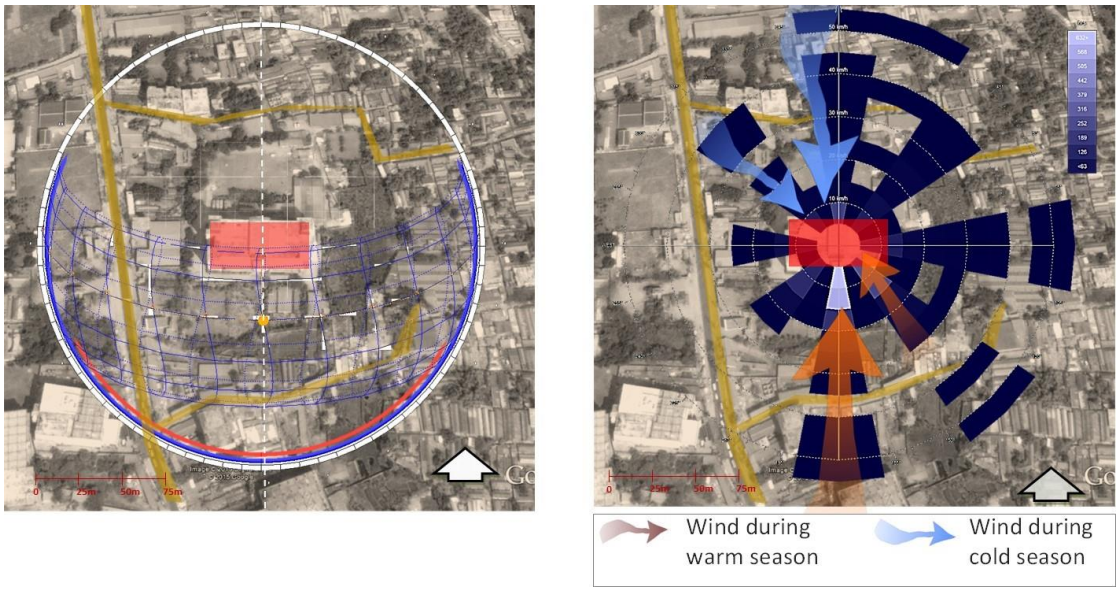


Figure 9-3: Sun-path diagram and wind-rose (source: Google Maps, author's 3D modelling and Ecotect Analysis 2011)

Figure 9-4 shows the shadow pattern at different times of day for the summer solstice, equinox and winter solstice. The north side of the building is subject to self-shading during all seasons. The south, east and west façades are subject to incident solar radiation. Figure 9-5 represents the morphological context of *RMG factory 3*. The building is sited in a semi-urban environment where adjacent buildings are industrial and remotely located. This figure indicates that prevailing winds should not experience

any major obstruction from north and south sides of the building. Hence, the major issue is the incident solar radiations on and round the building (Section 3.4.1).

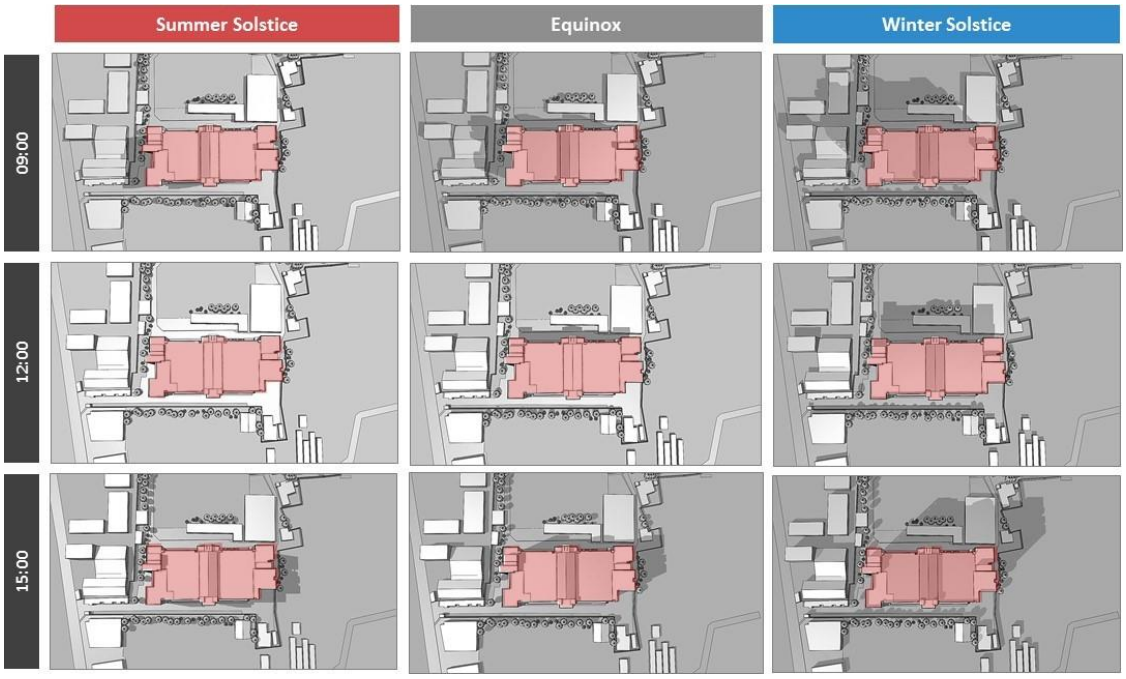


Figure 9-4: Shadow analysis of the *RMG factory 3* (source: Google Maps and author's 3D modelling in IES-VE 2017)

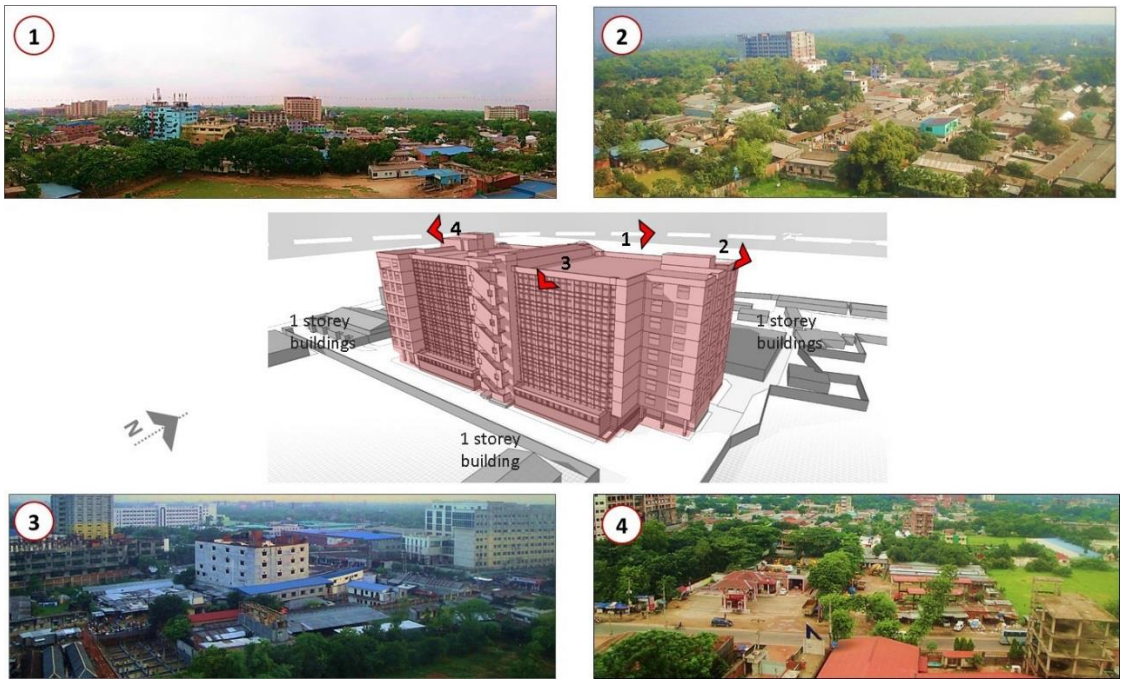
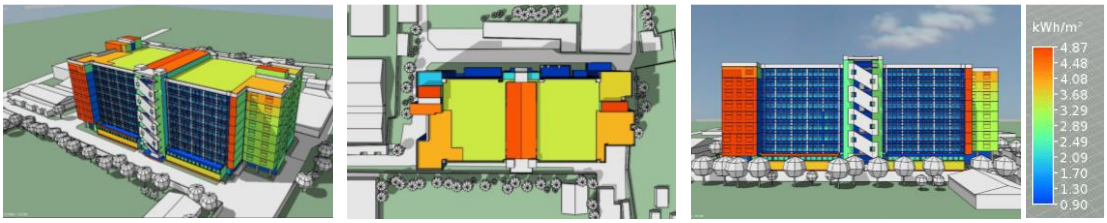


Figure 9-5: Morphological context of the case study building (source: author-generated 3D models and photographs)

Figures 9-6 and 9-7 show estimated distribution of incident solar radiation and field measured ST on all façades on a same day of the year 2015. Figure 9-6 reveals that roof gets the highest incident solar radiation (4.8KWh/m^2) on the day, while the south and west sides receives up to 2.8KWh/m^2 radiation. Hence, workspaces facing the south side and located on the top floor likely to receive solar and conductive heat gain. Figure 9-7 reveals that the west reached maximum surface temperature of up to 43.8°C after 3pm on 22 August 2015. Glazing on all façades affected the temperature profile.

Month	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00
Jan	-	-	2.54	14.63	25.70	35.11	41.86	44.76	43.07	37.23	28.42	17.72	5.86	-	-
Feb	-	-	4.97	17.82	29.88	40.54	48.69	52.64	51.07	44.56	34.84	23.30	10.75	-	-
Mar	-	-	10.59	24.03	36.97	48.88	58.49	63.17	60.45	51.89	40.45	27.72	14.39	0.78	-
Apr	-	4.03	17.67	31.38	44.97	58.13	69.78	75.48	69.44	57.70	44.52	30.91	17.21	3.57	-
May	-	8.60	21.89	35.42	49.09	62.78	76.21	84.73	74.03	60.51	46.81	33.15	19.65	6.42	-
Jun	-	9.45	22.42	35.69	49.17	62.79	76.48	89.34	76.02	62.33	48.72	35.24	21.98	9.03	-
Jul	-	7.62	20.68	34.04	47.60	61.28	74.97	87.39	76.95	63.27	49.59	36.01	22.61	9.50	-
Aug	-	4.91	18.40	32.07	45.77	59.30	72.03	79.83	73.12	60.56	47.07	33.37	19.70	6.18	-
Sep	-	2.48	16.18	29.74	42.90	55.10	64.78	68.23	62.93	52.43	39.92	26.64	13.03	-	-
Oct	-	-	13.10	25.91	37.81	47.97	54.81	56.24	51.65	42.77	31.54	19.07	5.94	-	-
Nov	-	-	8.51	20.47	31.24	40.02	45.61	46.75	43.11	35.65	25.69	14.21	1.82	-	-
Dec	-	-	4.27	15.96	26.47	35.12	40.89	42.72	40.17	33.83	24.80	14.05	2.21	-	-

Solar altitudes (% of exposed surfaces):



3D model with incident solar radiation | Solar radiation on roof | Solar radiation on south facade



Solar radiation on north facade | Solar radiation on east facade | Solar radiation on west facade

Figure 9-6: Distribution of Incident Solar Radiation on a clear sky day of the year (source: IES- VE solar analysis on the Equinox)

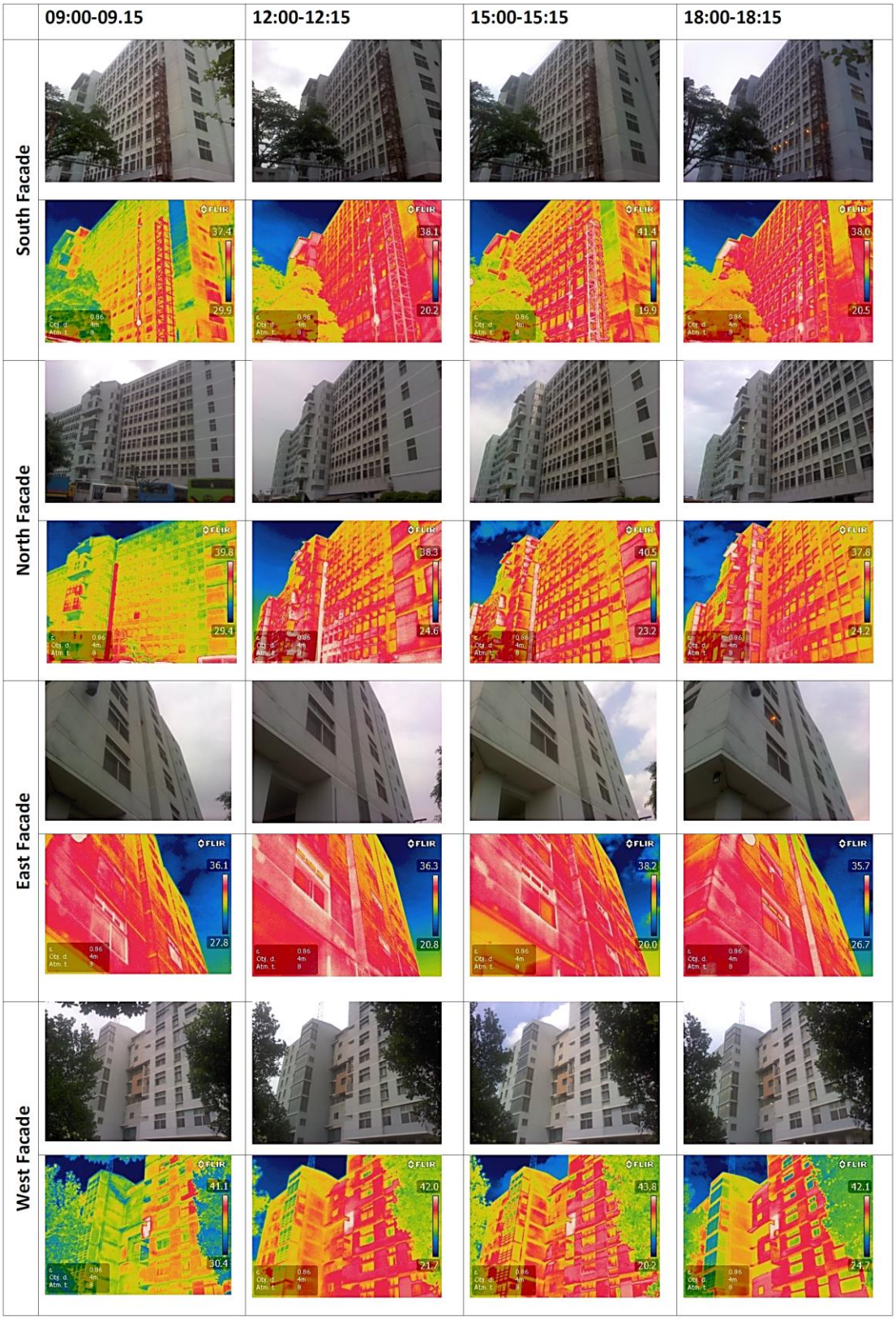


Figure 9-7: Surface temperature profile (not in same temperature scale) of all façades of *RMG factory 3* (source: field study on a partly sunny day, 22 August 2015)

Figure 9-8 provides a section through the building indicating the prevailing winds and position of the sun relative to the north and south facades.

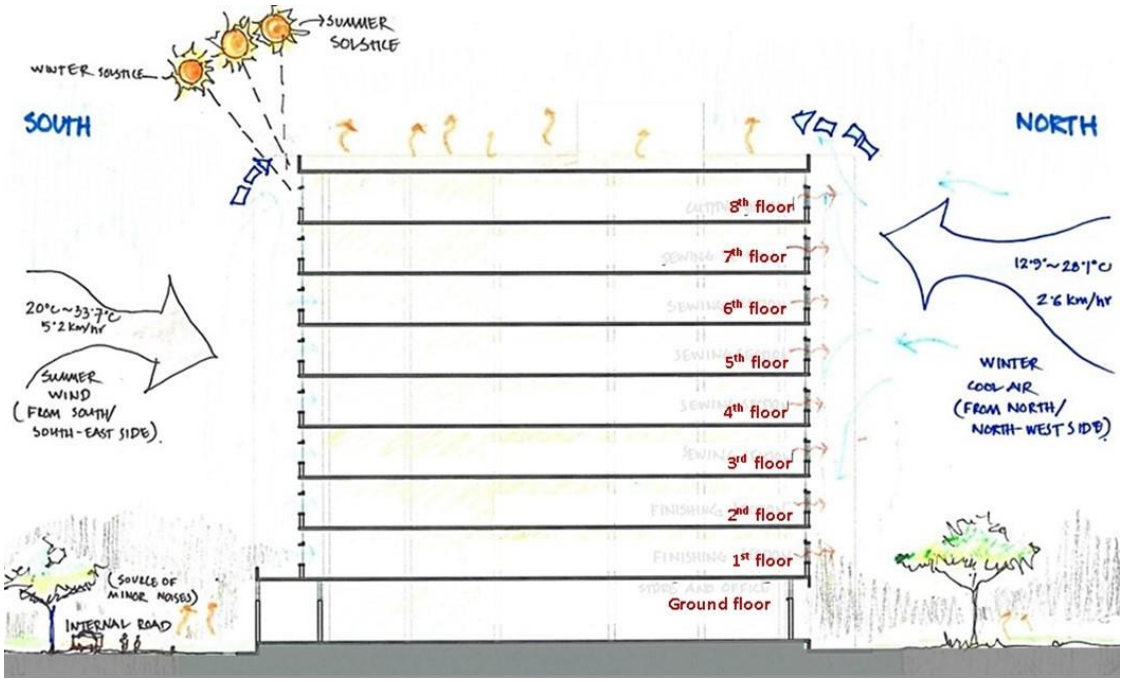


Figure 9-8: Observation of microclimate on a building section (source: author's schematic drawings)

Initial observation on the building morphology, solar exposure and predicted air regime indicate that south side of the building, roof and glazing elements are vulnerable due to incident solar radiation and solar control should be considered as a strategy to reduce external conductive heat gain.

9.4. Building Observation

9.4.1. Functional layouts and workspaces

The main production floors are located on the 1st to 8th floors (as shown in Figures 9-9 and 9-10). The entries are located on the south and north sides of the building. Other spaces are mainly for office, dining areas and storage (workflows are shown in Figure 9-10).

Panoramic views shown in Figure 9-11 represent that the density of workers is less in the CS and very high in the SS and FS. Figure 9-12 illustrates estimated density of workers per floor. On average there are 725 workers per production floor excluding the office spaces and storage areas.

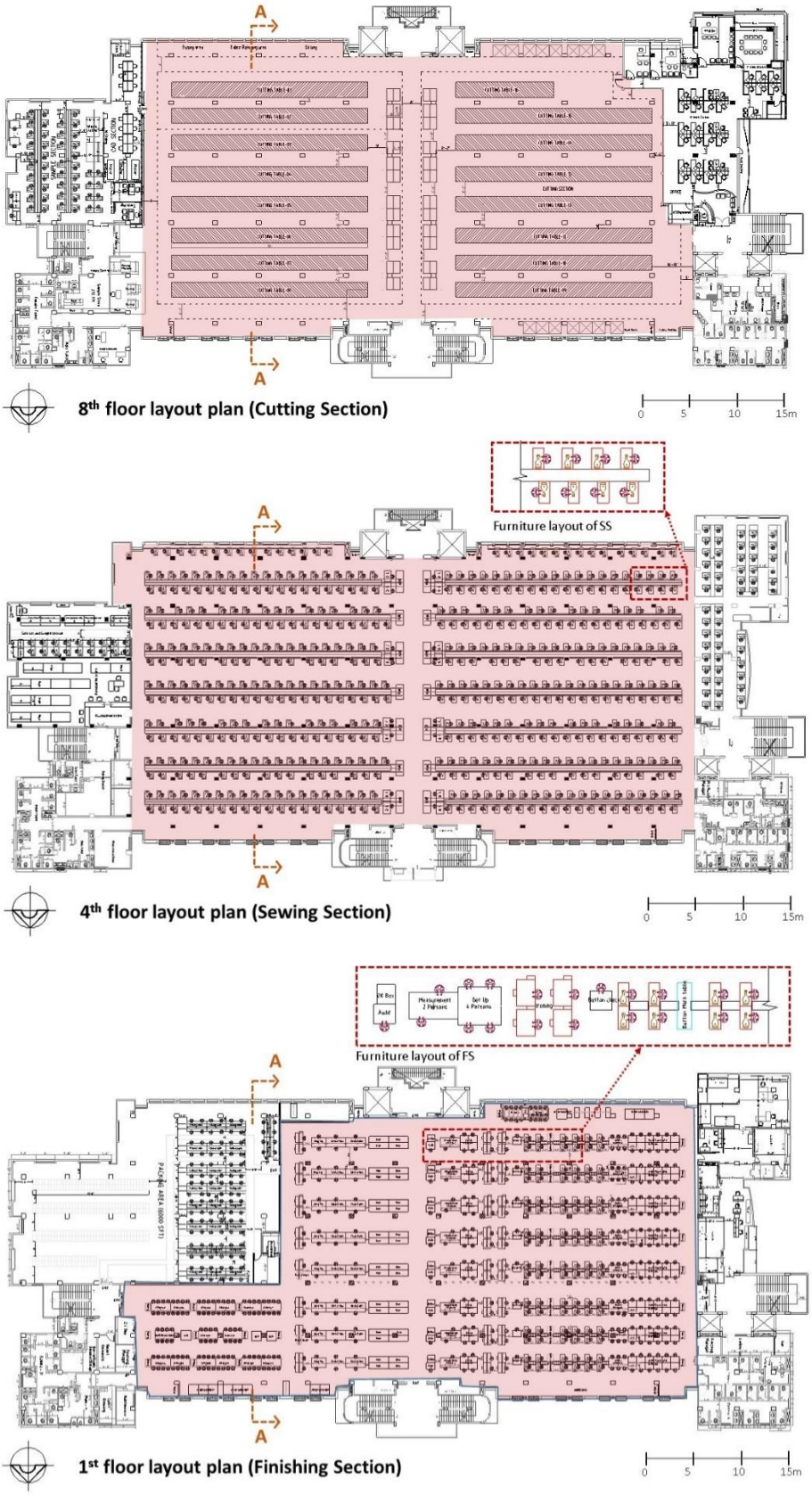


Figure 9-9: Functional layouts of key production spaces in *RMG factory 3*

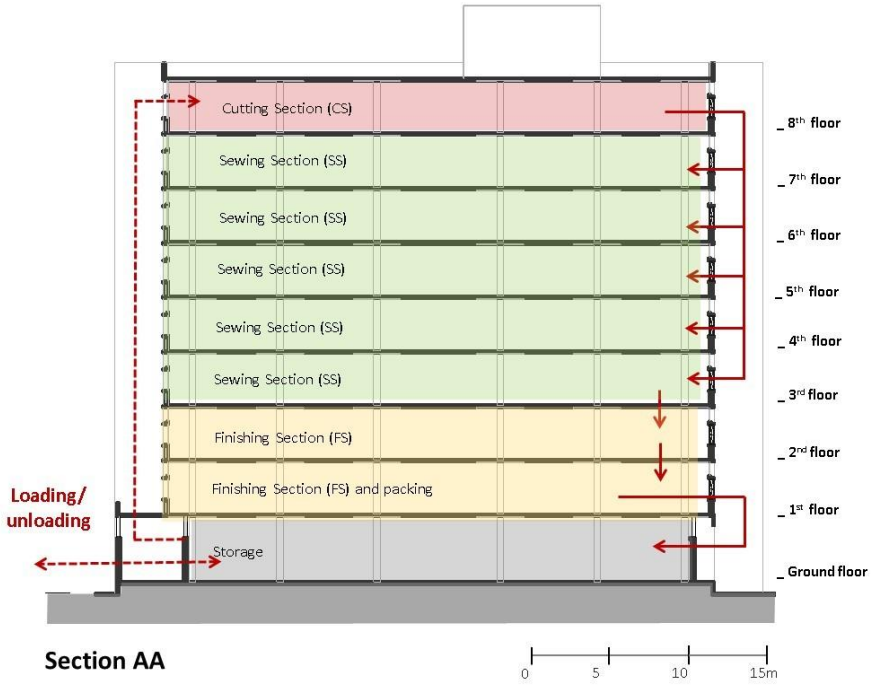


Figure 9-10: Location of the production spaces and activity flow in *RMG factory 3*



(a) CS



(b) SS



(c) FS

Figure 9-11: Panoramic views of (a) CS, (b) SS and (c) FS of *RMG factory 3*

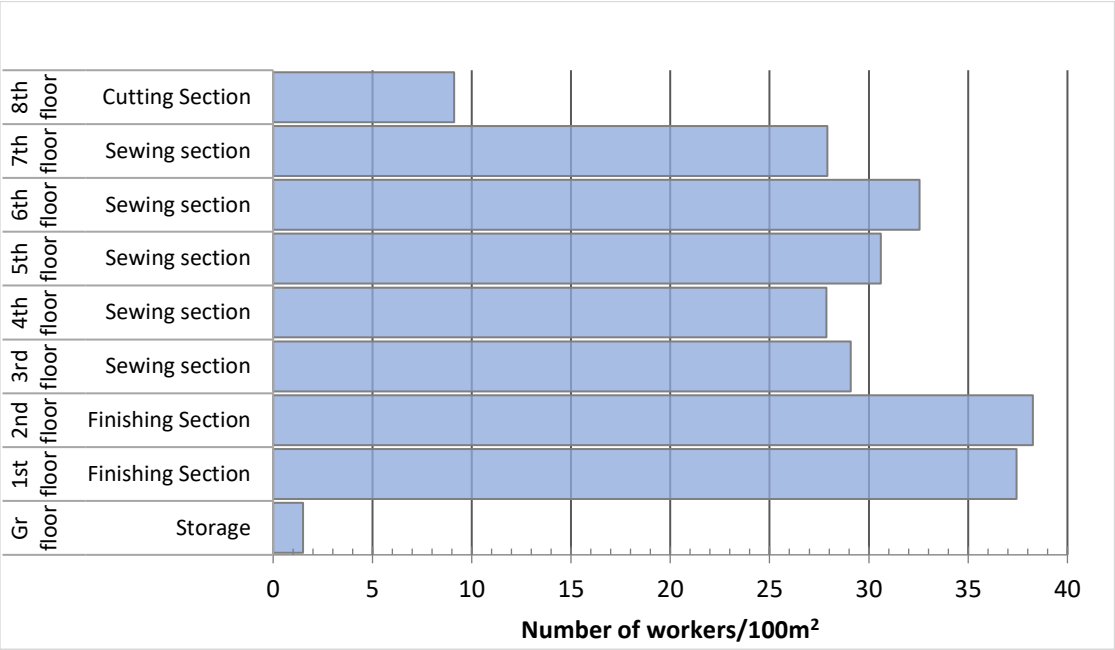
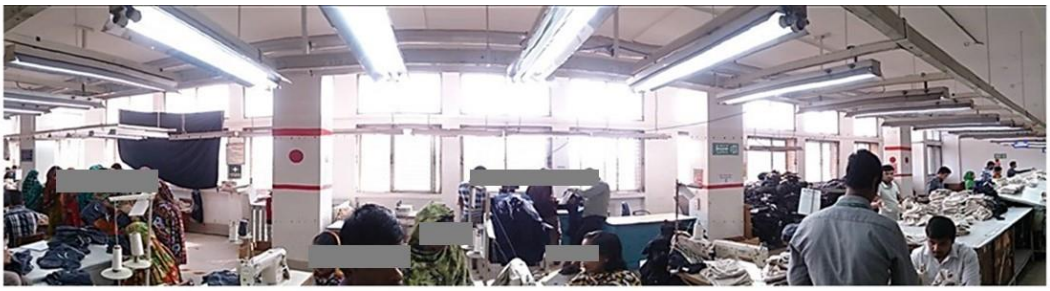


Figure 9-12: Estimated density of the workers in *RMG factory 3*

9.4.2. Existing ventilation strategy

The case study building is ventilated mainly by total 128 large (1.4m diameter) mechanically controlled extract fans placed mainly on the north facade of the building. The location of these dictates the indoor air flow regime, which was recorded as flowing from south to north direction. This active ventilation system make the windows (with 45% effective opening) and doors act as inlets that bring fresh air from immediate outdoor area. The width of the floor is 40m. Natural cross ventilation was not found to be occurred inside the production floors, as the building ceiling height to floor-plate width ratio (1:10.5) exceeds the threshold ratio (1:5), the rule of thumb cross for ventilation (Section 3.5.1). Figure 9-13 shows the south and north zones of a production floor (4^{th} floor) with inlets and outlets respectively. There is no ceiling fan in any of the production spaces.



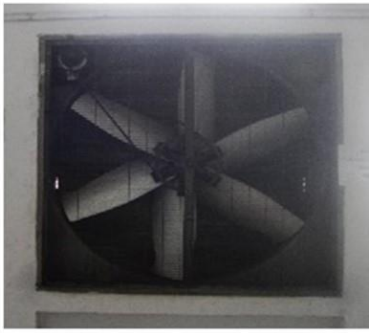
South zone of a production floor with ventilation inlets (windows)



North zone of a production floor with ventilation outlets (extract fans)



45% effective opening of windows as inlets



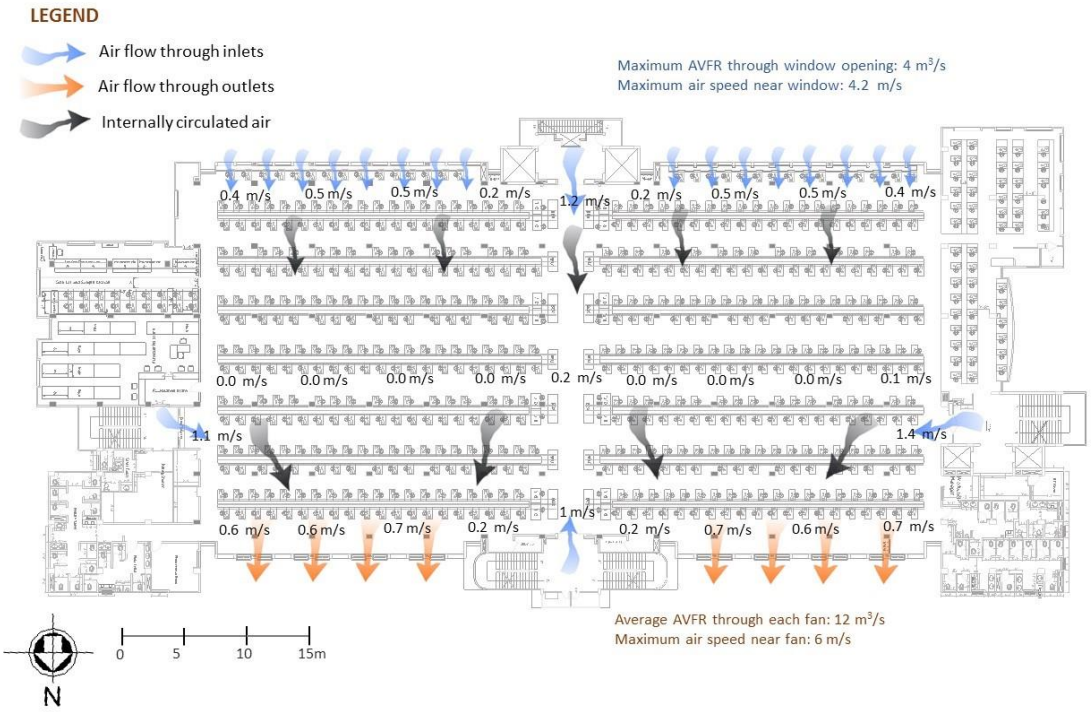
Extract fans as outlet

Figure 9-13: Existing production floors with inlet (sliding window) and outlet (extract fans) for elevated cooling

Figure 9-14 shows the 4th floor plan and the typical horizontal air flow pattern at work plane level in the 4th floor's production space (SS). Each extract fan was found to be capable of extracting air by 12 m^3/s volume flow rate (Section 5.4.5). Average air speed near these fans were recorded at 6 m/s. Average air volume flow rate at each window (45% of the openable area) was measured 4 m^3/s. Air speed through each window also found up to 4 m/s.

An approximate schedule of active ventilation (extract fans) and estimated volume flow rate (AVFR) recorded during three field surveys in the year of 2015 can be found in Appendix F-2. It was observed that the extract fans were commonly switched on at 9:00, 9:00 and 8:00 during the cool-dry, hot-dry and warm-humid seasons. No

ventilation was provided during unoccupied hours (19:00-07:00) including 24 hours of the weekend during which time all the windows were kept closed.



**There is no ceiling fan within the production spaces*

Figure 9-14: Measured air flow pattern of the 4th floor of *RMG factory 3* with the active ventilation (source: field studies in 2015)

The existing ventilation strategy of *RMG factory 3* indicated that there should be a significant difference in thermal performance of the production floors between the occupied and unoccupied hours of the factory.

9.4.3. Impact of internal heat gains

Similar to Section 7.4.3, Table 9-1 provides an overview of the sources of high gain and their STs during working hours measured on a typical day during the hot-dry season. The highest ST was observed in ironing workstations located at the ironing and fusing workstations. Given the number of equipment in the SS and FS, a significant amount of heat could be generated in the SS and FS resulting in environment with high AT (Appendix H-3).

Table 9-1: Sources of internal heat gain in RMG factory 3 with their surface temperatures (source: field studies)

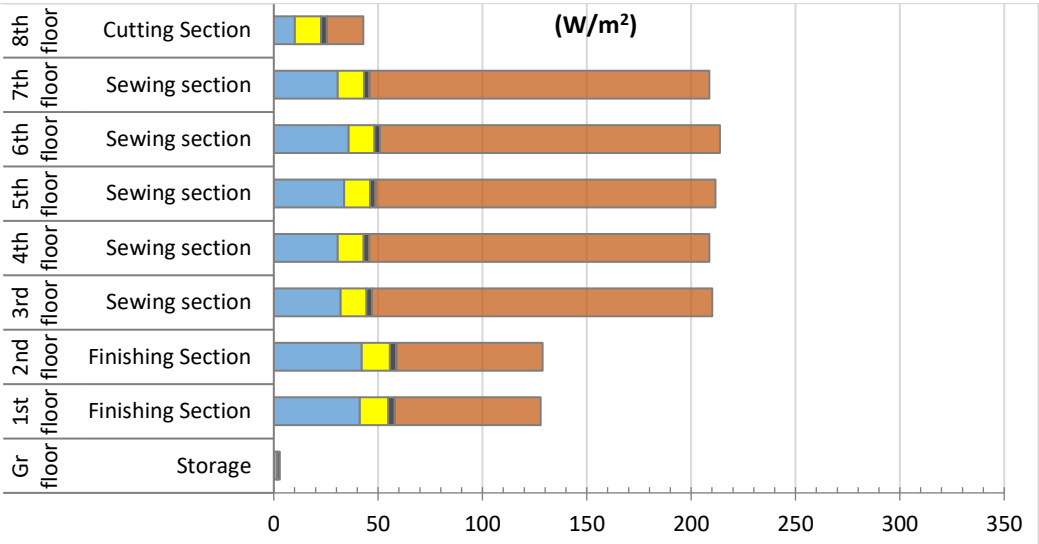


Thermal images of three production spaces (CS, SS and FS) are presented in Figure 9-15. This figure reveals that surface temperature ranges of 33.3-41.4°C, 34.4-42.3°C and 34.6-92.8°C were recorded in the CS, SS and FS respectively. This would have an effect on indoor AT and RH during working hours and might cause high temperature (Section 3.4.3).



Figure 9-15: thermal images of various production sections in RMG factory 3

Figure 9-16 illustrates internal heat gains that were for different floors of the building excluding the services and office areas (Sections 5.4.5 and 5.5.5). It reveals that the 3rd to 7th floors (SS) had the high internal heat gains up to 210 W/m^2. Field evidence from the thermal images and estimates of internal heat gain profile suggest that there is a risk high indoor temperature.



	Gr floor	1st floor	2nd floor	3rd floor	4th floor	5th floor	6th floor	7th floor	8th floor
	Storage	Finishing Section	Finishing Section	Sewing section	Sewing section	Sewing section	Sewing section	Sewing section	Cutting Section
Occupant heat gain (W/m2)	1.7	41.2	42.1	32.0	30.6	33.7	35.8	30.7	10.0
Heat gain from lights (W/m2)	0.2	13.6	13.6	12.5	12.5	12.5	12.5	12.5	12.6
Heat gain from fans (W/m2)	1.0	3.1	3.1	2.6	2.6	2.6	2.6	2.6	2.7
Heat gain from Equipment (W/m2)	0.0	70.1	70.1	163.0	163.0	163.0	163.0	163.0	17.6

Figure 9-16: Estimated internal heat gain (in W/m^2) of *RMG factory 3* building

9.4.4. Material and construction

The main construction type is RC concealed beam and column structure with concrete floor plates and 125mm thick external brick walls. Fixed and sliding windows with single glazing panes are located on the north and south facades all of which have same sill height (1.3m). The sliding windows have maximum effective opening 45%. The effective WFR is 1:55 which is not adequate for natural ventilation (Sections 2.7 and 3.5.1). The windows in the FS are protected by metal mesh reducing effectiveness of the opening.

Figure 9-17 and Table 9-2 provide an overview of the main construction materials of the case study building and reveal that it can act as a heavyweight building. The extensive area of glazing materials and 125mm external wall indicate that the building would be subject to conduction heat transfer through the building envelop including external walls (U-value of 1.52 W/m^{2}K) and glazing materials. It might result in significant external solar gain through the building envelope which could also cause high temperature inside workspace during day time.

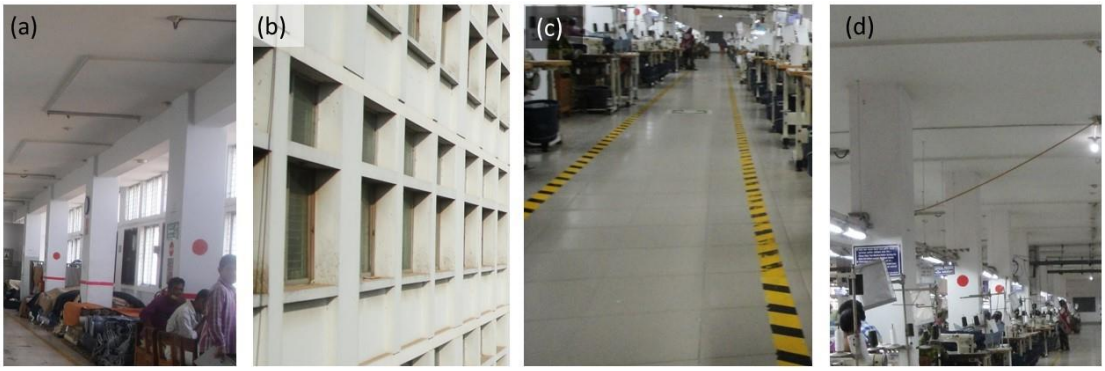


Figure 9-17: Various construction elements of *RMG factory 3*

Table 9-2: Main construction elements of *RMG factory 3* (source: author-generated based on field study)

Main construction elements	Description	Total Thickness (mm)	U-value (W/m^2K)	Thermal mass (KJ/m^2 K)	Specific heat capacity J/(kg K)
Ground floor slab	0.100m thick concrete floor with 10mm cement mortar (floor), 8mm ceramic floor tiles, 0.6m brick soling and sand filling underneath	378 *(including sand fill above the ground)*	1.81	310.0	800 (tiles) 800 (mortar on floor) 840 (concrete) 837 (brick soling) 1550 (Sand filling)
Suspended floor slab (floor/ ceiling)	0.15m thick RCC floor with 13mm thick light plaster (ceiling), 13mm cement mortar (floor) and 10mm ceramic floor tiles	180	3.224	136	800 (tiles) 800 (mortar on floor) 1000 (RC) 1000 (Fired clay)
External walls	0.1m brick work with 12.5mm medium weight plaster each side with paint	125	1.52	195.6	800 (brick work) 1000 (plaster)
Glazing with frames	Clear float 6mm glass, single glazed (G-value: 0.587, transmittance 0.78) with aluminium frames and recessed local shade	6mm	5.17 (including frame) 5.69 (glass)	-	-
Door	42mm thick steel swing doors	40mm	5.62	64.29	418.0
Local shading element (north and south facades)	0.15m thick reinforced concrete floor with 12mm thick light plaster (ceiling), 10mm cement mortar (floor) and 5mm cement coating	177	2.42	186.1	1000 (cement coating) 800 (mortar on floor) 1000 (RC) 1000 (Fired clay)
Roof slab	0.2m thick RCC with 5mm cement coating	213mm	0.698	153.4	1000 (cement coating) 1000 (RC)

9.5. Preliminary Assumptions

In addition to assumptions shown in Section 7.5, a number of assumptions can be made for further investigation (Sections 9.3 - 9.4):

- Incident solar radiations on the south façade and preheated outdoor air may affect the indoor thermal environment.
- High heat generating equipment and density of workers within the SS and FS (1st to 7th floors) may result in high temperature in these workspaces.
- Thermal comfort may also be affected due to deep floor plate, absence of ceiling fans and limitation within the extract fans control strategy.

The physical measurements and subjective field data, presented in Sections 9.6 - 9.8, will be tested considering these preliminary assumptions.

9.6. Continuously Monitored AT and RH

A comprehensive summary of continuously recorded AT and RH of the *RMG factory 3* buildings is presented in Table 9-3 in respect to the immediate outdoor thermal environment. The SDs of indoor condition did not indicate any significant fluctuation of AT (0.8-1.9°C) and RH (3.7-5.6%) compared with the variations observed in the outdoor condition. As the above observations only represent data collected over a week during each field study, this can be more explicitly visualised in Sections 0- 9.6.3.

Similar to Sections 7.6 and 8.6, the data set will be analysed for individual production sections. The recorded data from the 4th floor (SS) will then be assessed further, focusing on the horizontal and vertical profile of AT and RH produced by the different data logger sensors, the position of which are shown in Figure 5-12.

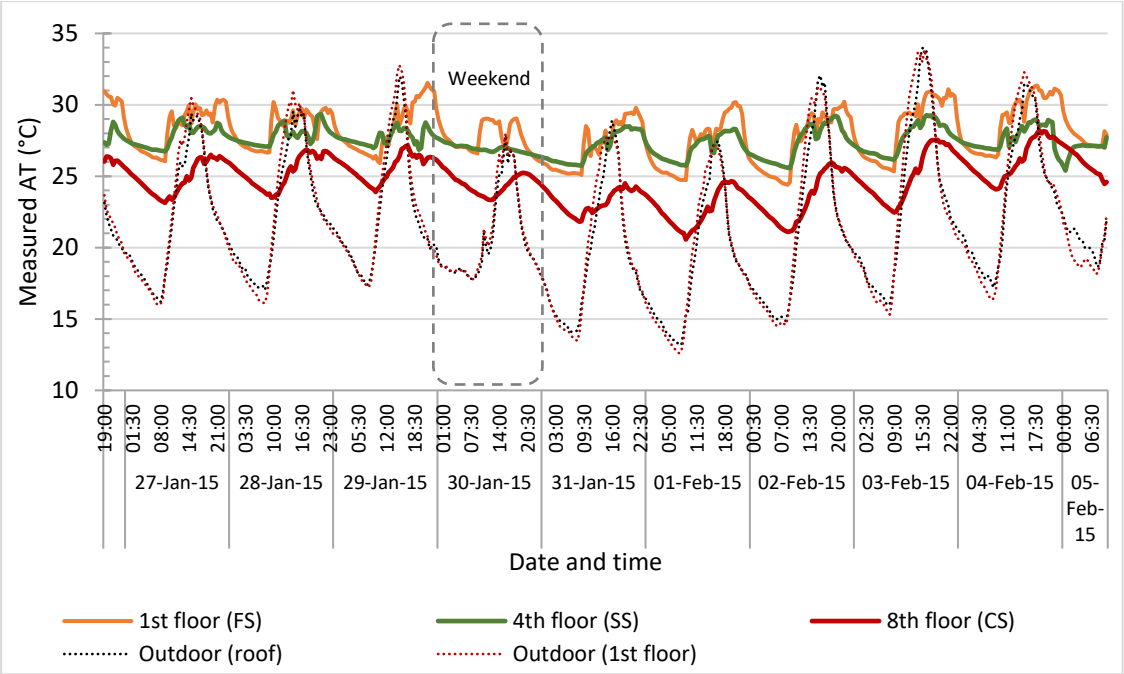
Table 9-3: Descriptive statistics of the continuously recorded indoor and outdoor environmental data (i.e. TA and RH)* in RMG factory 3 during all seasons (source: three field studies in 2015)

Season	Work section	Avg. AT_{in} (°C)		Avg. AT_{out} (°C)		Avg. RH_{in} (%)		Avg. RH_{out} (%)	
		Min - Max	Mean (SD)	Min-Max	Mean (SD)	Min - Max	Mean (SD)	Min - Max	Mean (SD)
Cool-dry	CS	20.6 - 28.2	24.7 (1.6)	13.2 - 33.9	21.4 (4.6)	30.5 - 59.4	46.6 (5.6)	20.2 - 86.3	59.0 (17.6)
	SS	21.3 - 29.3	27.4 (0.9)			31.4 - 52.4	41.5 (4.4)		
	FS	20.9 - 31.5	28.0 (1.8)			25.8 - 54.4	40.6 (5.2)		
Hot-dry	CS	25.1 - 33.8	29.7 (1.9)	20.9 - 35.9	27.4 (3.4)	51.8 - 81.9	66.0 (5.4)	45.0 - 99.3	76.5 (13.4)
	SS	26.7 - 32.8	29.9 (1.1)			52.5 - 81.6	66.1 (4.9)		
	FS	26.8 - 34.9	31.3 (1.5)			46.1 - 75.9	59.8 (5.2)		
Warm-humid	CS	26.3 - 32.0	29.8 (1.3)	24.3 - 35.5	28.4 (1.8)	65.4 - 91.9	79.4 (5.5)	63.8 - 100	95.0 (7.8)
	SS	27.2 - 31.8	30.1 (0.8)			65.8 - 88.9	79.0 (3.7)		
	FS	27.0 - 33.5	31.0 (1.0)			60.1 - 84.4	75.9 (3.9)		

**Same as Table 7-3* Figure 7-3*, ** Same as Table 7-3.*

9.6.1. Cool-dry season

Figure 9-18 reveals that the CS had a relatively low AT profile (ranging 21-27°C) while the SS and FS had higher range (up to 31°C) probably due to the high internal heat gain (Figure 9-16) from the sewing machines. As predicted in Section 9.5, the building acts as heavy-weight building and indoor spaces exhibit limited diurnal variations of AT compared with those recorded in outdoor. During the weekend and non-working hours deviations in AT that correspond to the pattern of use of the building can also be observed and the indoor ATs are unable to correspond with outdoor AT during night time. This is probably due to deep floor plate (35m) and lack of natural infiltration (i.e. windows were shut, and fans were switched off). The 8th floor tended to exhibit fluctuation of AT with the outdoor temperature as it is the top floor with the roof radiating heat during night time.



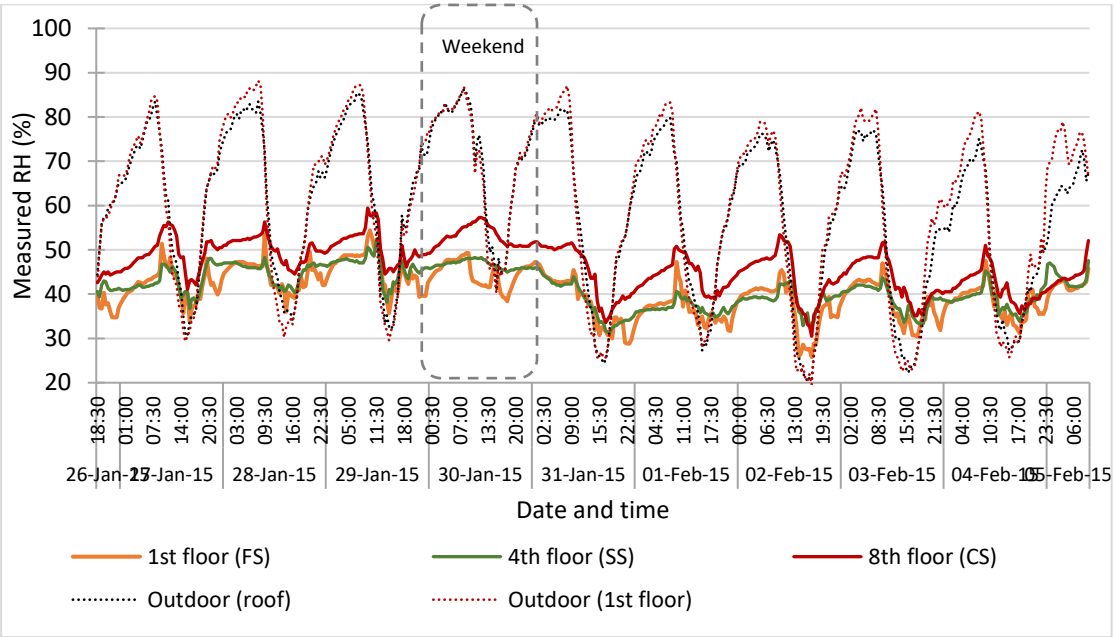
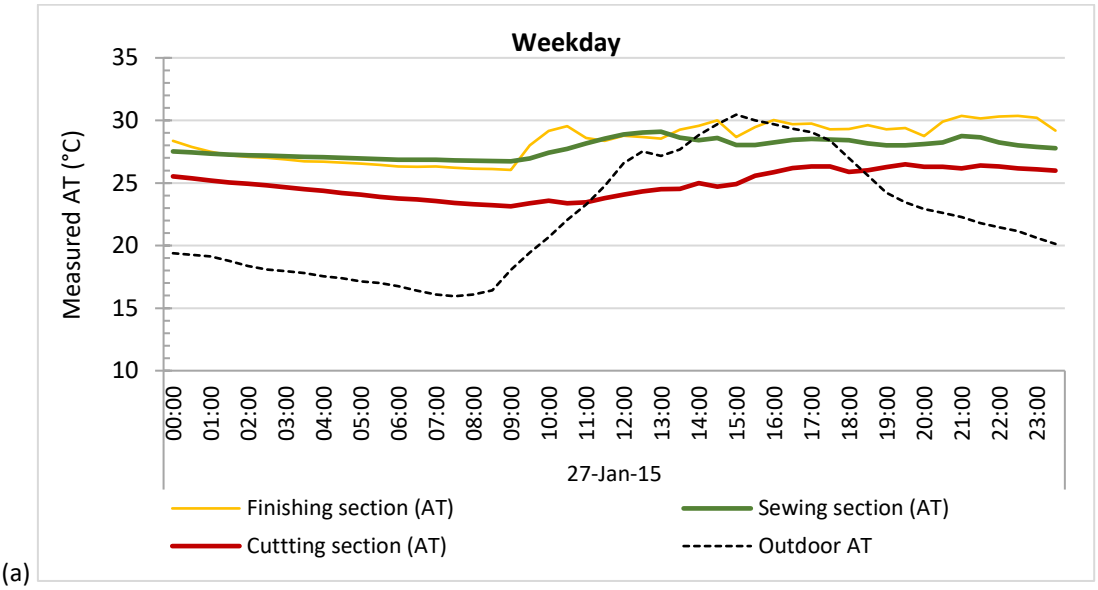


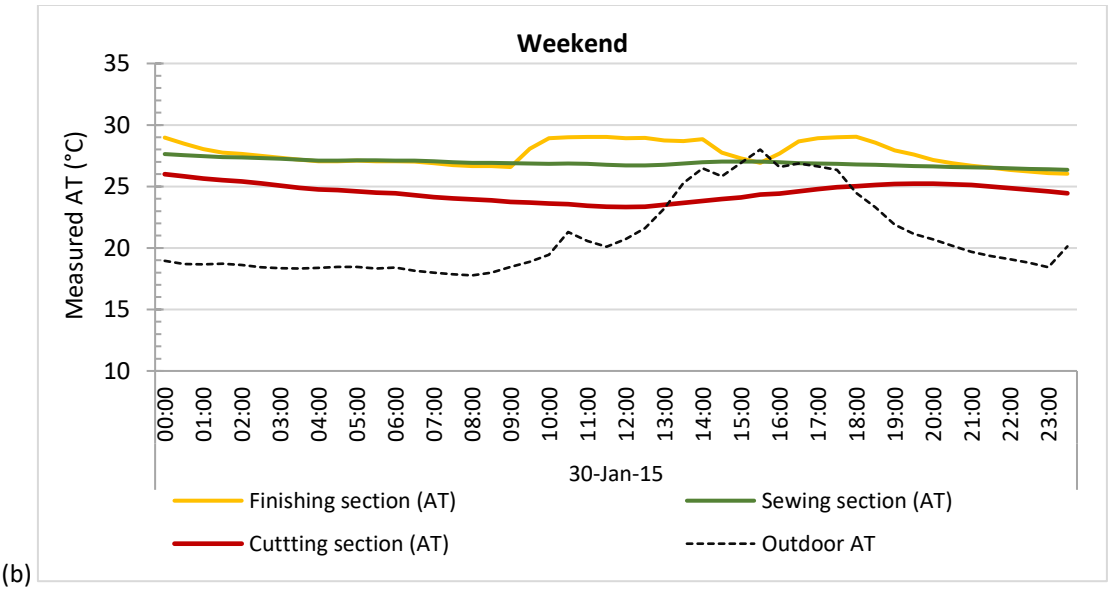
Figure 9-18: Measured AT and RH for production spaces during the cool-dry season (source: field study, year 2015)

Figure 9-19 clearly reveals that due to the internal heat gains the indoor AT was elevated from 26°C to 30°C for the weekday while in similar outdoor temperature conditions, the indoor AT was a steady (26-27°C) during the weekend. This indicates that the natural infiltration rate might be inadequate to cool down the indoor fabric including machinery and reduce the indoor AT to match low night time outdoor AT.

However, the FS still exhibited fluctuation of AT during the weekend as this production section was partially open during that weekend.



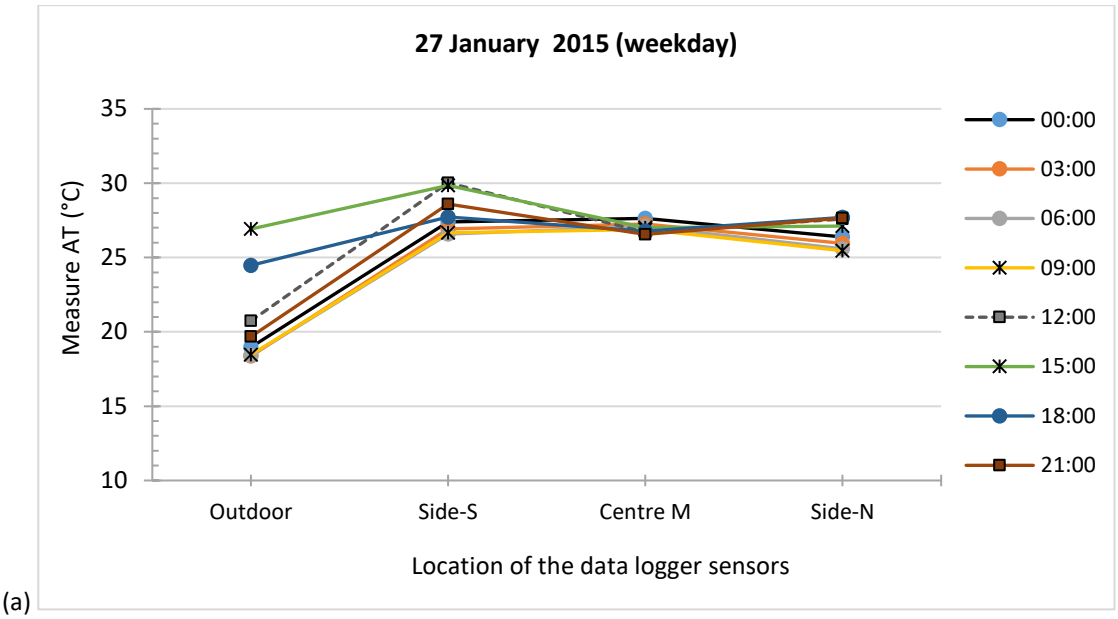
(a)



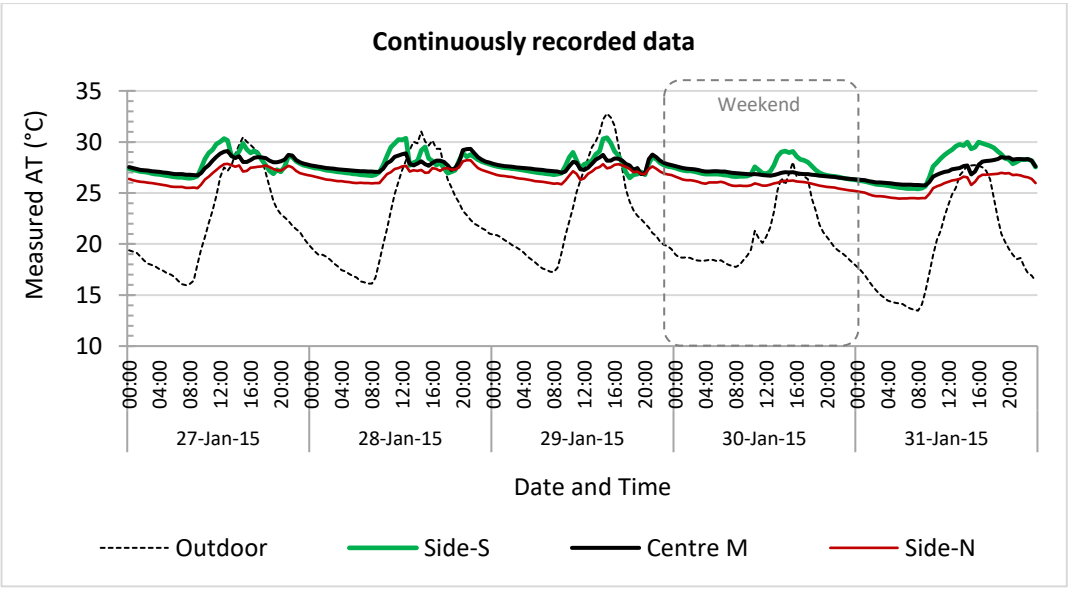
(b)

Figure 9-19: Measured AT for a typical weekday and weekend during the cool-dry season (source: field study, year 2015)

Figure 9-20 reveals that AT values in Side-S position (south zone) of the floor were at least 1-2°C higher than positions near the north side of the production floor and reached to its peak between 15:00 and 18:00 with a deviation of 3°C with the outdoor AT. It can be the effect of incident solar radiation on the south façade and glazing elements (Figure 9-8).



(a)



(b)

Figure 9-20: Measured AT profile recorded along the south to north axis of the 4th floor (SS) during the cool-dry season - (a) data for different times of day and (b) continuously recorded data

9.6.2. Hot-dry season

Figure 9-21 illustrates that the CS had relatively low AT profile (maximum 32°C) while the SS and FS had 3°C higher values (35°C) during peak hours (11:00-16:00) probably due to the high internal and external heat gains. However, during the weekend and holiday the FS and CS seemed to exhibit fluctuations of AT as these workspaces were partly open for an RMG shipment purpose and active ventilation systems were partially running.

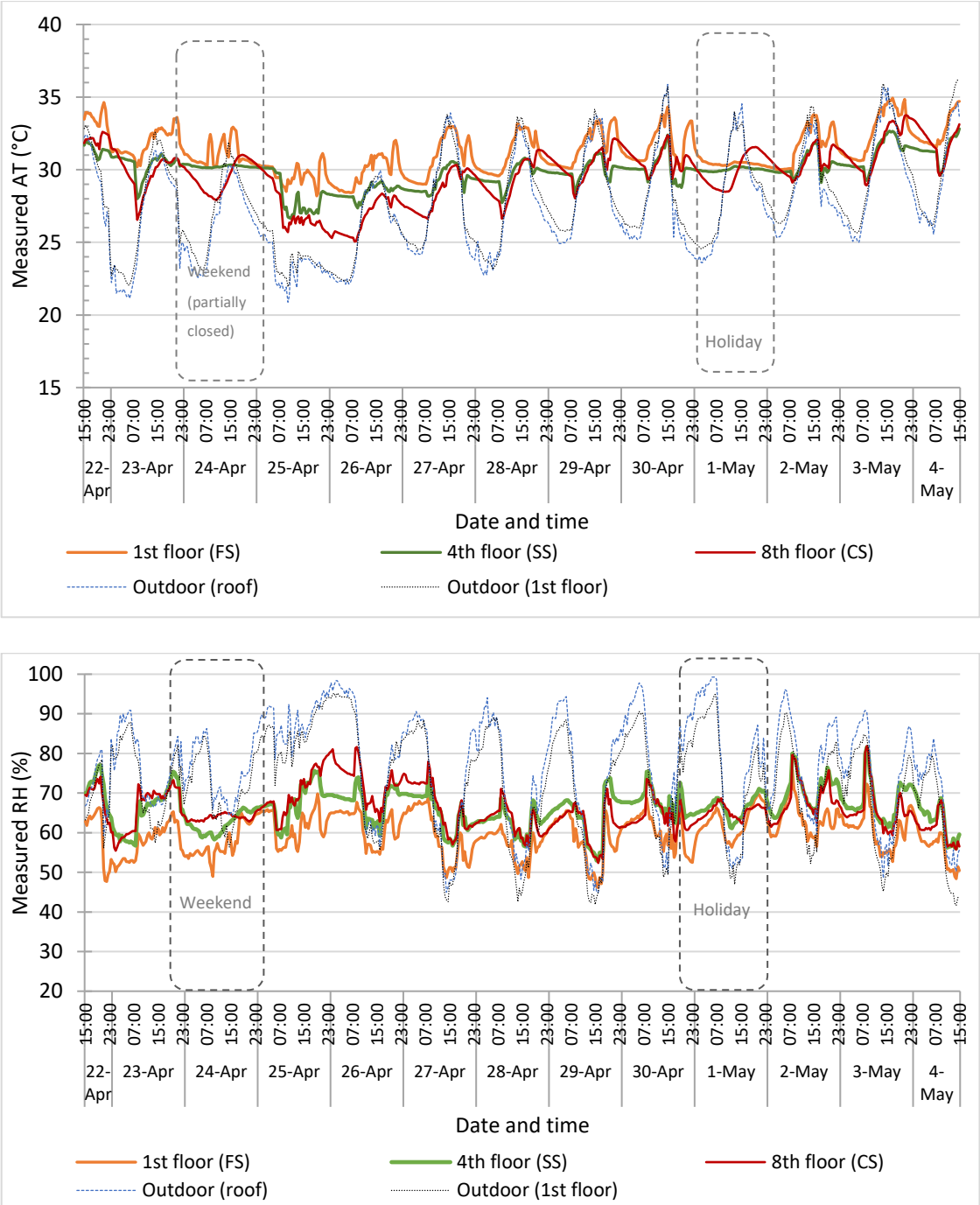


Figure 9-21: Measured AT and RH for production spaces during the hot-dry season (source: field study, year 2015)

Similar to previous Section 0, Figure 9-22 indicates the responses of *RMG factory 3* as heavy-weight building and indoor AT did not respond to the low night time outdoor AT.

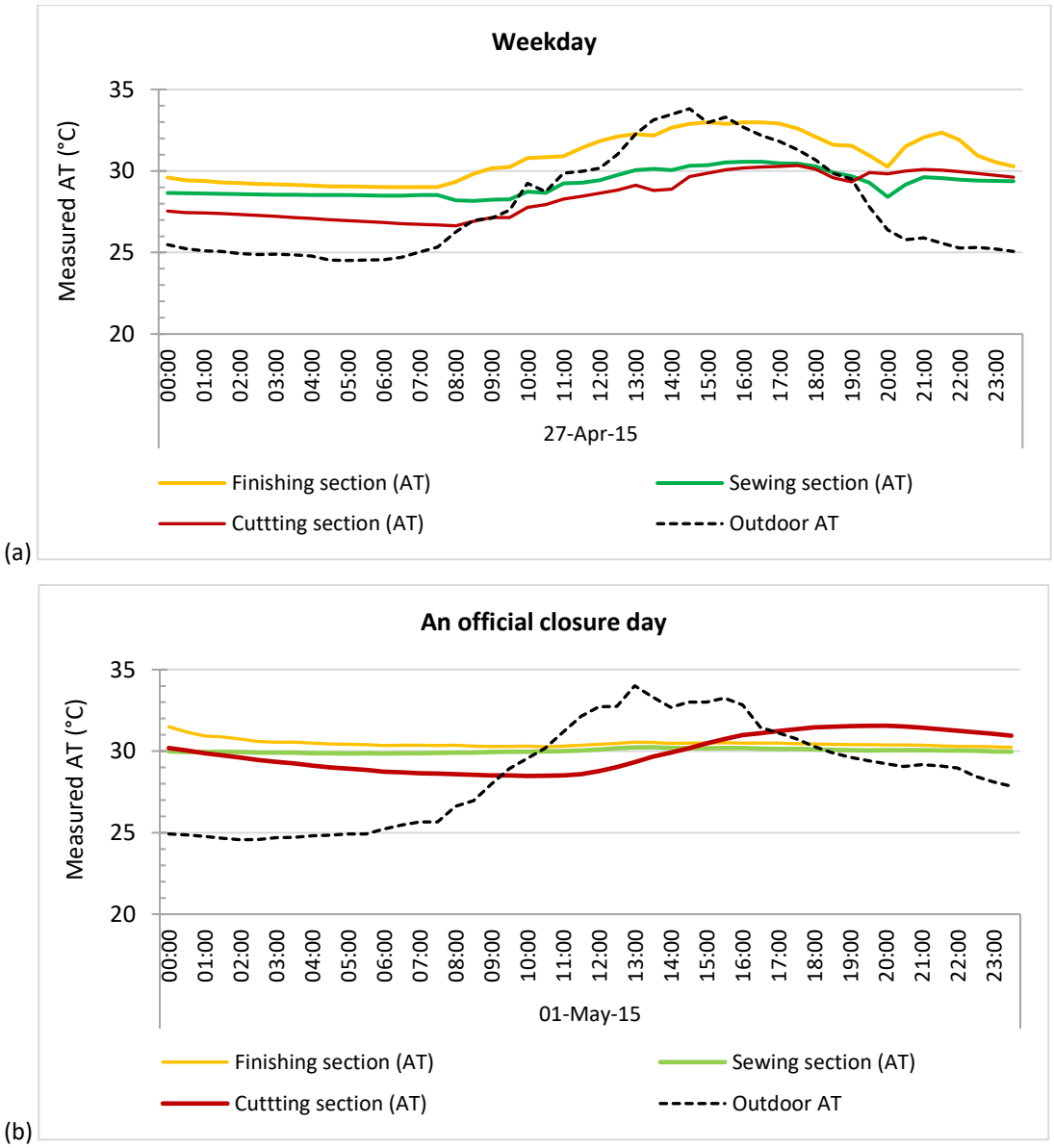
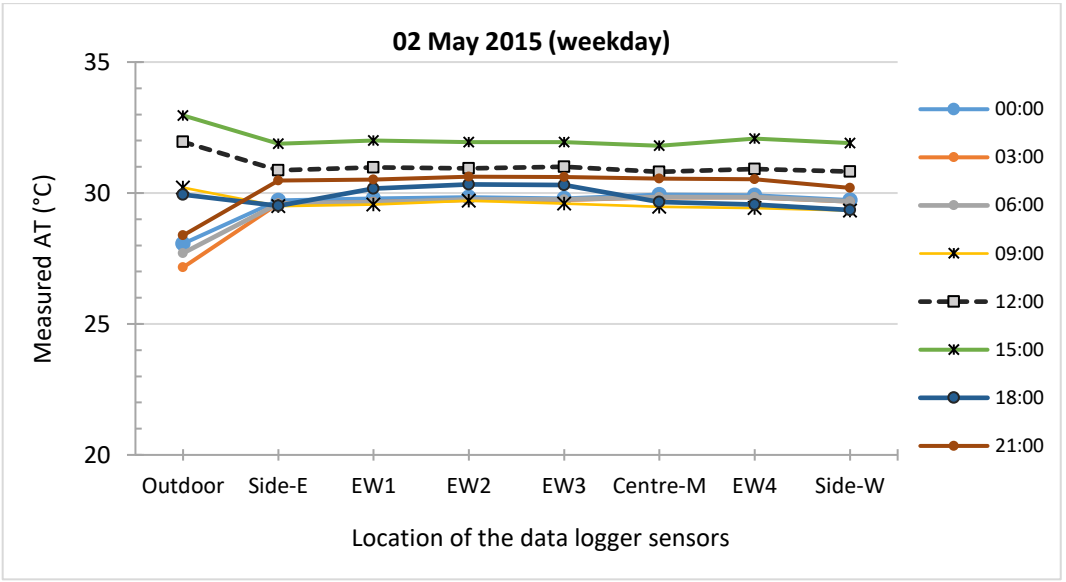


Figure 9-22: Measured AT for a typical weekday and weekend during the hot-dry season (source: field study 2015)

Figure 9-23 reveals that the AT values recorded along the east to west axis within the production space were relatively uniform. On the other hand, Figure 9-24 shows that AT values at positions Side-S and Centre-M deviated by around 1-2°C from the north side of the floor.

(a)



(b)

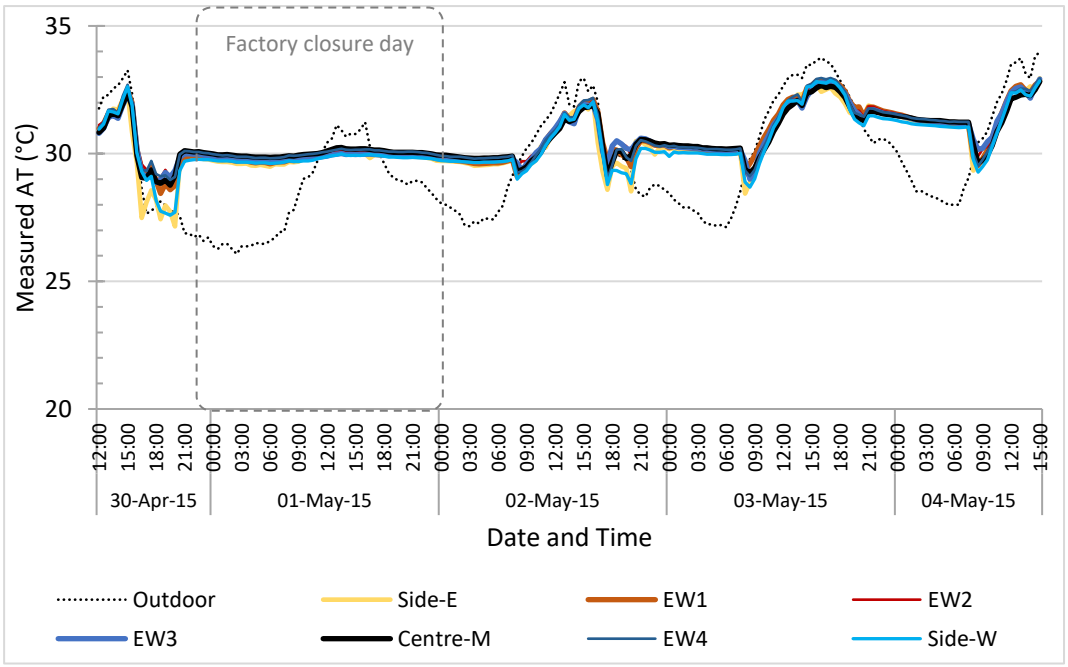


Figure 9-23: Measured AT profile recorded along the east to west axis of the 4th floor (SS) during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

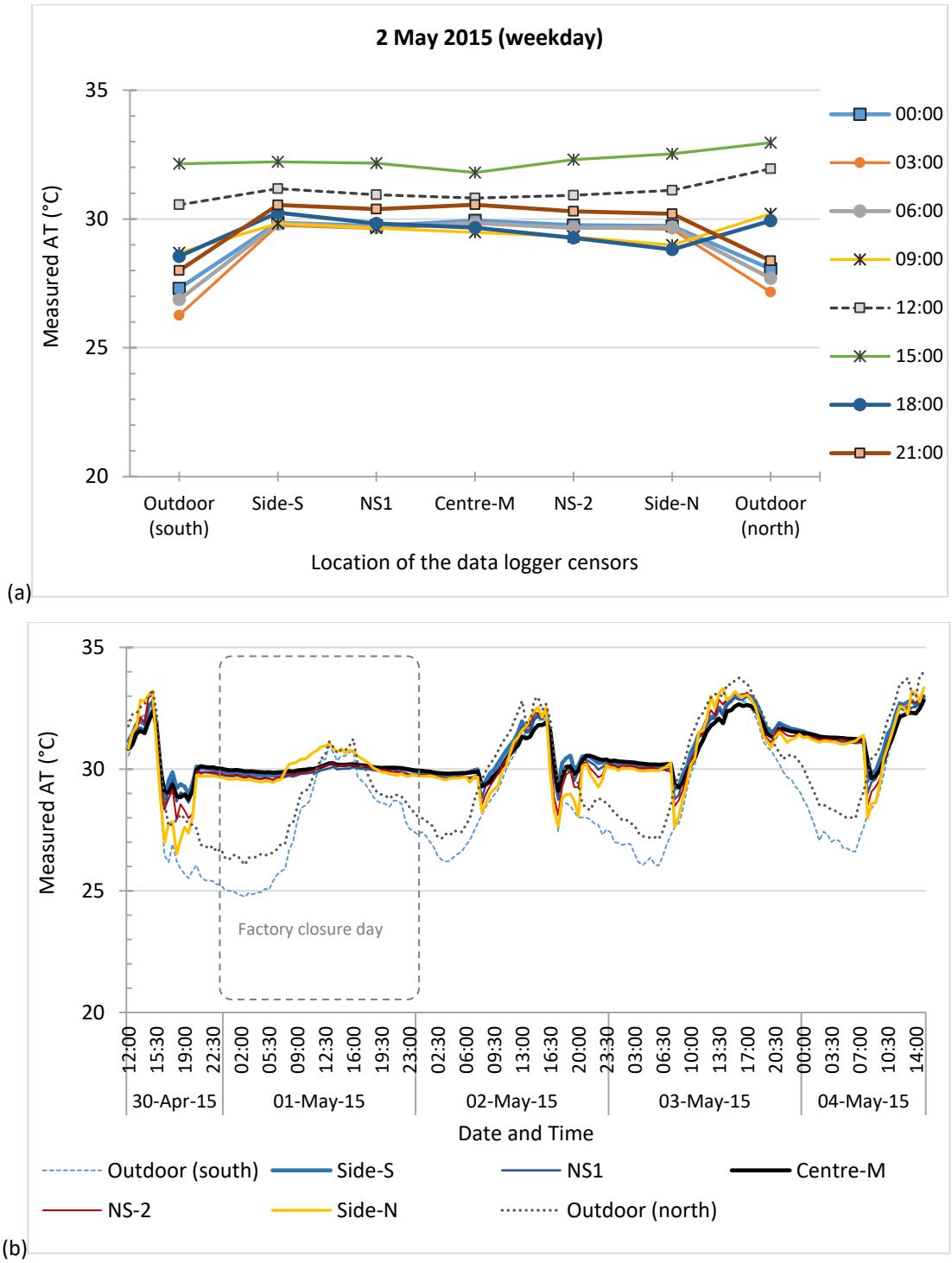


Figure 9-24: Measured AT profile recorded along the south to north axis of the 4th floor (SS) during the hot-dry season - (a) data for different times of day and (b) continuously recorded data

9.6.3. Warm-humid season

Figure 9-25 reveals that the CS showed low AT profiles than other production spaces during the warm-humid season. It can be observed that during the night time the difference in AT values between workspaces and outdoor of up to 3°C were recorded.

The FS always exhibited high AT profile. There were significant deviations in measured RH values between production sections which exhibited the RH levels of up to 91%.

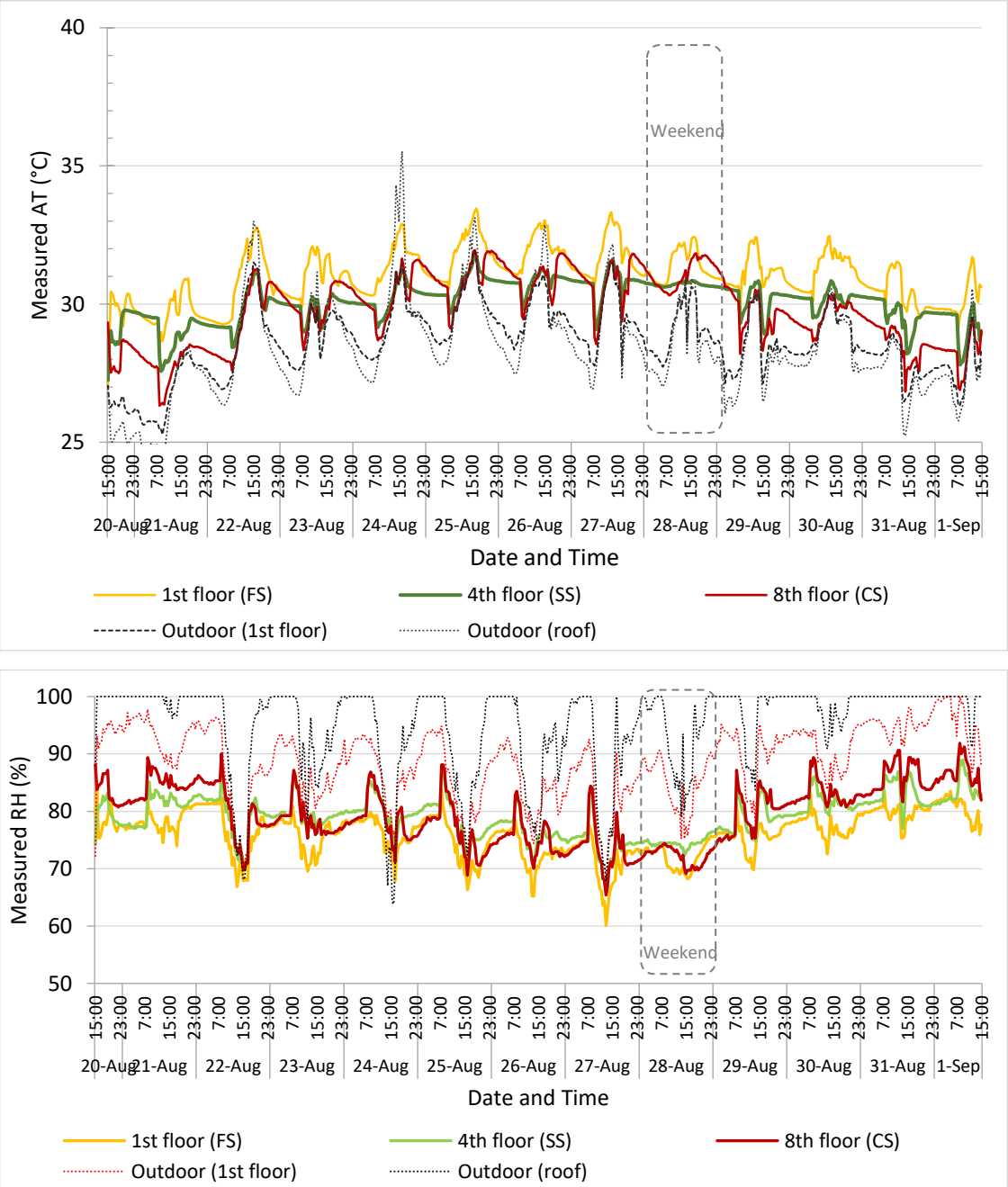


Figure 9-25: Measured AT and RH for production spaces during the warm-humid season (source: field study, year 2015)

Similar to previous two sections (Sections 0 and 9.6.2), Figure 9-27 revealed that indoor ATs for all production floors increased from 29°C to 32°C during the working hours of a weekday. When subject to a similar outdoor temperature profile, indoor AT values in the CS and SS were relatively constant (within the range of 30-31.5°C) during

the weekend. What these data explicitly illustrates is that even with a diurnal variation of outdoor AT of 3.5°C, indoor AT did not drop below 30°C during night time. Similar to the analyses of the two other seasons, this indicates that indoor production spaces lack adequate ventilation and infiltration to reduce the indoor AT to the low values of outdoor AT prevailing during night time.

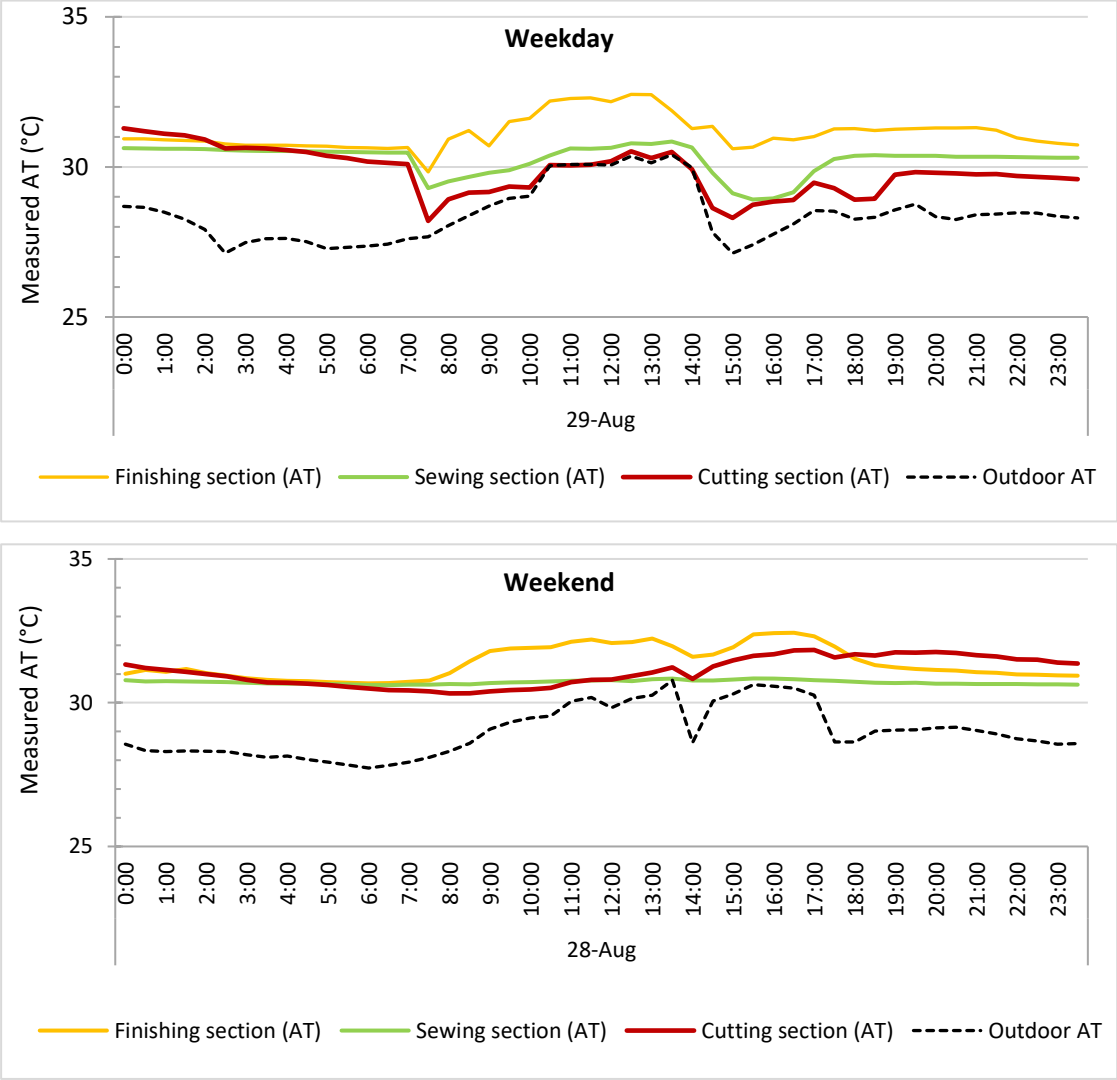


Figure 9-26: Measured AT for a typical weekday and weekend during the warm-humid season (source: field study, year 2015)

Figures 9-27 and 9-28 reveal that the AT values recorded along the east to west axis are relatively uniform. However, AT values recorded at the Centre-M and Side-N (north zone) positions reached the highest values (30.5-31°C). In contrast of other two season, the south exhibited low AT profile probably due to the effect of less incident solar radiation and frequent rains on the south façade.

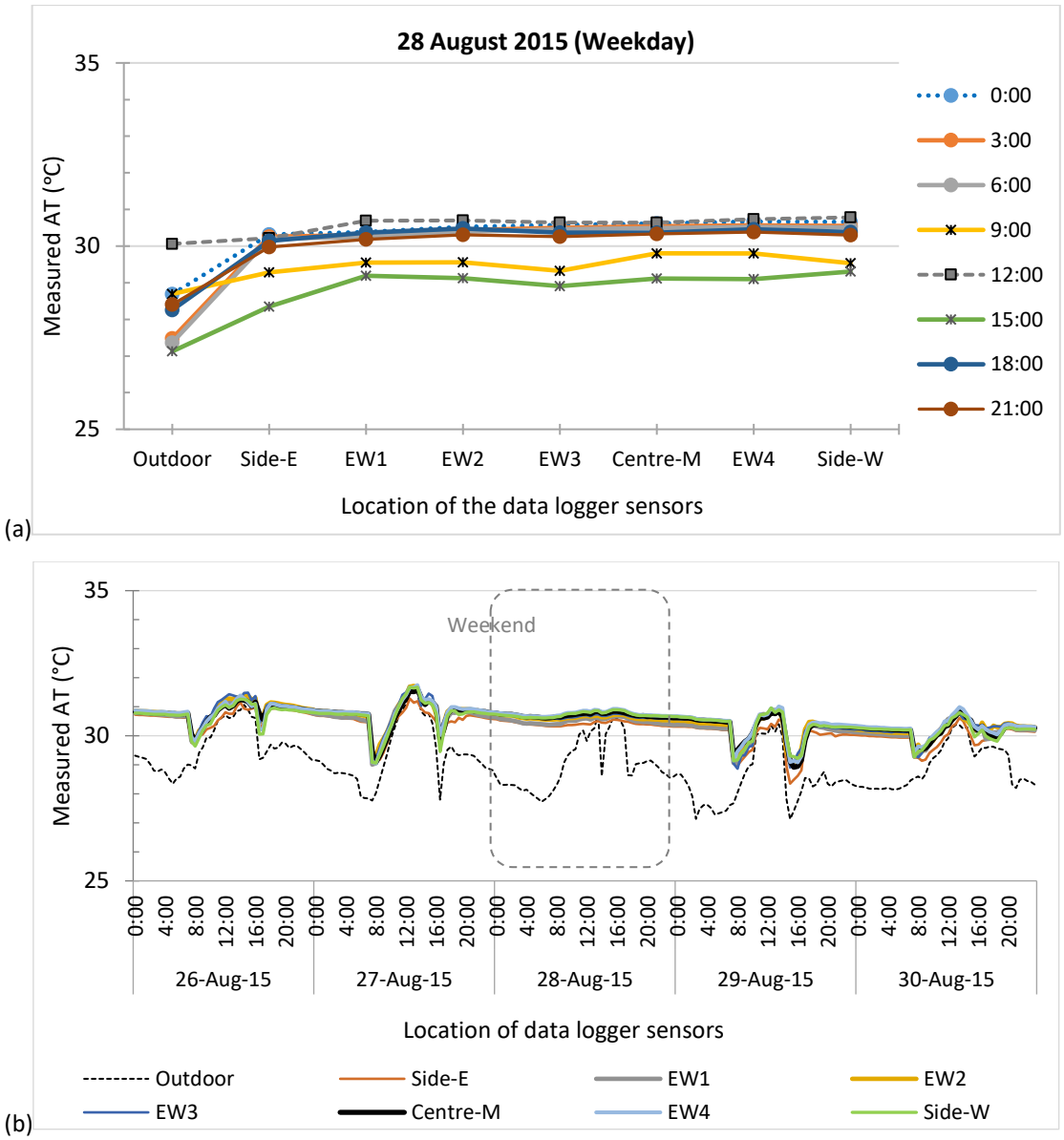


Figure 9-27: Measured AT profile recorded along the east to west axis of the 4th floor (SS) during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

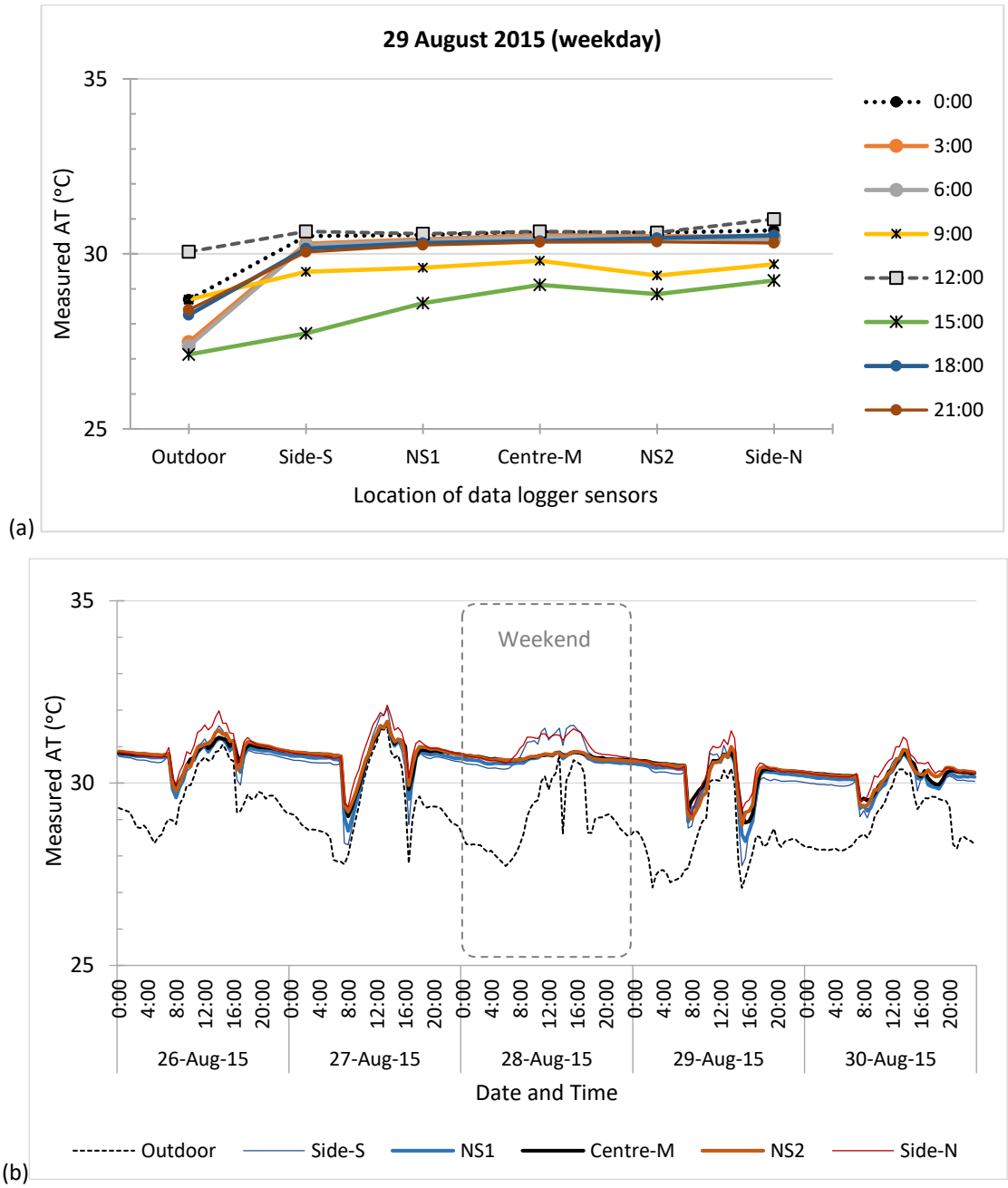


Figure 9-28: Measured AT profile recorded along the south to north axis of the 4th floor (SS) during the warm-humid season - (a) data for different times of day and (b) continuously recorded data

9.6.4. Key learning from monitored data

The continuous field data confirmed a few of the assumptions stated in Section 9.5. Similar to other case study buildings, the building responded as heavy-weight building during all seasons and the indoor AT of the workspaces remained constant during night time while the outdoor AT fluctuated. The impact of conductive heat gains through the south facades and heat loss through the roof was visible within the monitored data. The SS (4th floor) and FS (1st floor) also exhibited high indoor AT during all seasons. The

warm-humid season can be considered to be the 'worst-case' condition for maintaining occupant comfort due to having presence of high AT as well as high RH compared to other seasons (Figures 9-18, 9-21 and 9-25). It would be a key challenge to provide comfort to the workers by bringing cooler air from outdoor micro-climate and simultaneously keeping the RH level below 65% (Section 2.5.2). Further discussions on these issues are presented in Section 9.9.

9.7. Spot Measurements and Predicted PMV

9.7.1. Assessment of data based on assumed thermal comfort

The impact of seasonal variations can be explicitly observed in AT and RH values of this case study building (Table 9-4). For example, mean values of indoor AT were 27.5°C, 31.3°C and 30.7°C while the mean values of outdoor AT were recorded 25.2°C, 31.1 and 30.3°C during the cool-dry, hot-dry and warm-humid seasons respectively. Mean values of MRT are high (31.8°C) during the hot-dry and warm-humid seasons.

Table 9-4: Seasonal variations of the spot measured data* for the *RMG factory 3*

Season	Value type	AT (°C)	GT (°C)	RH (%)	Air speed (m/s)	WBGT (°C)	MRT (°C)	OT (°C)**	AT_{out} (°C)	RH_{out} (%)
Cool-dry	Mean	27.5	27.3	41.6	0.1	21.6	27.3	27.3	25.2	38.2
	SD	1.4	1.4	5.4	0.2	1.2	1.5	1.4	4.6	13.6
Hot-dry	Mean	31.3	31.3	66.2	0.2	27.6	31.3	31.3	31.1	65.7
	SD	1.4	1.4	5.9	0.2	1.1	1.5	1.4	3.9	11.2
Warm-humid	Mean	30.7	31.4	78.2	0.2	28.6	31.8	31.3	30.3	85.0
	SD	0.8	1.3	2.8	0.3	0.6	1.7	1.1	1.3	8.6

**Same as Table 7-4; **same as Table 7-4; ***same as Table 7-4*

.

From Figure 9-29, it can be observed that the AT ranges of 26-30°C, 30-34°C and 30-32°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Among these data range the SS and FS tended to exhibit higher AT range during all seasons. During the hot-dry and warm-humid seasons, the measured AT ranges exceeded the comfortable AT range as assumed in Section 2.5.2.

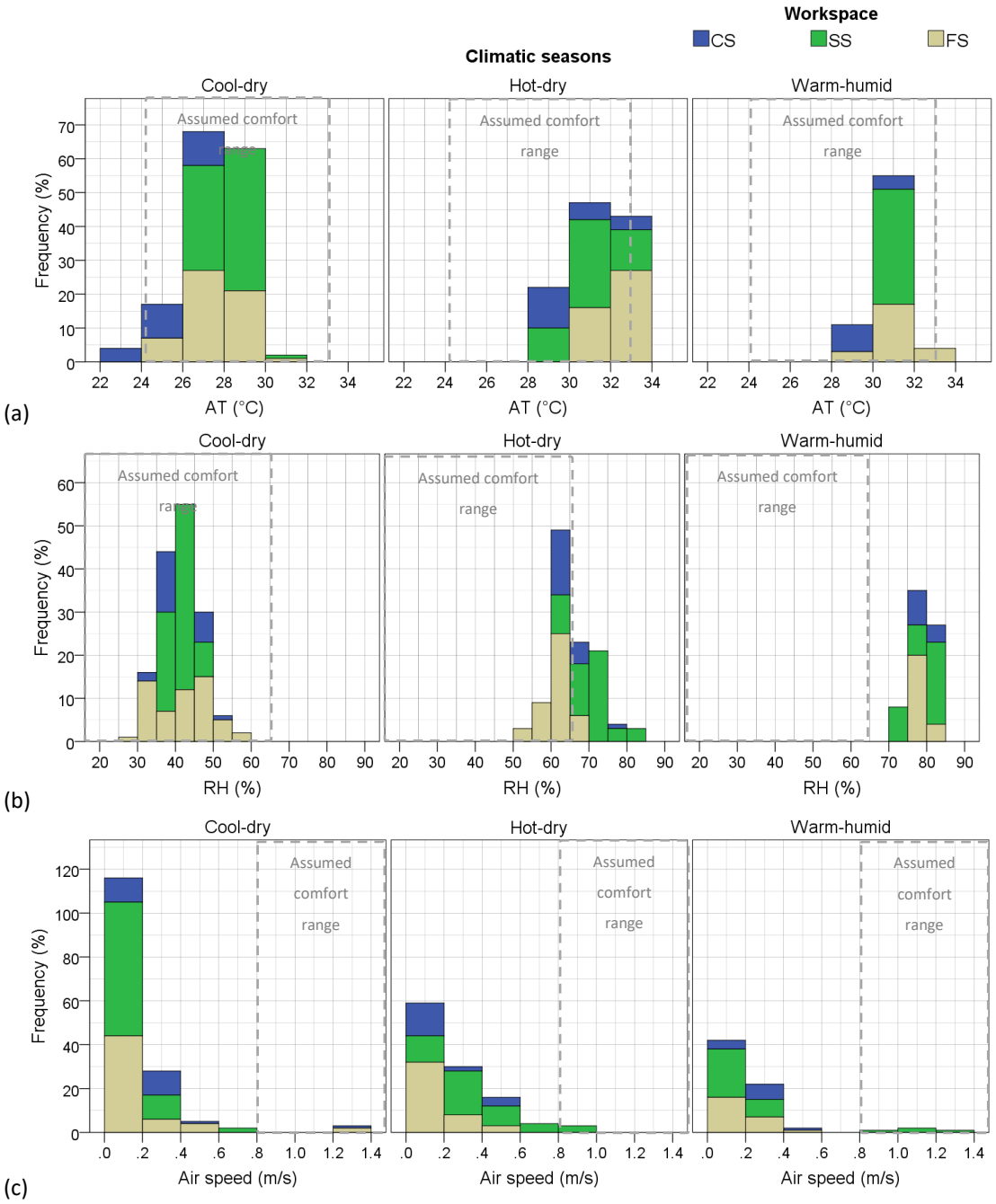


Figure 9-29: Frequency of spot measured AT, RH and average air speed and assumed thermal comfort ranges at workers' personal workstations in *RMG factory 3* (source: field studies, year 2015)

Figure 9-29(c) reveals that the approximate air speeds ranging of 0-0.2m/s, 0.0-0.4m/s and 0.0-0.4m/s were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. This suggests that the workers in the production spaces were more likely to experience an uncomfortable thermal environment throughout the year due to the low air velocity.

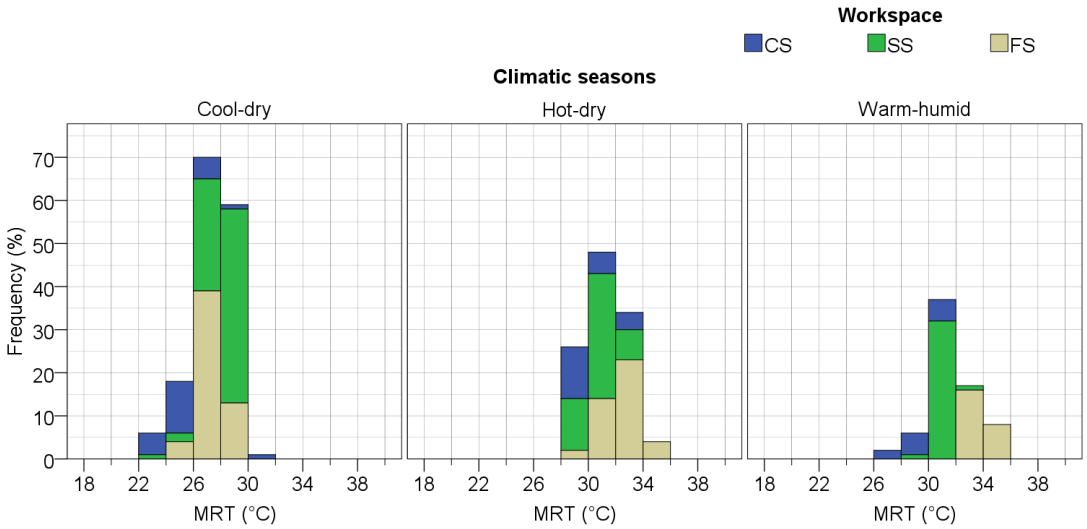


Figure 9-30: Frequency of spot measured MRT at workers' workstations in *RMG factory 3* (source: field studies, year 2015)

From Figure 9-30, it can also be found that the estimated MRT ranges of 26-30°C, 30-34°C and 30-34°C were found to occur frequently during the cool-dry, hot-dry and warm-humid seasons respectively. Apart from the CS during cool dry season, workers in the SS and FS tended to experience higher MRT range during all seasons.

9.7.2. Prediction of PMV

Figure 9-31 provides a visualisation of all recorded data and shows the distinct regions where the data for the different climatic seasons sit. The results indicate that 295 of workstations studied were outside of ASHRAE comfort zone with an average PMV of 1.42 over the three field studies (i.e. three climatic seasons). Similar to Sections 7.7.2 and 8.7.2, this represents the wider range of thermal condition during the cool-dry and hot-dry seasons. The results of this section are useful in serving as a reference for comparison with the actual comfort vote (Sections 9.8.1 and 10.4.1).

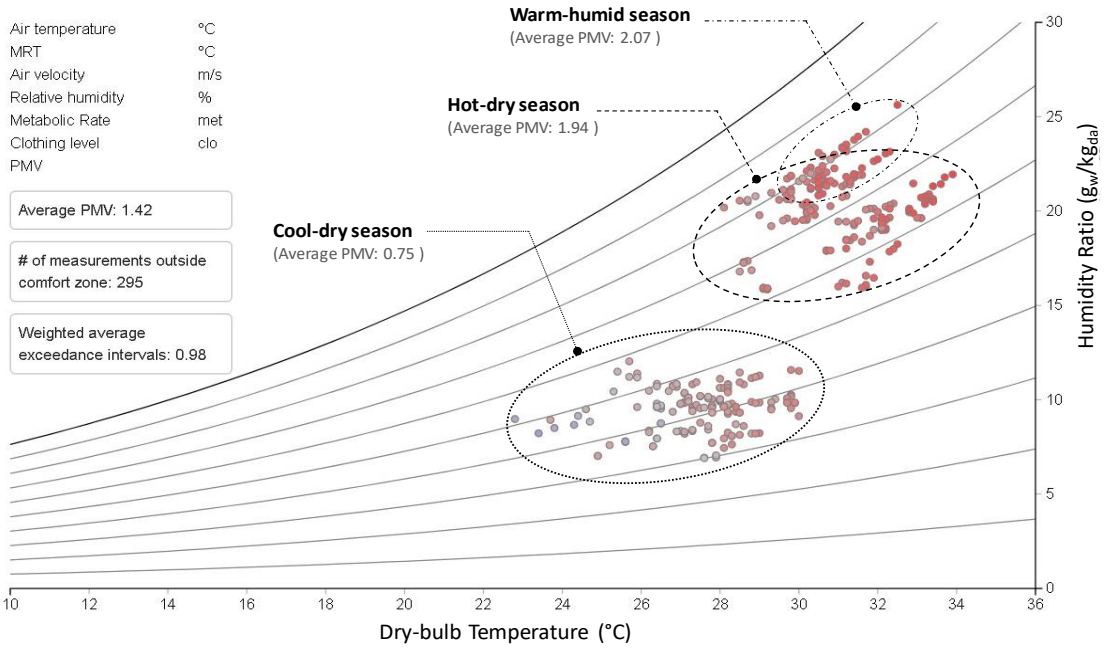


Figure 9-31: Prediction of thermal comfort vote and visualisation of measured data using a psychrometric chart (source: CBE thermal comfort tool 2013).

9.8. Workers' Subjective Feedback

9.8.1. Results from questionnaire surveys

Figure 9-32 provides histograms (frequency of ASHRAE 7-scale votes in percentage) of workers' vote on their existing thermal environment in terms of thermal sensation, humidity, airflow and freshness of air. Figure 9-32(a) reveals that approximately 65%, 48% and 40% of the workers responded with a 'neutral' vote for thermal sensation at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. Figure 9-32(b) reveals that 85%, 80% and 86.2% the workers provided a 'perfect' response in addition to their sensation toward humidity for existing temperatures at their workstations during the cool-dry, hot-dry and warm-humid seasons respectively. Similarly, Figure 9-32(c) and Figure 9-32(d) provide their votes for air speed and freshness of air at their workstations.

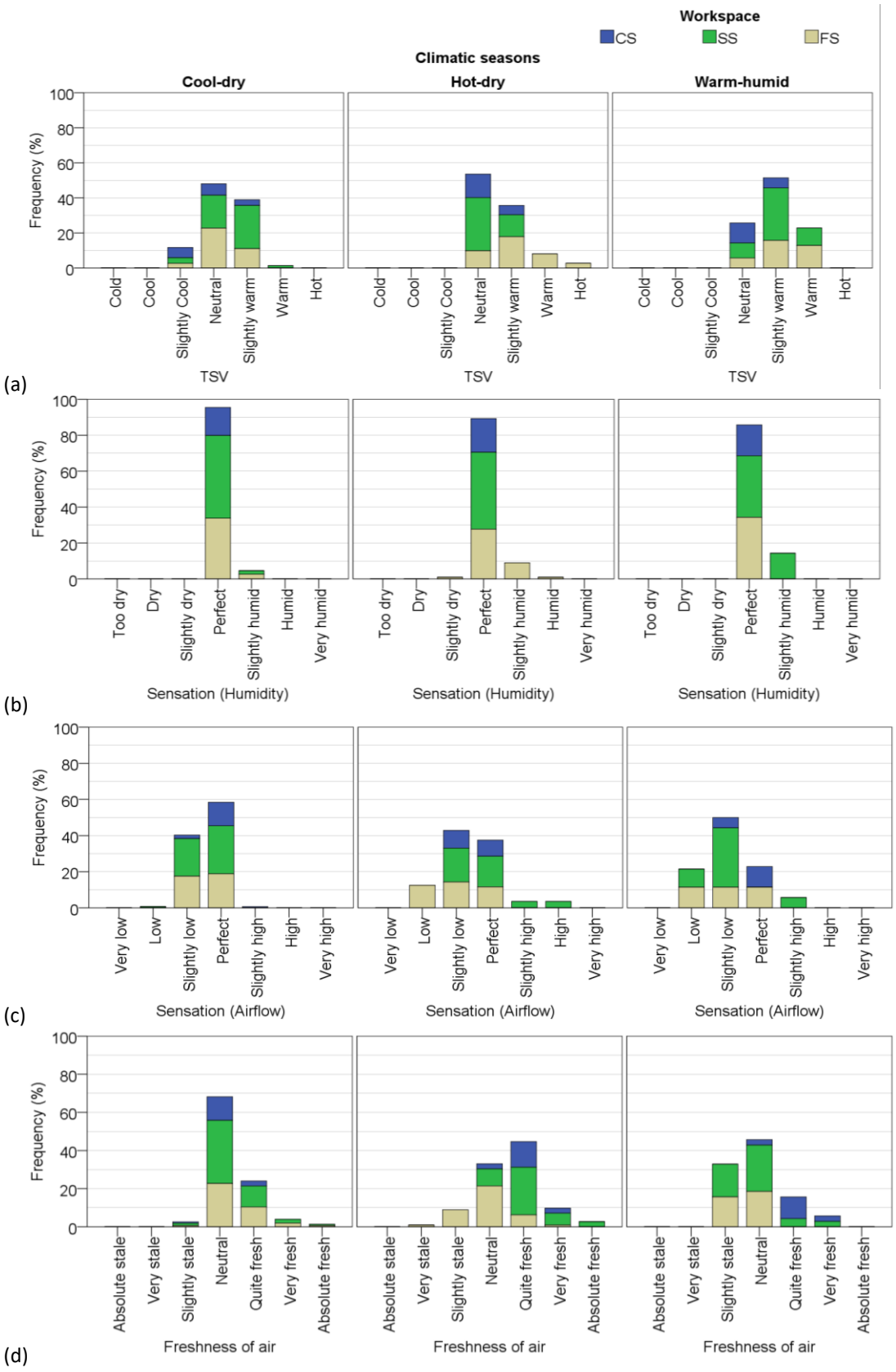


Figure 9-32: Histogram of workers' 7-scale votes on (a) Thermal sensation, (b) Humidity, (c) Airflow and (d) Freshness of air at their workstations during various seasons (source: field studies in *RMG factory 3*, year 2015)

Figure 9-33 shows workers' feedback on AT, RH and air speed they preferred at their existing workstations. The figure reveals that during the cool-dry and hot-dry seasons 65% and 55% of workers were more satisfied with the thermal environment since they voted for 'no change'. However, only 40% votes for 'no change' were received during the warm-humid season. The results indicate that during the warm-humid season, workstations needed major improvement to reduce the high AT. Result for each in isolation suggests that the combined effect remains are of discomfort.

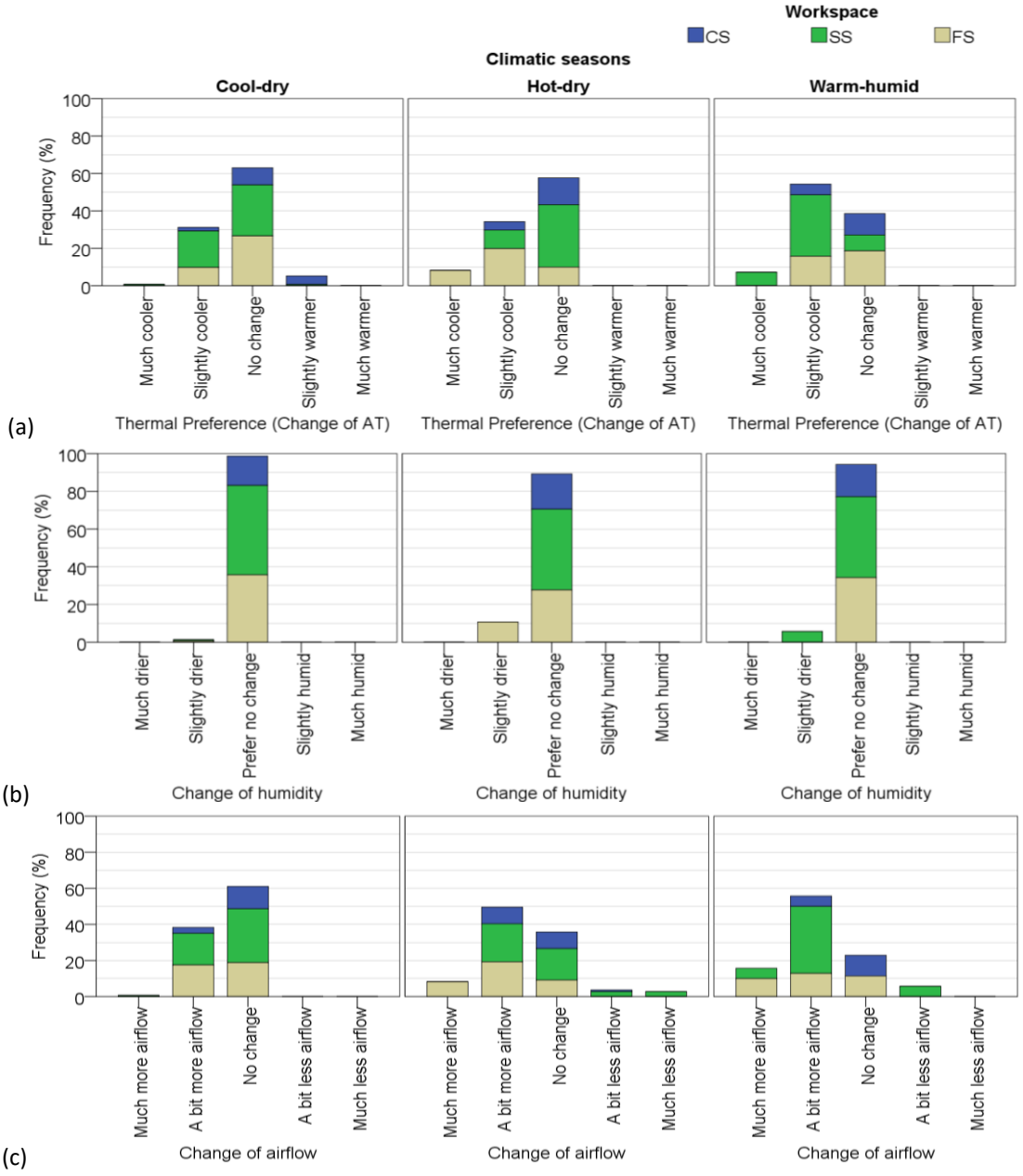


Figure 9-33: Histogram of workers' 5-scale votes on preferences to changes of (a) AT, (b) Humidity and (c) Airflow at workstations during key seasons (source: field studies in *RMG factory 3* in 2015)

Figure 9-34 also indicates that the standard level of overall acceptance (80%-90%, as mentioned in Section 2.5.1.1) was not met in the workspaces of *RMG factory 3* during the hot-dry and warm-humid seasons (further explained in Chapter 10).

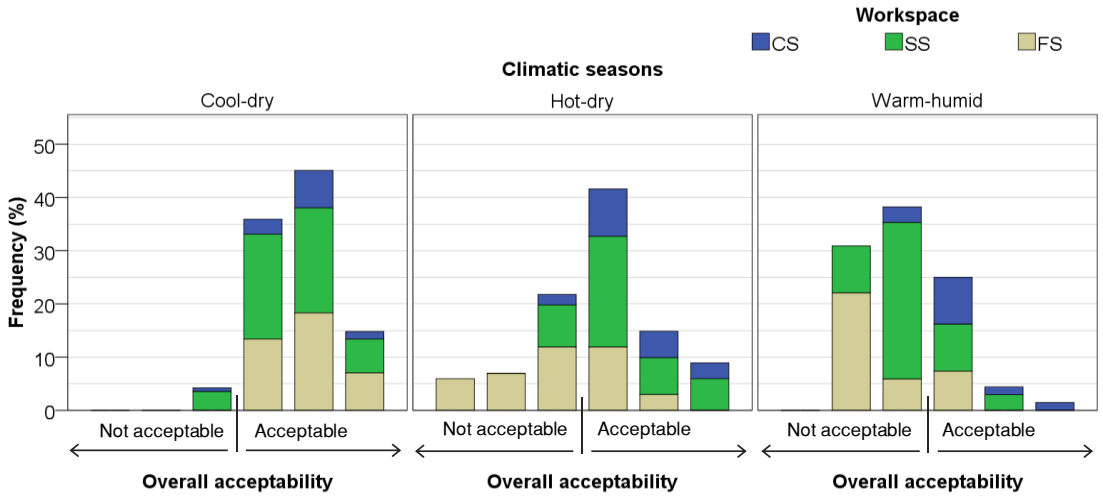


Figure 9-34: Histogram of workers' votes on overall acceptability of their existing thermal environment during various seasons (source: field studies in *RMG factory 3*, year 2015)

9.8.2. Results from focus group discussion

Table 9-5 provides summary of workers' feedback from two focus group discussions in *RMG factory 3*. Workers whose workstations located near inlet windows prefer to keep the windows open for their thermal comfort. However, direct high speed flow on the workers' work-planes next to the window was highlighted as an issue. In contrast, workstations in the middle of the floor plate perceived negligible air speed and suffered from discomfort during all seasons. Both questionnaire surveys and focus group discussions provided common feedback on improving working environment and ensuring sensible airflow during the hot-dry and warm-humid seasons.

Table 9-5: Summary of the workers' perception and adaptive measures from two focus groups

Season	Group	Perception and issues within their existing ventilation strategy and thermal experience	Adaptive measures to resolve the issues and ensure their thermal comfort
Cool-dry	one	- Workers feel slightly cold during 8am-10am and after 5pm. They prefer the cold environment that makes them work faster. - They feel comfortable until lunch time. They cannot control the extract fans personally. - They prefer the solar radiation from the south side.	- They shut the windows or ask floor manager to turn off the extract fan, if they feel cold.
	two	- They feel slightly hot due to lack of airflow. Workers at the FS (ironing section) always feel hot. - They are comfortable from 8-10am and after 6pm. Rest of the hours they feel discomfort.	- They reduce their work speed and ask the floor manager to turn on the extract fan, if they feel hot.
Hot dry	one	- Workers at the CS and FS feel neutral to slightly hot and very hot- humid during this season. - All of them feel very hot around lunch time due to walking to and from home for lunch. - They start to feel cool and comfortable after 5pm and during storms.	- They keep the windows open to keep themselves comfortable. - Drinking cold water as well as saline water, splashing water on their body are the common measures.
	two	- Workers at the FS feel uncomfortable all the time. - The others feel slightly hot between 8-9am. After 9am workstations become very hot with no airflow. - Workers from the CS feel slightly hot.	- Reducing work-speed, drinking water, saline water are the common adaptive strategies.
Warm humid	one	- They always feel humid resulting in sweating. - Workers at the FS feel very tired while standing and headache due to dehydration. - Workers at the CS feel slightly warm. - High speed airflows disrupt their works in the SS.	- Drinking saline and cold water, having a shower, splashing water on their body and keeping the windows open during rains are the common adaptive strategies.
	two	- All of them feel very hot and humid during this season. - They experience less discomfort when it rains outside.	- Changing their dresses, drinking saline water, using personal pedestal fan and standing near windows or doors for fresh air are the common adaptive measures.

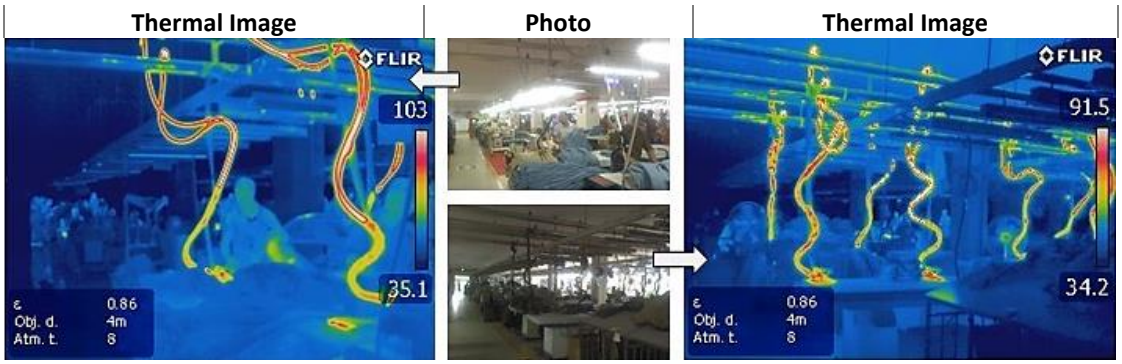
Table 9-6: Workers' overall feedback on expected improvement

Group one	Group two
- They prefer their workstations located near windows than those near outlets. - They expressed their desire to open the windows fully without hampering their work. - They suggested to rethink window design as they experience high air speed at work-plane level.	- They suggested to provide more fresh air supply to their workstations through natural ventilation. - They also prefer their workstations located near inlet-windows.

9.9. Existing Issues and Proposed Improvements

9.9.1. Ventilation strategy during unoccupied hours

Results from the data logging (Section 9.6) reveal that the outdoor AT was cooler dropping by up to 13°C at night. During the warm-humid season, this deviation in AT between indoors and outdoors within the day was up to 5°C. It was also found that at night, when the external AT was sufficiently low to provide passive cooling of the building fabric, the windows were closed, and the extract fans remained switched off.



Before lunch break (at 12:00 on 22 Aug 2015) During lunch break (at 13:30 on 22 Aug 2015)

Figure 9-35: Surface temperature profile of the FS (RMG factory 3) before and during a lunch break

Thermal images, such as those shown in Figure 9-35 indicated that the surface temperatures inside the production floors either increased or remained within the same range in the absence of the active ventilation during unoccupied hours (i.e. lunch breaks). For instance, the recorded surface temperatures of the workstations and machinery in the FS of *RMG factory 3* building recorded a maximum of 91.5°C during the unoccupied hours and 103°C during occupied hours at the daytime. Ventilation for an extended period, in particular the Night cooling strategy (Section 3.7.1), may be a more effective to improve the daytime thermal environment.

9.9.2. Effect of size and operation of the inlet-windows

According to the workers' feedback (Table 9-5), workstations located close to windows were perceived as thermally comfortable. However, they also experienced draughts, which cause disruptions to their work. Figure 9-36 provides two evidences where the window type affects the airflow rate and generates an undesirable air flow pattern.

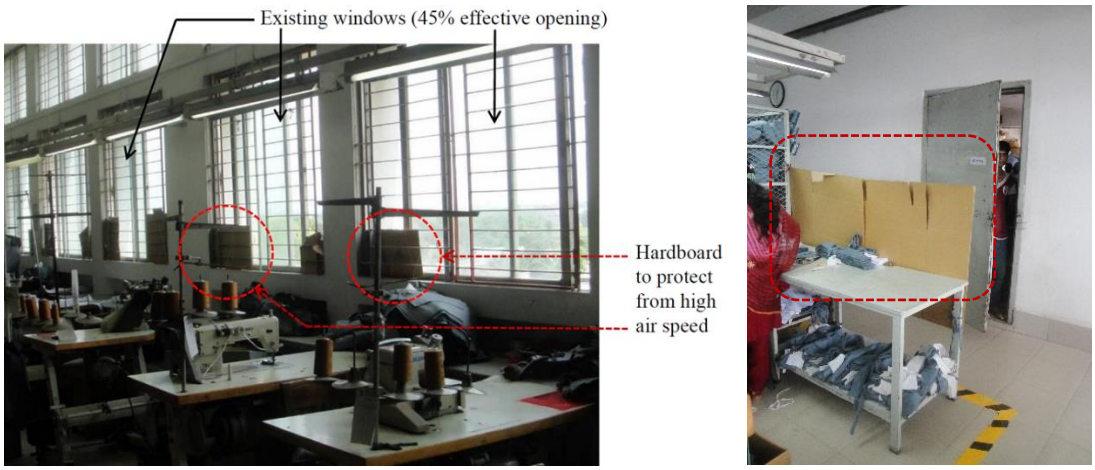


Figure 9-36: Sliding windows at ventilation inlets with hard boards and boards near doors to protect workers from direct high speed air flow

Similar experiment was undertaken, as shown in Section 7.9.2, in *RMG factory 3* building. Figure 9-37 and Table 9-7 show the results from the experiment and illustrates that changing the effective opening area from 45% to 5% increased internal AT by approximately 1.3°C and exhibits time lags of around 1-2 minutes. Increasing the window opening area caused reduction of indoor AT, the temperature taking longer to respond to the change (similar Scenario shown in Section 7.9.2).

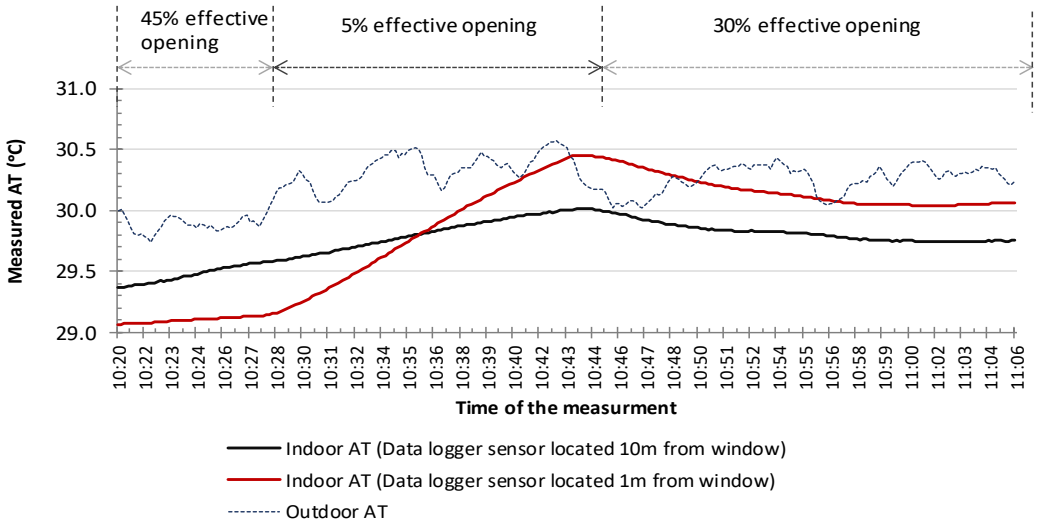
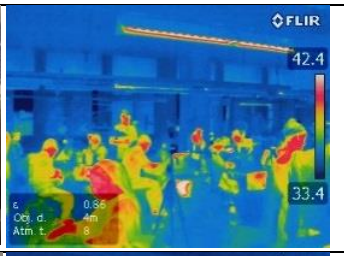


Figure 9-37: Effect of the inlet window-opening area on indoor air temperature (source: field experiment on the 24 August 2015)

Table 9-7: Effect of changing inlet area on surface temperature (source: field experiment on 24 August 2015)

Time (thermal imaging)	Effective inlet size	Range of ST (°C)		Deviation from the first state with 45% open (°C)		Photo	Thermal image
		Min.	Max	Min	Max		
10:22	45%	33.4	42.4	-	-		
10:45	5%	34.9	44.5	1.5	2.1		
12:58	30%	34.6	43.0	1.2	0.6		

As referred in the Sections 3.7.2, 7.9.2 and 8.9.2, changing the configuration and location of inlet-windows may improve thermal comfort of these workspaces.

9.9.3. Efficiency of equipment and passive ventilation

The daily electrical energy demand in production spaces of *RMG factory 2* (shown in Appendix G) reveals that up to 5050 KWh, 2290 KWh and 17875 KWh of the electrical energy are consumed per day by existing lights, extract fans and other production equipment respectively. . The annual expenditure for consuming electricity and running fuel-generators during power cuts are approximately US$29000 and US$176300 respectively. When combined with the high internal heat gain from the equipment in this case study building (Section 9.4.3), same suggestions (as shown in Section 7.9.3) are applicable here. As shown in Sections 3.7.3 and 6.7, stack induced ventilation can be applicable improving comfort and saving energy.

9.9.4. Functional layout and segmentation

From spot measurements, it was found that the highest AT was experienced in the SS and FS during all seasons. The location of the spots with low air speed and high AT were investigated by the researcher and were found near the 'ironing work-zone' of the SS and FS, which locally increased the AT due to high heat output of the equipment (Section 9.4.3). Figure 9-38 provides onsite evidences showing how workers spontaneously use hardboard baffles to protect them from undesirable wind and how they are exposed to high heat radiating equipment within the common workspace. Appendix H-3 shows the zones categorised by the researcher to show that these hot zones with its functional layout were not considered while designing the ventilation system from inlets of the building to outlet. These aspects should be considered to tackle indoor high temperature issue.

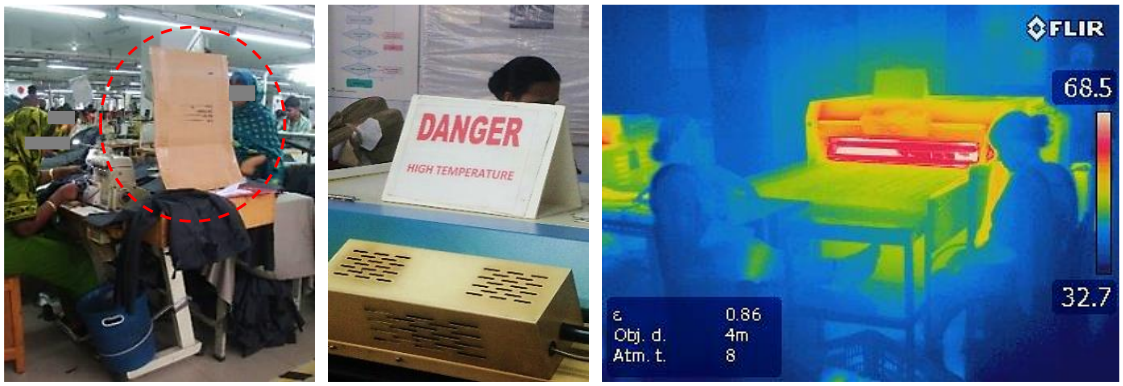


Figure 9-38: Workstations with hardboards to protect workers from undesirable airflows and the presence of high heat radiating equipment

9.9.5. Personalised control for occupants

From focus group discussions (Section 9.8.2), it was found that workers prefer personalised control over the air velocity at their workstations. Workers near windows had a degree of flexibility to control air flow by operating the nearby windows. However, workers in the middle zone should have additional extended airflow from the side and personal control strategy.

Figure 9-39 reveals that the workstations in the middle part of the floor (i.e. workstations located around 15m to 25m away from the inlet windows) were subject to high (up to 32.3°C) AT and were unlikely to get airflow above 0.8m/s. These results suggest that enhancing the airflows to the workstations by installing more personal

fans and extending workers' personalised control over the ventilation and comfort strategy might improve the overall thermal comfort of the workers, especially for those located far from the inlets.

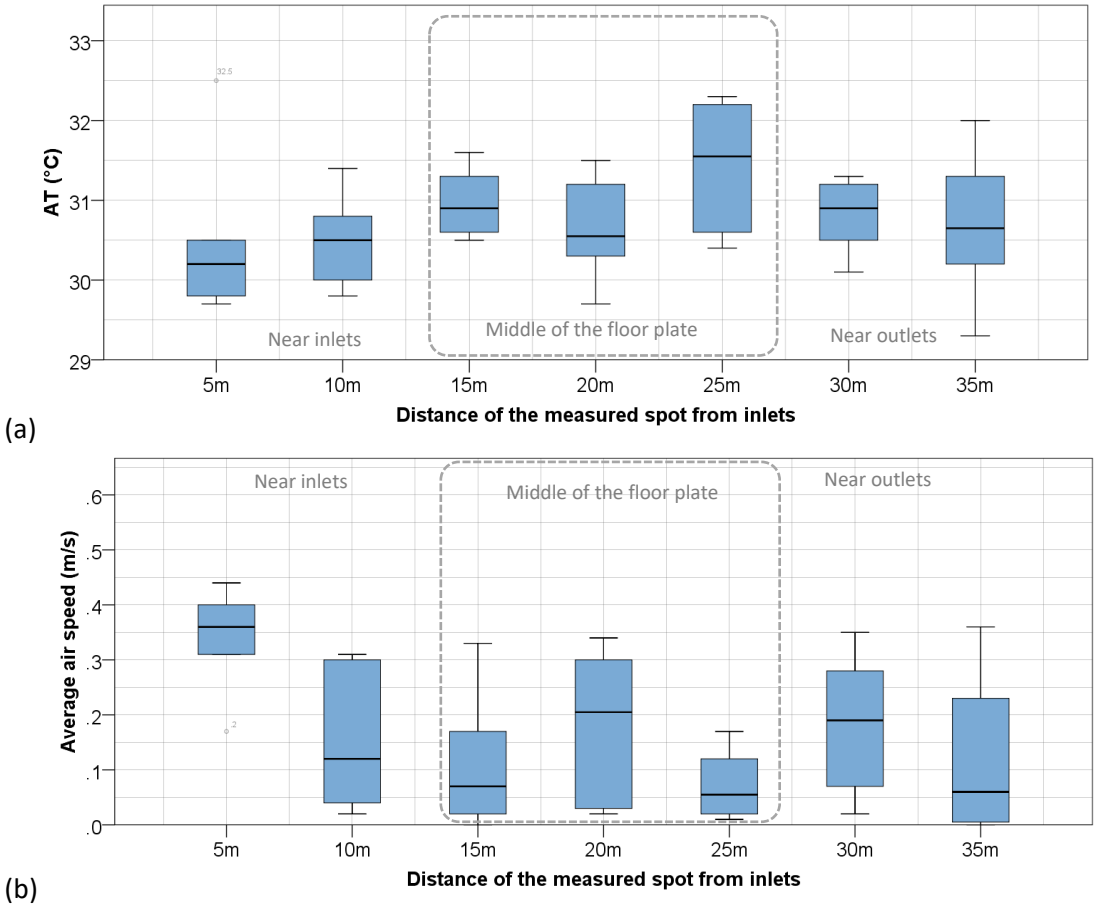


Figure 9-39: Ranges of spot measured (a) air temperature and (b) average air speed in terms of the distance of the spot from inlets (source: field study during the warm-humid season, year 2015)

9.9.6. Construction materials and thermal mass

Results from Sections 9.3 and 9.6 showed that the south façade and roof of the case study building were subject to incident solar radiation affecting the CS and the south zone of other workspaces. Hence, the treatment of this building elements can help to control solar gain. Hence, suggested strategies in Section 7.9.6 also applies to *RMG factory 3*.

9.10. Summary

This chapter aimed to present field investigation including environmental conditions of workspaces and issues related to workers' thermal comfort of an existing case study

building (*RMG factory 3*) and to propose a range of design solutions to improve these issues. The key findings of this chapter are as follows:

- The outdoor climate data measured at this building site indicated high amount of heat gain during the sunshine hours and the presence of relatively low ranges of outdoor AT during night time of all seasons.
- Due to constrained active ventilation and operation of windows bounded to working hours, the indoor air and ST of the workstations remained hot during unoccupied hours in all three climatic seasons.
- Results from on-site spot measurement and workers' response study suggested that it would the major challenge to ensure thermal comfort at their workstations during the warm-humid season due to simultaneous presence of high AT and high RH.
- Full day ventilation including operation during night time and weekends was proposed as one of improvement strategies for *RMG factory 3*.
- Sliding windows restricted outdoor air to flow in the workspaces and had a direct impact on increasing indoor AT causing a maximum deviation up to 1.3°C.
- Changing the factory's existing equipment with lower heat generating models and passive stack ventilation coupled with the existing ventilation strategy, may result in simultaneous saving of electrical energy.
- Field measurements and subjective responses confirmed that workers having their workstations located remotely from the ventilation inlets suffer from discomfort due to simultaneously high AT and low air speed.
- Changing the existing functional layout and enhancing personalised control over the ventilation strategy could improve the overall comfort condition
- There were provisions to reduce external conductive heat gain during day time and accentuate night time cooling by refurbishing the existing building materials to materials with low U-values and high thermal masses.

The next Chapter (Chapter 10) will present a comparative statistical analysis of the thermal comfort inferred from responses from workers in between three case study buildings and will indicate the most feasible strategies agreed by the building owners.

CHAPTER 10. COMPARATIVE ANALYSES: THERMAL COMFORT GUIDELINES AND WORKABLE STRATEGIES

This chapter provides comparative analyses of field survey data from the three case study buildings with an objective to establish thermal comfort guidelines for RMG factory workers. Feedback from the building owners is described and workable design strategies are outlined.

CHAPTER 10. COMPARATIVE ANALYSES: THERMAL COMFORT GUIDELINES AND WORKABLE STRATEGIES

10.1. Introduction

Previously Chapters 7, 8 and 9 provided detailed field investigations in three case study buildings. They focused on evaluating existing indoor environmental conditions of workspaces in three types of production spaces during three different climatic seasons and proposed a number of possible improvement strategies. This chapter is an extension of these three chapters and provides a comparative analysis of thermal conditions within three case study buildings. It identifies the comfortable working conditions for the workers within three types of workspace during three different seasons. This chapter also reveals the workable solutions that building owners and directors see value in implementing within their RMG factories to improve the present condition.

10.2. Chapter Aim and Scope

The main aim of this chapter to address the following sub-question of this doctoral research:

> *"What are the thermal comfort guidelines and the workable design strategies to minimise the environmental issues within these workplaces?"*

Hence, the key objectives of this chapter are to compare the deviations among three case study buildings' indoor thermal environment and analyse the quantitative impact of the varied thermal conditions on workers' indoor thermal perception in different seasons of a year. Through a range of cross tabulations and statistical analyses (Section 5.5.8), the chapter will identify the thermal comfort guidelines, such as, NT, temperature range, preferred air speed and direction, preferred distance from the inlet, to execute their certain production works comfortably. The additional objective is to identify the common design strategies that are feasible to implement within the existing case study buildings.

10.3. Variations in Indoor and Outdoor Environment

10.3.1. Comparative study of continuous AT and RH

Indoor and outdoor ATs for the SS of the three case study buildings are compared in Figure 10-1. It shows that the SS remained hot reaching ATs of up to 32°C during the hot dry seasons. From Sections 7.6, 8.6 and 9.6, it can be found that during the cool-dry and hot-dry seasons, peak outdoor AT occurs between 11:00 – 16:00 tackling the presence strong solar radiation. During the reminder of a day, the outdoor AT was cooler dropping by up to 10°C at night.

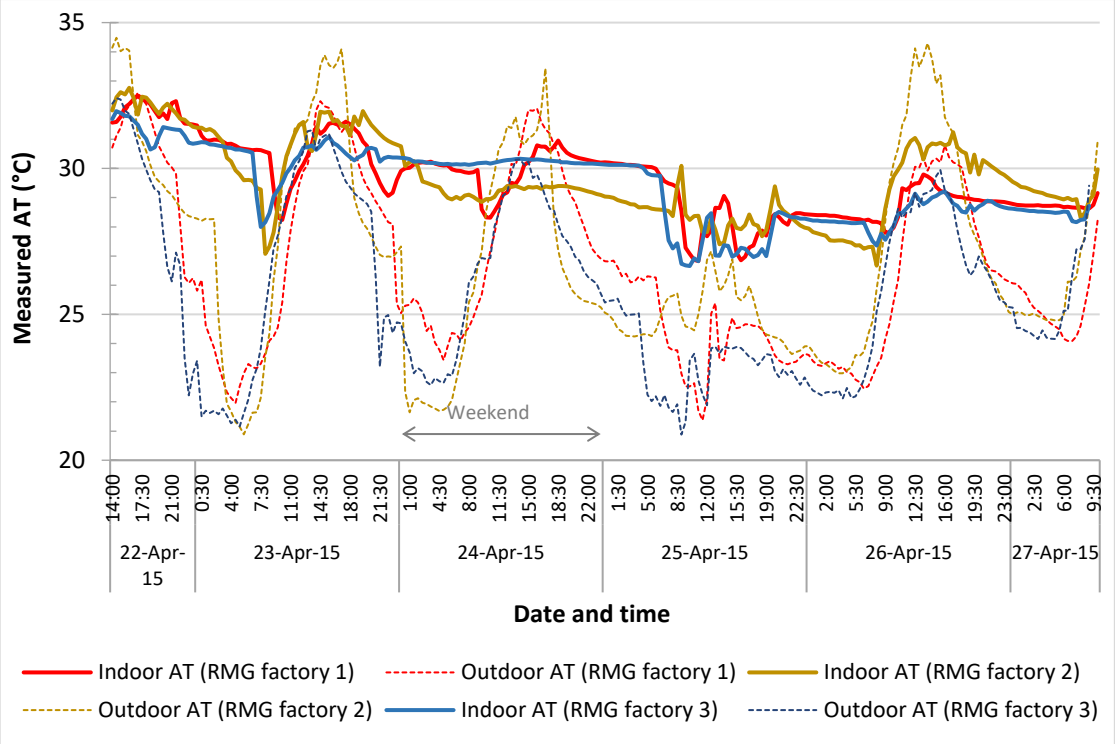


Figure 10-1: Measured AT from the SS in three case study buildings during the hot-dry season

A comprehensive summary of continuously recorded AT and RH of three RMG buildings are presented in Table 10-1 in respect to the immediate outdoor thermal environment. Recorded outdoor AT and RH revealed that the mean outdoor AT varies from 19.3°C to 21.4°C (mean RH: 59.0% - 73.6%) during the cool-dry season, from 27.4°C to 28.8°C (mean RH: 59.0% - 73.6%) during the hot-dry season and from 28.1°C to 30.1°C (mean RH: 84.2% to 95%) during the warm-humid season. SD during both the cool-dry and hot-dry seasons showed the higher diurnal ranges of AT (SD: 3.4°C - 5.2°C) and RH (SD: 13.4% – 19.6%) in compared to that of the warm-humid season (SD of AT:

1.8°C -2.6°C, SD of RH: 7.8%-12.8%). However, RH is relatively higher in the warm-humid season (highest AT: 36.9°C and RH: 100%). Hence, the warm-humid season was considered the 'worst-case' condition in terms of bringing a fresh air from outdoor micro-climate. Table 10-1 comprehends that the outdoor micro-climate conditions of all three RMG buildings represented the environmental characteristics of the three seasons of Bangladesh regardless the sites were in different locations.

Table 10-1: Descriptive statistics of the continuously recorded indoor and outdoor environmental data (i.e. TA and RH)* in all case study buildings (source: field study in the year of 2015)

Season	Case study	Work section	**Avg. AT_{in} (°C)**		**Avg. AT_{out} (°C)**		**Avg. RH_{in} (%)**		**Avg. RH_{out} (%)**	
			Min - Max	Mean (SD)	Min-Max	**Mean** (SD)	Min - Max	Mean (SD)	Min - Max	**Mean** (SD)
Cool-dry	*RMG Factory 1*	CS	21.0 - 28.1	24.3 (1.3)	11.8 - 32.3	**19.3** (5.2)	41.1 - 69.1	51.7 (4.4)	26.1 - 94.6	**71.2** (19.6)
		SS	21.2 - 30.7	26.6 (1.7)			34.9 - 67.3	45.7 (4.3)		
		FS	23.5 - 28.1	25.9 (0.8)			37.7 - 67.0	51.3 (5.3)		
	RMG Factory 2	CS	22.9 - 27.7	25.0 (1.1)	12.7 - 28.7	**19.3** (3.7)	43.6 - 68.0	56.2 (4.5)	43.9 – 96.1	**73.6** (13.9)
		SS	23.1 - 31.6	26.9 (1.8)			41.3 - 69.6	52.3 (4.8)		
		FS	20.3 - 30.0	24.5 (2.0)			43.0 - 73.9	60.5 (5.2)		
	RMG Factory 3	CS	20.6 - 28.2	24.7 (1.6)	13.2 - 33.9	**21.4** (4.6)	30.5 - 59.4	46.6 (5.6)	20.2 - 86.3	**59.0** (17.6)
		SS	21.3 - 29.3	27.4 (0.9)			31.4 - 52.4	41.5 (4.4)		
		FS	20.9 - 31.5	28.0 (1.8)			25.8 - 54.4	40.6 (5.2)		
Hot-dry	*RMG Factory 1*	CS	26.2 - 33.9	30.0 (1.5)	20.9 - 37.9	**27.4** (4.3)	44.9 - 75.6	60.9 (4.9)	27.1 - 97.5	**74.2** (15.8)
		SS	26.5 - 34.3	30.2 (1.7)			40.8 - 77.5	60.5 (6.2)		
		FS	26.2 - 34.2	30.3 (1.5)			43.3 - 75.4	61.7 (5.1)		
	RMG Factory 2	CS	25.8 - 32.8	30.0 (1.5)	20.9 - 36.3	**28.8** (3.5)	46.5 - 78.7	67.2 (6.0)	38.2 - 99.9	**74.0** (13.8)
		SS	26.2 - 33.7	31.1 (1.7)			43.4 - 85.8	63.4 (5.9)		
		FS	25.6 - 34.9	31.2 (2.1)			43.3 - 81.5	62.9 (6.5)		
	RMG Factory 3	CS	25.1 - 33.8	29.7 (1.9)	20.9 - 35.9	**27.4** (3.4)	51.8 - 81.9	66.0 (5.4)	45.0 - 99.3	**76.5** (13.4)
		SS	26.7 - 32.8	29.9 (1.1)			52.5 - 81.6	66.1 (4.9)		
		FS	26.8 - 34.9	31.3 (1.5)			46.1 - 75.9	59.8 (5.2)		
Warm-humid	*RMG Factory 1*	CS	30.7 - 34.7	33.2 (0.7)	25.7 - 36.9	**30.1** (2.6)	58.7 - 79.8	68.7 (3.5)	51.8 - 100	**84.2** (12.8)
		SS	29.8 - 35.0	32.8 (0.9)			56.7 - 82.3	69.0 (4.4)		
		FS	29.7 - 34.9	32.3 (1.1)			58.6 - 87.2	71.7 (5.5)		
	RMG Factory 2	CS	27.1 - 32.0	29.5 (0.9)	25.1 - 33.2	**28.1** (2.0)	70.4 - 90.4	79.8 (4.2)	70.8 - 100	**92.8** (8.5)
		SS	28.9 - 33.3	30.9 (1.1)			67.1 - 88.1	74.5 (4.6)		
		FS	28.3 - 34.3	30.9 (1.5)			65.6 - 89.9	75.2 (6.3)		
	RMG Factory 3	CS	26.3 - 32.0	29.8 (1.3)	24.3 - 35.5	**28.4** (1.8)	65.4 - 91.9	79.4 (5.5)	63.8 - 100	**95.0** (7.8)
		SS	27.2 - 31.8	30.1 (0.8)			65.8 - 88.9	79.0 (3.7)		
		FS	27.0 - 33.5	31.0 (1.0)			60.1 - 84.4	75.9 (3.9)		

**Same as Table 7-3, ** Same as Table 7-3.*

The mean indoor AT of the CS, SS and FS is always higher than the mean outdoor AT (e.g. CS: 24.3°C, SS: 26.6°C and FS: 25.9°C while outdoor mean AT: 19.3°C in *RMG factory 1*) during both working and unoccupied hours. However, SD values of all indoor cases (i.e. indoor AT and RH) did not clearly reveal the fluctuation of outdoor AT and RH during the cool-dry and hot-dry seasons, as discussed in the previous paragraph. Hence, the indoor data set of Table 10-1 represented the thermal condition the built environments in all seasons. However, these data did not reveal the thermal conditions that the workers actually experience during the working hours at their workstations.

10.3.2. Comparative study of spot measurements

A comparative summary of the actual thermal conditions (i.e. average spot measurements of all workspaces of all case studies is illustrated in Table 10-2. The impact of seasonal variations can be observed in AT and RH in case studies (e.g. mean values of indoor AT are 27.1°C, 31.1°C and 31.2°C while the mean values of outdoor AT are 23.1°C, 30.9°C and 30.8°C in three seasons respectively), same as the previous Table 10-1. Similar situations can be observed for the values of RH. Mean values of WBGT, MRT and OT were also illustrated as the actual thermal condition of workstations. The higher air speeds within *RMG factory 1* indicated the result of higher AVFR and a higher number of ceiling fans, though the AT and WBGT are relatively high in *RMG factory 1* during the warm-humid season. However, the small SD values (e.g. 0.9^{o}C to 1.4^{o}C for WBGT) among the all three case studies in this Table 10-2 justified that the selected cases can be analysed together assuming the climatic season as the first key variable for adaptive comfort (Lin et al., 2011), though outdoor microclimate diversity and urban geometry have significant impact on outdoor thermal perception.

Table 10-2: Seasonal variations of the spot measured database* in three case study buildings

Season	Case study	Value type	AT (°C)	GT (°C)	RH (%)	Air speed (m/s)	WBGT (°C)	MRT (°C)	OT (°C)**	AT_{out} (°C)	RH_{out} (%)
Cool-dry	*RMG Factory 1*	Mean (SD)	26.7 (1.9)	26.8 (1.2)	52.2 (7.0)	0.5 (0.7)	21.8 (1.4)	27.1 (1.8)	26.8 (1.3)	23.2 (2.5)	55.4 (10.7)
	RMG Factory 2		27.0 (1.4)	26.8 (1.6)	60.0 (5.6)	0.3 (0.3)	23.1 (2.2)	26.7 (2.0)	26.9 (1.6)	20.8 (3.6)	73.5 (13.0)
	RMG Factory 3		27.5 (1.4)	27.3 (1.4)	41.6 (5.4)	0.1 (0.2)	21.6 (1.2)	27.3 (1.5)	27.3 (1.4)	25.2 (4.6)	38.2 (13.6)
	All cases	Min - Max	20.2 - 30.0	20.2-31.0	29.7 - 73.7	0.0 - 3.5	18.1-25.6	20.7 - 33.6	21.1 - 30.8	14.1 - 33.9	17.1 - 98.0
		Mean (SD)	**27.1** (1.5)	**27.0** (1.5)	**51.0** (10.1)	**0.3** (0.4)	**22.0** (1.9)	**27.0** (1.8)	**27.0** (1.5)	**23.1** (4.3)	**55.6** (20.2)
Hot-dry	*RMG Factory 1*	Mean (SD)	30.0 (1.7)	29.9 (1.7)	66.0 (6.5)	0.5 (0.2)	26.3 (1.3)	29.8 (1.9)	29.9 (1.7)	29.0 (3.9)	66.3 (14.3)
	RMG Factory 2		32.0 (1.0)	32.0 (1.0)	64.9 (5.8)	0.3 (0.3)	28.1 (1.0)	31.9 (1.1)	32.0 (1.0)	32.9 (1.8)	60.2 (6.4)
	RMG Factory 3		31.3 (1.4)	31.3 (1.4)	66.2 (5.9)	0.2 (0.2)	27.6 (1.1)	31.3 (1.5)	31.3 (1.4)	31.1 (3.9)	65.7 (11.2)
	All cases	Min - Max	26.4 - 34.4	26.4 - 34.4	46.4 - 82.4	0.0 - 2.5	23.2-30.2	24.8 - 34.8	26.2 - 34.3	15.3 - 36.0	35.3 - 92.5
		Mean (SD)	**31.1** (1.7)	**31.0** (1.6)	**65.7** (6.1)	**0.4** (0.3)	**27.3** (1.4)	**30.9** (1.8)	**31.0** (1.6)	**30.9** (3.7)	**64.3** (11.6)
Warm-humid	*RMG Factory 1*	Mean (SD)	32.5 (0.7)	33.9 (1.5)	72.8 (3.4)	0.4 (0.2)	30.0 (0.7)	35.6 (2.6)	33.6 (1.3)	33.6 (1.6)	69.0 (8.8)
	RMG Factory 2		30.4 (0.7)	31.6 (1.4)	79.6 (3.4)	0.3 (0.1)	28.7 (0.6)	32.7 (2.2)	31.3 (1.2)	28.6 (1.9)	91.3 (9.3)
	RMG Factory 3		30.7 (0.8)	31.4 (1.3)	78.2 (2.8)	0.2 (0.3)	28.6 (0.6)	31.8 (1.7)	31.3 (1.1)	30.3 (1.3)	85.0 (8.6)
	All cases	Min - Max	28.1 - 33.8	28.1 – 35.7	68.4 - 85.9	0.0 - 1.3	26.7-31.3	27.1 – 38.8	28.6 – 35.3	25.1 - 36.9	51.7 - 100
		Mean (SD)	**31.2** (1.2)	**32.7** (1.8)	**77.0** (4.3)	**0.3** (0.2)	**29.1** (0.9)	**33.3** (2.7)	**32.0** (1.6)	**30.8** (2.6)	**82.2** **(12.8)**

**During the working hours only, **same as Table 7-4; ***same as Table 7-4*

Table 10-3 provides an insight into the thermal conditions of three type of production spaces. Despite the impact of the key variable (i.e. outdoor thermal environment and solar radiation pattern in three seasons), the variations in work-sections' indoor thermal condition were also statistically significant. For instance, the AT, GT, WBGT,

MRT and OT of the CS are relatively lower than sewing and ironing sections in all climatic seasons. Values of GT reveal that the CS produces less radiant heat than the other two sections. The FS which includes cloth ironing activities produces the highest heat during the hot-dry and warm-humid seasons (i.e. 31.8°C and 32.9°C with SD of 1.3 and 1.9 respectively). The values of GT and MRT also reflected the internal heat gain profiles shown in Chapters 7, 8 and 9 (e.g. internal heat gain at the CS varies from 45-110W/m^2 while 180-225W/m^2 at the SS and 150-220W/m^2 at the FS) and in the thermal images.

Table 10-3: Variations of mean values in three different production work sections*

	Seasons	Work section*	AT *(°C)*	GT *(°C)*	RH *(%)*	Air speed *(m/s)*	WBGT (°C)	MRT *(°C)*	OT *(°C)* **	AT_{out} *(°C)* ***	RH_{out} *(%)* ***
Mean (SD*)	Cool-dry	CS	**26.0** (1.3)	**25.8** (1.1)	**48.9** (12.2)	**0.2** (0.2)	**20.7** (1.9)	**25.7** (1.5)	**25.8** (1.0)		
		SS	**27.4** (1.6)	**27.3** (1.5)	**53.0** (9.5)	**0.2** (0.3)	**22.5** (2.0)	**27.3** (1.8)	**27.3** (1.5)	**23.1** (4.3)	**55.6** (20.2)
		FS	**27.1** (1.3)	**26.9** (1.3)	**46.6** (9.2)	**0.4** (0.7)	**21.5** (1.1)	**26.9** (1.5)	**26.9** (1.3)		
	Hot-dry	CS	**30.0** (1.6)	**30.0** (1.6)	**66.2** (3.5)	**0.3** (0.3)	**26.4** (1.5)	**30.0** (1.8)	**30.0** (1.6)		
		SS	**31.0** (1.6)	**31.0** (1.6)	**66.8** (6.7)	**0.4** (0.3)	**27.4** (1.2)	**30.8** (1.8)	**31.0** (1.6)	**30.9** (3.7)	**64.3** (11.6)
		FS	31.8 (1.4)	**31.8** (1.3)	**62.3** (3.7)	**0.3** (0.2)	**27.7** (1.4)	**31.9** (1.3)	**31.8** (1.3)		
	Warm-humid	CS	**30.3** (1.2)	**30.0** (1.0)	**79.5** (3.9)	**0.3** (0.1)	**28.1** (0.7)	**29.7** (1.4)	**30.1** (1.0)		
		SS	**31.3** (1.0)	**32.5** (1.4)	**76.7** (4.1)	**0.3** (0.2)	**29.2** (0.6)	**33.9** (2.1)	**32.3** (1.3)	**30.8** (2.6)	**82.2** (12.8)
		FS	**31.4** (1.4)	**32.9** **(1.9)**	**76.3** (4.5)	**0.3** (0.2)	**29.4** (1.1)	**34.0** (2.9)	**32.6** (1.6)		

**SD= Standard Deviation; **same as Table 7-4; ***same as Table 7-4*

Analysing the mean WBGT (Table 10-3) revealed that the workstations had 15.4%-22.2% lower WBGT in term of risk factor criteria (i.e. lower risk factor: ≤26.5°C) of heat stress on workers' body (Parsons, 2006, Chowdhury et al., 2017b). However, the SS and FS during the hot-dry season and all workspaces during the warm-humid season were within the 'moderate' (26.7°C -29.3°C) and 'moderate to risk' (29.4°C -31.0°C) factor (Chowdhury et al., 2017b, Parsons, 2006). This also implied that the indoor conditions during these two seasons were uncomfortable for the workers. Retaining the existing RH range, the only ways to elevate comfort level were reducing the AT (Equation 5-6) and increase air speed by fans (Nicol and Roaf, 2005).

The observed variations of indoor and outdoor thermal condition fostered evaluating the actual comfort condition and neutral temperature (NT) of the RMG factory workers according to the two variable cases which are the climatic seasons and work-section types (Chowdhury et al., 2017b, de Dear et al., 2015, Brager et al., 2004, de Dear and Brager, 2001).

10.4. Neutral Temperature and Comfort Benchmarks for Workers

10.4.1. Predicted vote vs actual comfort vote

Figure 10-2 shows that 777 of studied workstations (i.e. 85.6% of the total 908 working locations) were outside of ASHRAE comfort zone with an average PMV of 1.24 over the three climatic seasons. In particular, 68.2% of 384 measurements fell outside ASHRAE comfort zone (PMV: 0.64) during the cool-dry season with the weighted average exceedance intervals: 0.31. Of the 327 measurements made during the hot-dry season 97.2% fell outside the ASHRAE comfort zone (PMV: 1.64, weighted average exceedance intervals: 1.15) and 100% of 197 measurements taken during the warm-humid season (PMV: 1.76, weighted average exceedance intervals: 1.26) were found to lie outside of ASHRAE comfort zone. It also represents the wider range of thermal condition during the cool-dry and hot-dry seasons rather than that during the warm-humid seasons.

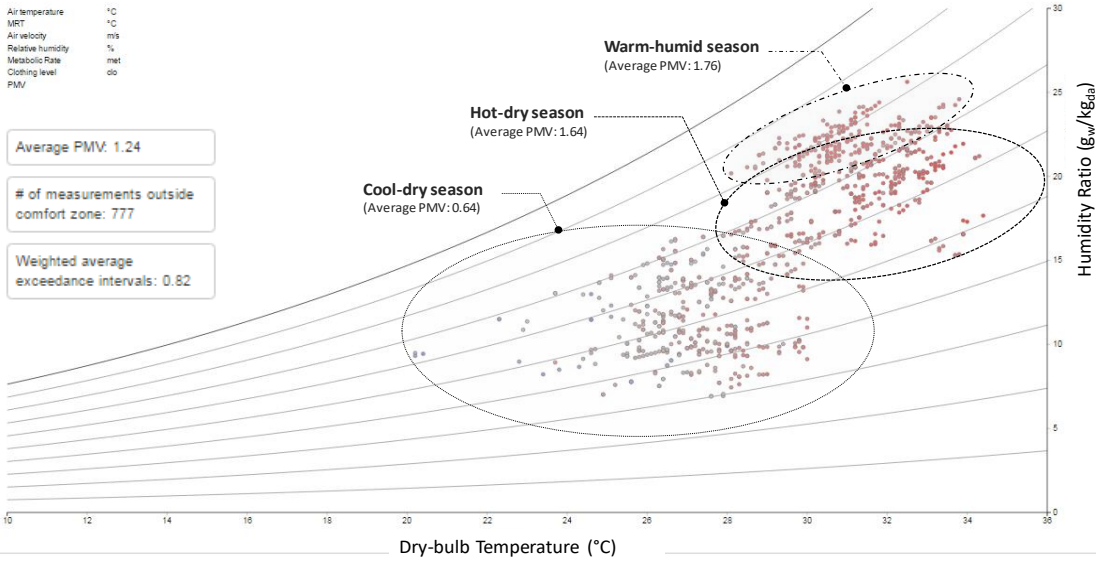


Figure 10-2: Visualisation of measured data* using a psychrometric chart

However, the actual feedback of the workers revealed that 314 (42%) out of 747 workers (excluding the total 161 subjects being not sure about their comfort level) were uncomfortable at their workstations. This is still lower than the 85.6% found by the CBE tool. In particular, only 10.7% out of 309 (excluded 77 'not sure' vote), 56.8% out of 219 (excluded 75 'not sure' vote) and 73.9% out 188 subjects (excluded 9 'not sure vote') were uncomfortable with the thermal environment during season 1, 2 and 3 respectively. It implied that rest of the workers (i.e. 43.6% of the 747 respondents) were either acclimatised or adapted with their indoor environment to be comfortable (Brager et al., 2004). There are the physiological and psychological effect of acclimatised users while we consider thermal comfort and it is usually within the close range of the neutral comfort (Indraganti, 2010, Shajahan and Ahmed, 2016, de Dear and Brager, 2001). It fostered to investigate further on workers' actual neutral temperature and adaptive comfort zone.

The total 72.1% participants among which 96.1%, 59.1% and 30.8%, during the cool-dry, hot-dry and warm-humid seasons respectively, were voted as 'overall acceptable' about their workstations. In another way, 53.13%, 83.9% and 66.4% of acceptability rate found in *RMG Factory 1*, *RMG Factory 2* and *RMG Factory 3* case studies. This indicated the *RMG Factory 1* had the less acceptable working environment while *RMG Factory 2* had the more acceptable one. 74.78%, 69.9% and 62.2% occupants worked in the CS, SS and FS respectively, accepted the overall thermal environment. However, Rijal et al. (2002) suggested that 80% -90% of the occupants should accept the environment as comfortable (Figure 2-6). It should be around the central three scales (vote -1, 0 and +1) of ASHREA seven-point TSV scales (-3 to +3).

10.4.2. Cross tabulations between various scales and thermal data

To examine the actual thermal comfort vote, TSV scale (ASHRAE scale) was cross-tabulated against the TPV scale (McIntyre scale) (Appendix E-1). Total 56.7% of the participants voted within (+1, 0, -1) scale and the 45.8% of the measured environment revealed as the neural TSV also voted as 'no change' in preference scale. However, 28.5% of the workers, who voted as slightly warm (ASHRAE +1 vote) also suggested preferring cooler environment. 3.7% of workers who voted slightly cool (-1), had also voted for 'no change' while the 7.2% of participants who felt slightly warm (+1) voted

'no change' as their preference. This cross-tabulation validated the previous findings suggesting the occupants with 'no change' vote do not fully have 'neutral' thermal sensation. This result is also consistent with those obtained by a number of previous studies (Shajahan and Ahmed, 2016, Feriadi and Wong, 2004, Peeters et al., 2009).

A summary of the statistical database on the votes collected from the workers about their thermal environment was presented in Table 10-4.

Table 10-4: Statistical summary of subjective votes in four different scales

Seasons	**All votes**	**Thermal sensation vote (TSV)**		**Thermal preference vote (TPV)**		**Thermal Comfort vote (TCV)***		**Overall acceptability vote (OAV)**	
		All votes	'Neutral' votes	All votes	'No change ' votes	Votes excluding 'not sure'	'Comfortable' votes	Votes excluding 'not sure'	'Acceptable' votes
	Nos.	Mean (SD)	Nos. (%)	Mean (SD)	Nos. (%)	Nos.	Nos. (%)	Nos.	Nos. (%)
Cool-dry	384	+0.21 (0.66)	216 (56.3)	+0.17 (0.49)	285 (74.2)	309	276 (89.3)	363	349 (96.1)
Hot-dry	327	+0.63 (0.75)	157 (48.0)	+0.50 (0.68)	174 (53.2)	250	108 (43.2)	311	216 (59.5)
Warm-humid	197	+1.16 (0.87)	47 (23.9)	+0.86 (0.68)	61 (31.0)	188	49 (26.1)	191	59 (30.8)

**Author generated customise scale for crosschecking purpose only*

The percentage of votes and mean values clearly illustrated that the workers' thermal experience is distinctly different in different seasons, so as their votes. Figure 10-3 showed the various range of AT voted as the neutral thermal sensation ranges. It gave an insight into the workers' neutral AT range from 23.7^{o}C-29.5^{o}C during the cool-dry season, 26.3^{o}C -33.9^{o}C during the hot-dry season and 28.3^{o}C -31.7^{o}C during the warm-humid season. However, from the Figure 10-3**,** it was not confirmed whether this neutral temperature range was also accepted and preferred by the workers in their workstations.

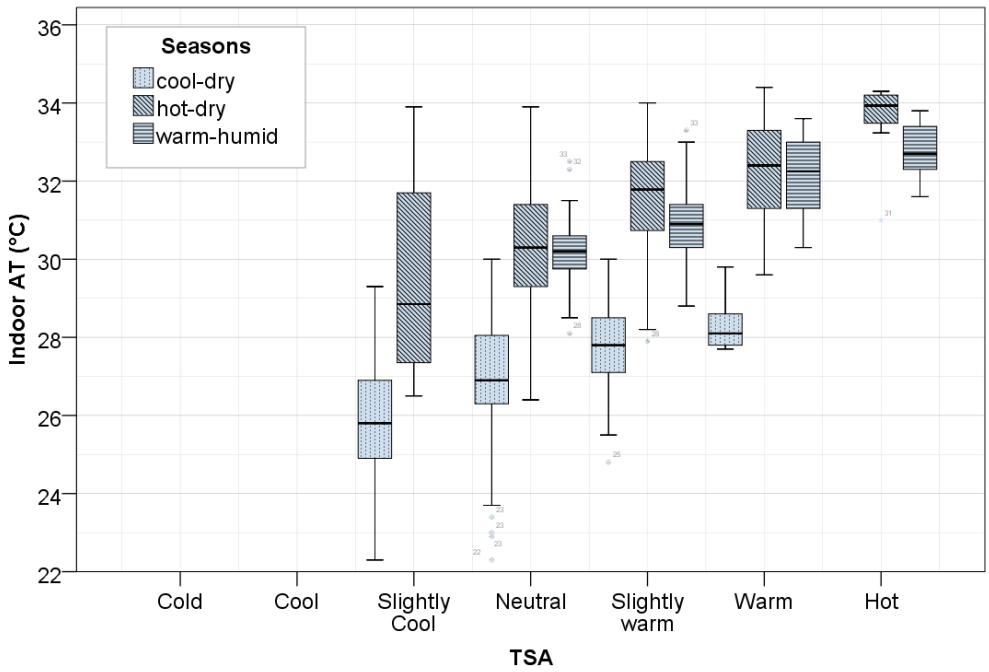


Figure 10-3: Indoor AT ranges measured against TSV during different climatic seasons

While these AT ranges (voted as 'neutral'), in Figure 10-3**,** reflected mainly the impact of climatic seasons, the MRT ranges (voted as 'neutral') of Figure 10-4 represented the variations of thermal environment the workers actually experienced (Halawa et al., 2014) in different production spaces as a combined effect of AT, GT and AV. In addition to the impact of climatic seasons, variations of MRT ranges are clearly visible in different work sections.

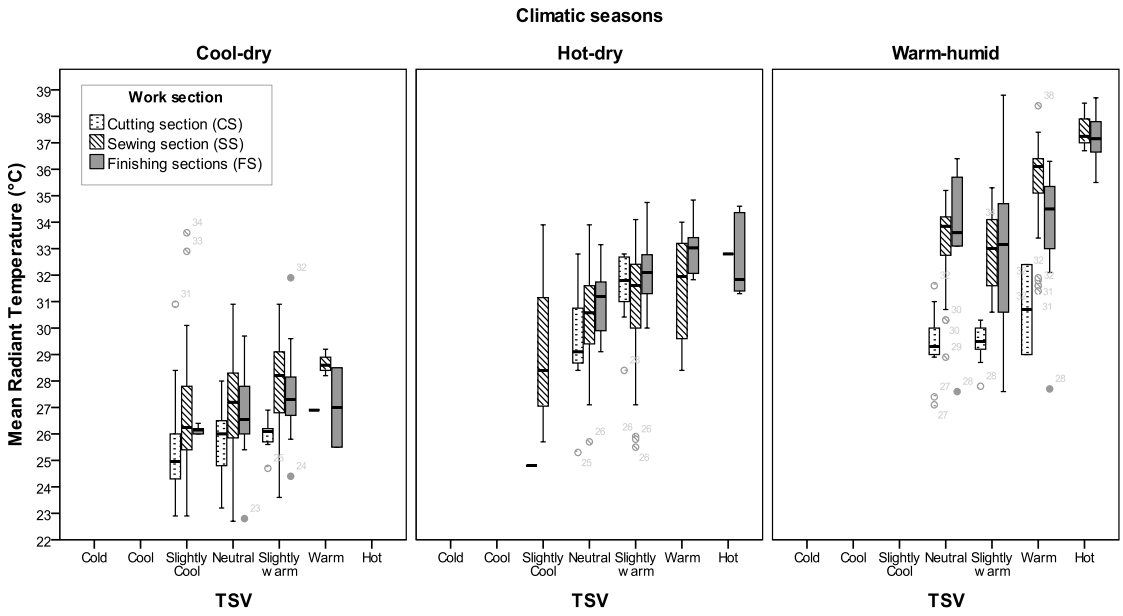


Figure 10-4: Indoor RMT ranges against TSV during different production sections

In particular, during warm humid climate, the workers have high tolerance level in sewing and finishing activities while air speed levels were significantly high (up to 1.8m/s) and AT. RH of the FS was high due to not only monsoon period, but also excessive steam generated in ironing activity in the FS. Local area discomfort can also be the reason of radiant temperature asymmetry up to 5^{o}C (ASHRAE, 2013) which was prominent in ironing work (Sections 7.4.3, 8.4.3 and 9.4.3). It might have reduced the acceptance of the thermal conditions at the FS. It was also observed that WBGT data within low to moderate risk for heat stress in the SS and FS also gained neutral TSV.

10.4.3. Neutral temperature and comfort ranges

According to previous research (Indraganti, 2010, Shajahan and Ahmed, 2016), the neutral range of OT can express the actual thermal comfort range that the users desire considering their flexibility to control their environment. However, the OT database could only include those occupants in RMG factories whose air velocity above 0.2m/s and had control on manoeuvring the windows and switching 'on/off' the nearby fans to control their air speed. 52.2%, 83.5% and 23.5% of participant's workstations in the case study 1, 2 and 3 fulfilled above category correspondingly. However, the neutral OT range, which combined TG and MRT, may not represent preference range of the workers at all zones of the production floors. Neutral AT and the comfort range of AT were also calculated since ASHRAE comfort diagram considers the assumption that MRT is equal to AT (Halawa et al., 2014).

Table 10-5 illustrates the neutral temperatures and thermal comfort ranges with 90% acceptability rate (i.e. from -0.5 to +0.5 TSV scale) for the RMG factory workers derived from the linear regression analyses of TSV and TPV with the AT and the OT.

During the cool-dry season, the workers' neutral AT occurred within 25.9ºC-26.1ºC in all sections while 26.3ºC, 25.8ºC and 25.3ºC were their preferred AT. Regression analyses with OT also provide similar neutral OT with 0.4-0.8% low deviations from the same analyses with AT. However, predicted neutral temperature with PMV method provides 0.4-1.2ºC less NT (3.2% -5.4% deviations).

Table 10-5: Neutral temperature and comfort ranges for RMG factory workers in various production spaces and during different seasons

Season	Work section	Neutral Temperature (°C)					Comfort range (°C) (in 90% acceptability)			Details of the linear regression analysis among TSV and AT***		
		Actual*				Predicted ** (CBE tool: PMV Method)	Actual *		Predicted ** (CBE tool: PMV Method)	Slope	Intercept	R^2
		(ASHRAE 7-point scale)		(McIntyre preference scale)			(ASHRAE scale)					
		TSV vs AT	TSV vs OT	TPV vs AT	TPV vs OT		TSV vs AT	TSV vs OT				
Cool-dry	CS	25.9	25.9	26.3	26.0	24.6	24.4 - 27.5	24.1-27.5	23.1 - 26.1	0.32	-8.2	0.29
	SS	26.1	25.9	25.8	25.6	24.5	22.8 - 29.1	**22.7-29.1**	23.1 - 26.4	0.16	-4.19	0.15
	FS	26.0	25.9	25.3	25.2	24.4	23.8 - 28.4	**23.1-28.5**	22.2 - 26.5	0.22	-5.64	0.22
Hot-dry	CS	28.5	28.6	28.9	29.0	23.8	25.5 - 31.5	25.5-31.5	21.8 - 24.5	0.16	-4.6	0.30
	SS	27.1	26.3	26.8	26.5	25.6	22.9 - 30.3	**22.3-30.4**	23.9 - 27.2	0.13	-3.52	0.10
	FS	29.8	**29.8**	**30.0**	30.0	26.7	28.9 - 30.9	**28.6-31.0**	28.1 - 31.5	0.46	-13.81	0.50
Warm-humid	CS	28.9	28.7	28.9	28.5	28.8	27.7 - 30.1	27.7-30.0	**27.6 - 29.9**	0.42	-12.18	0.65
	SS	29.4	29.8	29.0	28.9	29.3	28.6 - 30.1	**28.7-30.9**	**28.4 - 30.0**	0.57	-16.61	0.64
	FS	27.8	27.5	27.6	26.9	27.5	26.1 - 28.9	**25.4-29.1**	**26.0 - 28.7**	0.38	-10.32	0.33

**Based on the regression analysis with the actual response from the workers during the field studies.*

*** Based on the linear regression analysis with the ASHRAE 55 2013 PMV index by using the field spot-measurement as input data in the CBE comfort tool.*

**** Regression analyses between the 'ASHRAE-55 7-point thermal sensation vote (TSV) and the AT collected during the field studies.*

Similarly, during the hot-dry season, the preferred neutral AT are 28.9°C, 26.8°C and 30°C (with up to 1.4% deviations from TSV regression cases). However, predicted NT were 23.8°C, 25.6°C and 26.7°C in the CS, SS and FS (i.e. 3.3°C, 1.2°C and 3.3°C lower respectively). In these both seasons, the thermal comfort ranges were also higher than the predicted range (e.g. actual range was 22.9°C - 30.3°C, predicted range was 23.9°C - 27.2°C in the SS during the hot-dry season). Comparing the mean AT and MRT in Table 10-2 and Table 10-3 shows that the workers have adapted higher temperature due to their exposure to a wider range of AT variations within a day during these two seasons. This findings also benchmark the standards and validate findings of previous research (Chowdhury et al., 2017b, de Dear et al., 2015, Luo et al., 2015, Schweiker and Wagner,

2015, Zhao et al., 2014, Toe and Kubota, 2013, Schweiker et al., 2013, Mishra and Ramgopal, 2013, Brager et al., 2004, de Dear and Brager, 2001) regarding thermal adaptation with the wider indoor and outdoor temperature in different building sectors. Hence while designing the ventilation and thermal regulations for occupants, raising set point AT to higher than standard may potentially save energy consumption (Yang et al., 2014).

During the warm-humid seasons, both actual neutral temperature and comfort ranges were very similar to predicted ones with a minor deviation up to 2.2% (0.6°C). It also noticeable that, even workers had higher air speed and lower MRT in the FS (Figure 10-4), they still preferred certain AT range (26.1°C - 28.9°C) avoiding local discomfort (ASHRAE, 2013). It also implied that the workers have less adaptive capacity during humid environment (i.e. with the presence of high RH) (Toe and Kubota, 2013) unless they were exposed to preferred air flow to their body skins by fans (Indraganti et al., 2014) and have enough adaptive measures to elevate their comfort (Schweiker and Wagner, 2015, Schweiker et al., 2013). The ironing section which also produces high GT should be treated separately to ensure workers' thermal comfort.

On the other hand, for dry seasons the NT and comfort ranges can be followed maintaining the air speed range synchronised with the AT which varies with contextual factors and the time of the day (Chowdhury et al., 2017b, O'Brien and Gunay, 2014, Toe and Kubota, 2013, Humphreys et al., 2013) (Table 10-5). The adaptive ranges found in standards and codes, including the previous research in similar context, also support the findings of this research (Toe and Kubota, 2013).

10.4.4. Acceptability of the measured comfort ranges

By using the adaptive comfort model in CBE tool, only 125, 36 and 25 'comfortable' votes (while the actual general comfort vote 161, 85 and 27) were achieved during the cool-dry, hot-dry and warm-humid seasons respectively. It also indicated that CBE comfort tool's PMV and adaptive comfort methods with minor adjustments (Luo et al., 2015, Yau and Chew, 2012) are more applicable for determining the comfort ranges of the RMG workers during the warm-humid season. However, workers can adapt higher AT range during the cool-dry and hot-dry climates than the predicted range due to

adaptation to wider outdoor cold or hot environment (Section 2.5.1) and their indoor behavioural, psychological and physiological adaptive processes (Schweiker et al., 2013) in this tropical climatic context of Bangladesh.

Form field survey, total 624 workers (68.7%) accepted the overall thermal environment. It has been found from the data that only 452 numbers (49.9%) of the working environment met the compliance with the ASHRAE Adaptive comfort standard (by using the CBE comfort tool) among which 242 workers (53%) has personal ability to control the nearby fans and/or operate the nearby windows to control the air velocity. CBE comfort tool predicted only 122 no. (50.4%) among the spots would be within the comfortable range (90% acceptability rate) and all of them (242 spots) would be within the adaptive comfort zone. It indicates that providing sufficient adaptive opportunities in their work environment may also increase the acceptability rate (Mishra and Ramgopal, 2013).

On the other hand, from the field study, it has been found that 83.9% of the 242 workers also accepted the overall environment. However, it is also noticeable that 188 nos. of the rest of the spots which do not comply with adaptive comfort range but have operating control or 119 nos. which neither comply with adaptive comfort standard nor has control were still acceptable by the workers. The regression analyses with OT also gave comfort ranges with up to 0.7°C higher adaptation capacity. Due to various GT and AT, MRT also varied according to the type of the workspaces. For the value of air speed less than 0.2m/s, OT=MRT=GT (Equations 5-7 and 5-8), this finding also connected the a previous research where RH influenced adaptive comfort during the hot-dry season while air speed affected that during the warm-humid season (Toe and Kubota, 2013).

10.5. Personalised Control and Adaptive Behaviour

In terms of personal behavioural adaptation, increasing Fan speed or on-off (46%), opening-closing the windows (31%), reducing activity (13%), Tying up hair (5%), changing the dress (2%) and the body posture (3%) were the common activities as found from the questionnaire survey. While ‘opening windows’ was found as a widespread activity in a research by Mishra and Ramgopal (2013), ‘drinking water’

(including saline water), freshen up with cold water in the toilet, standing near to the inlet windows and fans were also counted as adaptive and cultural traits to cope with these workspaces with high temperature (as found from the questionnaire survey). They also highlighted about their limitations to operate the windows and fans due to long distances from their desks. Hence, ensuring the personalised control for workers may not only improve thermal comfort perception by psychological influence but also give a paradigm shift from the conventional centralised ventilation control (Brager et al., 2004, Brager et al., 2015, Luo et al., 2016, Raja et al., 2001).

The NT and comfort ranges were compared with the Table 10-2, Table 10-3 and Figure 10-3. It was noticed that outdoor mean AT can be utilised predicting 95% acceptability rate (Humphreys et al., 2013, de Dear and Brager, 2001) during the cool-dry season and a certain period of the day during hot-dry season. MRT needed to be reduced and the air speed needed to be maintained within comfortable range. Since, in this study, RH and GT range vary with the types of season and production section, AV is the parameter which is closely associated with the ventilation and personalised controlling system (Brager et al., 2015, Rupp et al., 2015, Brager et al., 2004) confirming workers' higher acceptability (e.g. from the air speed above 0.2 m/s workers may have chilling effect) and reduction of energy consumptions (Veselý and Zeiler, 2014). Therefore, further investigation was required to understand how workers responded to their working environment with the variations of the air flow and direction of the air flow.

10.6. Preferred Air Flow Directions and Air Speed Ranges

10.6.1. Preferred directions for airflow

The warm-humid season was considered as the 'worst case' scenario with a consistent AVFR in each case study buildings and only 197 subjects with their workstation conditions were examined. The histogram of the mean AV (n/s) in terms of overall acceptability vote indicated that mean AV (n/s) increased with the acceptability vote (up to 0.85m/s. from the south). On the other hand, mean AV (u/d) decreased against the same vote (as low as 0.7m/s).

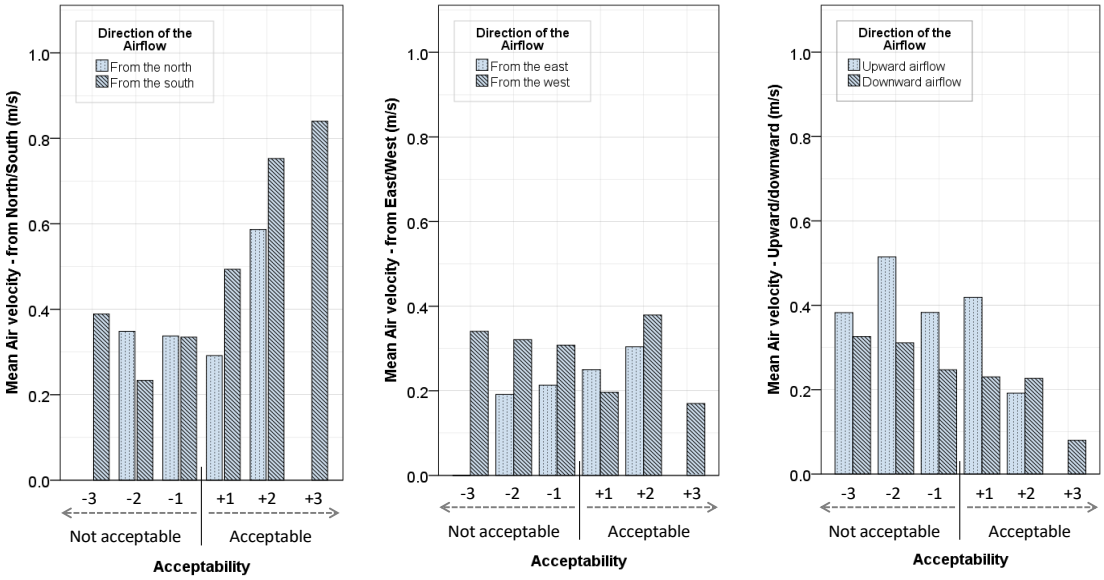


Figure 10-5: Acceptable mean air speed from different directions

For further investigation, 'Spearman' correlation analyses were executed between the environmental data, air speed (from different directions), with the AT and subjective votes. The Spearman's non-parametric correlation analysis was held for each case study building's workspaces separately. Since similar results were found for individual cases, Table 10-6 illustrates that AV (n/s) has positive correlations of 0.322, 0.260 and 0.369 (significant at the 0.01 level, p-value <0.0001) with the overall acceptability vote, preference vote (air flow) and comfort vote (air flow) respectively. It implied that AV (n/s) was more acceptable and desirable to workers at their workstation. It also validated the generalised suggestion from ILO (1998) of designing airflow pattern from the side windows in textile factories and a recent research by Chowdhury et al. (2017b) which was predicted by simulations that RMG production zone with openings toward N-S orientation were high in the performance matrix (average AT 32.4°C, SD 0.98–1.84°C). In contrast, AV (u/d) had negative correlation of 0.180 with the preference vote. It also implied that increase of upward and downward air speed was not preferable to the workers at their work desk.

Table 10-6: Nonparametric correlations (Spearman's rho) between AV (from different directions), AT and subjective votes on air flow

Variable	AV (n/s)	AV (e/w)	AV (u/d)	AT	Overall Acceptability	Preference vote (Air flow)	Comfort vote (Air flow)
AV (n/s)	1	0.559**	0.483**	-0.102 (p=0.153)	**0.322****	**0.260****	**0.369****
AV (e/w)	0.559**	1	0.565**	0.113 (p=0.113)	0.061 (p=0.394)	0.002 (p=0.973)	0.055 (p=0.444)
AV (u/d)	0.483**	0.565**	1	**0.455****	-0.119 (p=0.096)	**-0.180*** (p=0.011)	-0.112 (p=0.117)
AT	-0.102 (p=0.153)	0.113 (p=0.113)	0.455**	1	**-0.590****	**-0.644****	**-0.601****
Overall Acceptability	0.322**	0.061 (p=0.394)	-0.119 (p=0.096)	-0.590**	1	0.840**	0.821**
Preference vote (Air flow)	0.260** (p=0.0002)	0.002 (p=0.972)	-0.180* (p=0.011)	-0.644**	0.840**	1	0.854**
Comfort vote (Air flow)	0.369**	0.055 (p=0.444)	-0.112 (p=0.117)	-0.601**	0.821**	0.854**	1

***Correlation is significant at the 0.01 level (where, significance p-value < 0.0001 unless otherwise stated).*

**Correlation is significant at the 0.05 level.*

Correlation between AV (u/d) and AT was also found as significant as +0.455. It indicated that upward and downward air flow might increase the AT within their workspaces and reduced their acceptability and comfort (with significant correlations -0.591 and -0.601) as shown in Table 10-6. Additionally, it was observed that overall acceptability vote on the thermal environment had significant positive correlations of 0.840 and 0.821 with the preference and comfort vote of air flows respectively.

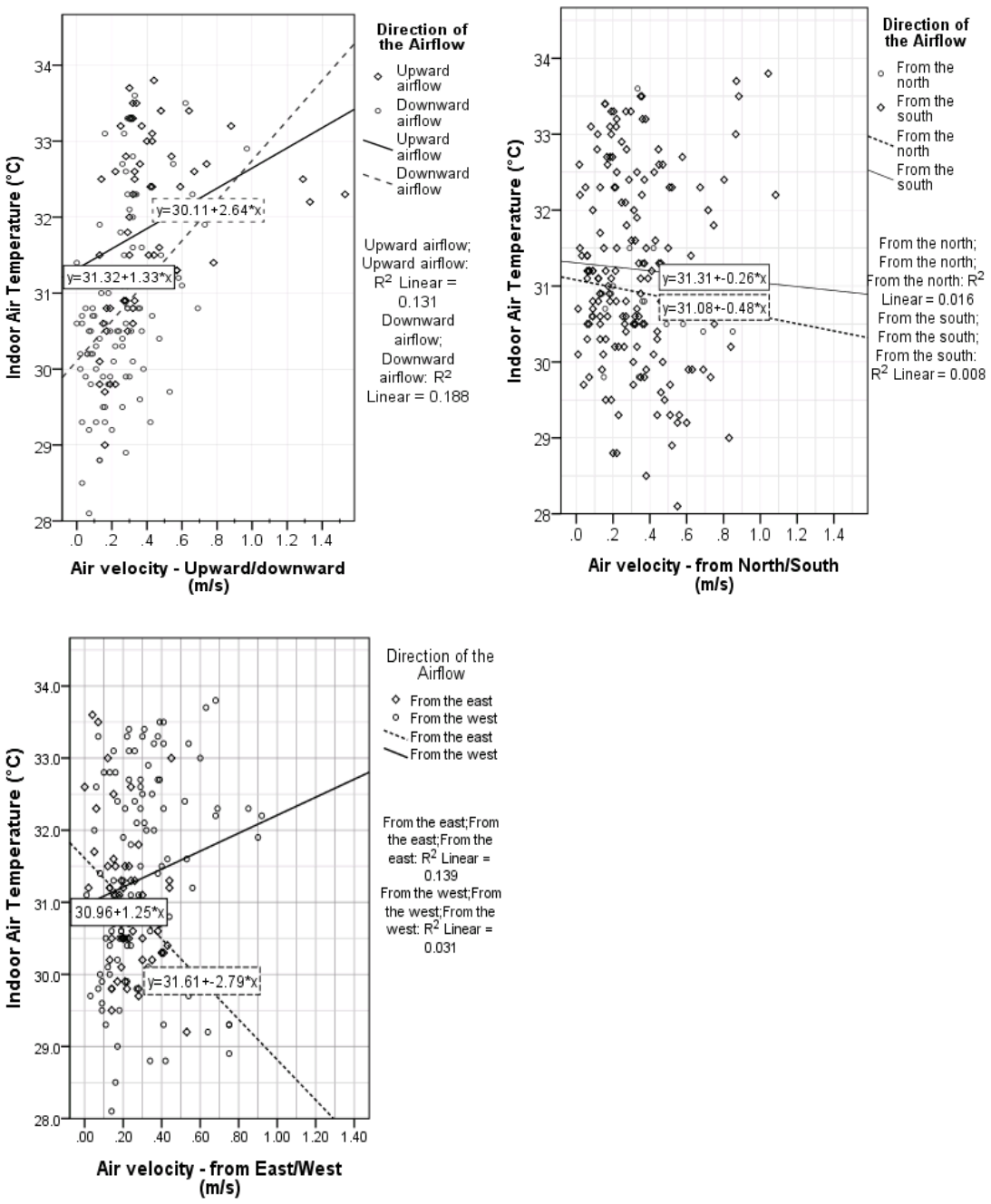


Figure 10-6: Regression analyses between AV (from different directions) and Indoor AT

Further linear regression analyses (Figure 10-6) between AV (from different directions) and Indoor AT revealed that AT increased with both upward and downward AV with the positive slopes of 1.33 and 2.64 of the regression line (where, R^2=0.131 and 1.88). It was determined that for every 1 m/s increase of upward and downward air flow could increase 1.3°C and 2.6°C of AT of the workspaces. Similarly, positive slope of 1.25 of the regression line (R^2=0.031) with AV (from the west) revealed that for every unit (1 m/s) rise of AV from west side would increase 1.2 of AT of the workspaces. In

contrast, the inverse slopes (-0.26, -0.48 and -2.79) of the regression lines between AT and AV from south, north and east sides determined that air flow from these directions significantly helped to reduce the workspaces' AT. The relationship of increasing AT with the airflow from up, down and west trigger to that cause of heat sources (e.g. sewing machine's motor at the bottom, lighting equipment and convective hot air near to the ceiling) and additional radiative heat from the exposed west façade of the buildings. These finding also indicated to ventilation design should consider preferred range of air flow from the south, north and east side, avoiding the air flow from the top, bottom or even west side. Further investigation may be required to examine the relationship of increased AT of workstations for having ceiling fans.

10.6.2. Preferred air speed ranges

Table 10-7 illustrates the mean and acceptable ranges of air velocities (i.e. 90% acceptability range, -0.5 to +0.5) for the worker to execute the production work in different kind of workspaces comfortably.

Table 10-7: Preferred air velocity* at different workstations

	Work section	**Comfortable Air Speed, m/s (Bedford sensation scale)**		**Preferred Air speed, m/s (McIntyre preference scale)**	
		'Perfect' vote Mean (SD)	Comfortable air speed range	'no change' vote Mean (SD)	Preferred air speed range
Average air flow (from all direction)	CS	0.3 (0.13)	0 – 0.6	0.3 (0.12)	0.4 – 1.6
	SS	0.3 (0.14)	0.4 – 1.2	0.3. (0.10)	1.6- 3.8
	FS	0.3 (0.26)	1.2 – 3.0	0.3 (0.14)	Undefined**
From east side	CS	0.4 (0.14)	0 – 0.7	0.5 (0.04)	0.5 – 0.9
	SS	0.3 (0.08)	0.8 – 2.5	0.3 (0.08)	0.3 – 0.6
	FS	03. (0.12)	Undefined**	0.3 (0.12)	0.4 – 0.8
From north/south side	CS	0.4 (0.20)	0 – 1.2	0.5 (0.18)	0.4 – 1.1
	SS	0.5 (0.25)	0.7 – 1.8	0.5 (0.23)	**1.2 - 2.8**
	FS	0.4 (0.22)	1.2 – 2.5	0.3 (0.17)	**2.8 – 5.8**

** AT, GT and RH were within the fixed range found in different type of working sections during warm humid season (Table 10-2)*

***the slope of the regression line was not high enough to define the air speed range.*

Table 10-7 reveals that they preferred higher ranges of air velocity at the SS and FS, especially from north/south side (e.g. 1.2 -2.8m/s, higher than 0.7-1.8). In all production sections, the mean air velocities were minimum 0.3m/s while the preferred ranges were also suggested above 0.3m/s. It indicated that to air speed should be maintained as minimum as 0.4m/s in all section with the highest air speed of 1.1m/s, 2.8m/s and 5.8m/s for cutting, sewing and finishing (i.e. ironing) works respectively in RMG factories. The maximum air speed range also reflected allowable air speed to conduct the certain nature of work, such as the CS involved in cutting small pieces of clothes and desired less air speed. It was inclusive to less AT and GT of the CS.

Previous research (Chowdhury et al., 2015, Fatemi, 2012) proposed 0.6 m/s as a mean comfortable air velocity. However, it cannot be generalised and applied to all production section. The FS accepted an air speed well above than the previous values as suggested in standards, which also support the findings from Cândido et al. (2010) about the acceptability of higher air speed for user's thermal comfort. Thus, this research outcome specified the mean and allowable range of the air speed for certain production section which would be useful for enhancing the existing ventilation system or designing a new with more personalised air movement (Brager et al., 2015, Brager et al., 2004).

10.7. Threshold Distance from Inlets or Workspace Width

Figure 10-7 provided an insight into the distribution of AT from air-inlet windows to air-outlet in different time of the day inside the *RMG factory 1* and *RMG factory 3* buildings (the SS only keeping the other variables constant). It was found that the indoor AT rose above the targeted comfort range of AT from the centre-M point of the building floor, especially after 11 am. Hence, reducing AT and ensuring preferred AV were mainly required to ensure worker's comfort, as recommended by Toe and Kubota (2013) in their study.

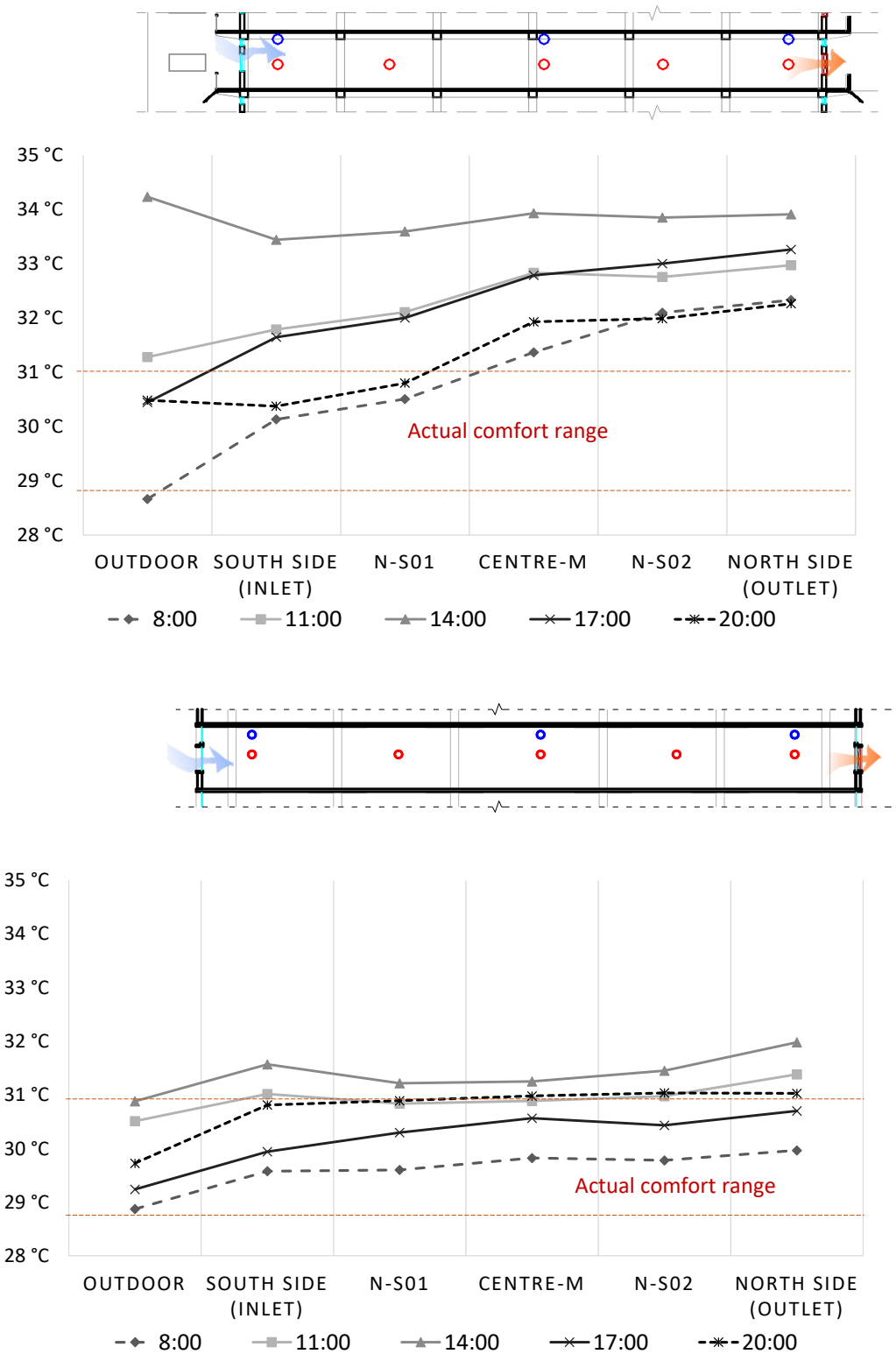


Figure 10-7: AT profile* along the inlets to outlets axis at (a) 1st floor (SS), RMG factory 1 and (b) 4th floor (SS), *RMG factory 3*

**During working hours of the hottest day at sewing floor during the warm-humid season (8 August 2015 and 26 August 2015)*

To observed the effect of 'distance of inlet' on workers' thermal sensation, TSVs and 'airflow sensation votes' were presented against the average air-inlet distance in a boxplot diagram (Figure 10-8). It revealed that all the 'warm' and 'hot' votes were gathered between 20-30m distances, while neutral votes were gained within a maximum of 16m distance (*RMG factory 3* only).

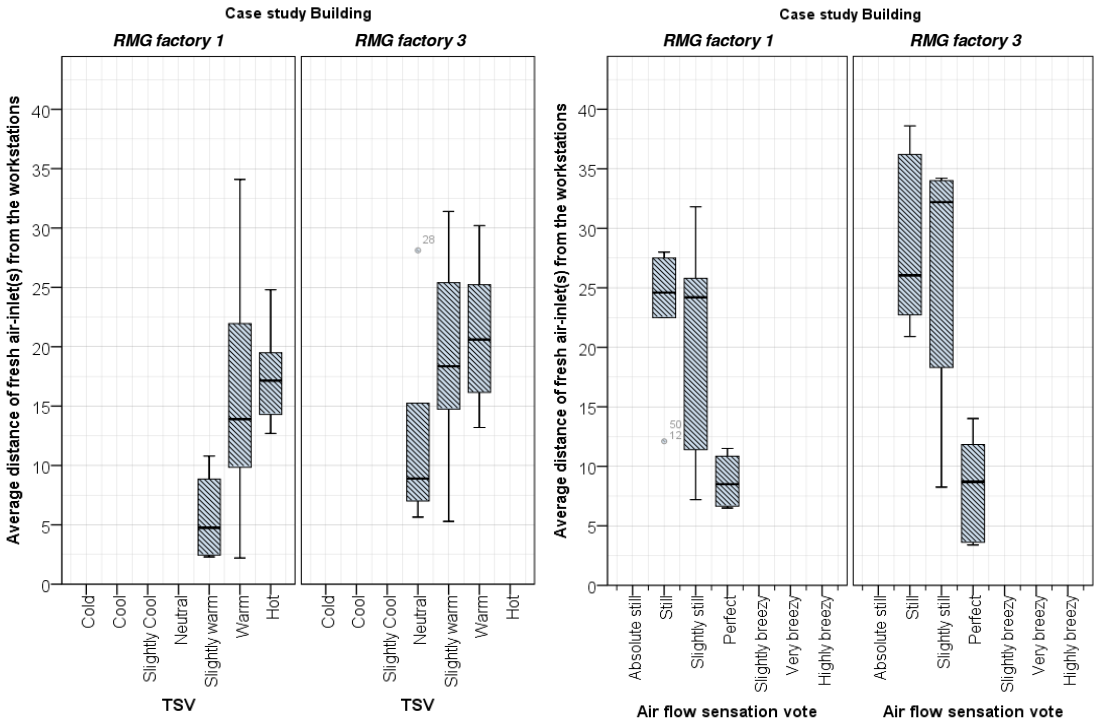


Figure 10-8: Subjective vote distributions in terms of workers' location in the SS

To identify whether there were correlations between 'distances of the inlets' and 'sensation votes', Spearman's non-parametric correlation analyses were executed (Table 10-8). Significant correlations of -0.5 and -0.324 were found with TSV and 'air flow sensation vote' respectively. It implied that workers comfort declined with the rise of distance from ventilation-inlets. Correlations between AV and distance of inlets reveals that AV also decreased with the significant correlation coefficients of -0.325 and -0.261. These correlations are also reliable with the statement that air loses the velocity by the distance it travels from the inlet windows (Heiselberg et al., 2001). However, the results were unable to recommend the ideal distance of inlets from a workspace for ensuring workers' thermal comfort.

Table 10-8: Non-parametric correlations (Spearman's rho) between 'distance from ventilation inlets', 'thermal parameters' and 'votes'

Variables	Average distance from ventilation inlet(s)	OT	AT	TSV	AV (from N/S)	AV (Average)	Air flow sensation vote
Average distance from ventilation inlet(s)	1	**0.320****	**0.390****	**0.500****	**-0.325****	**-0.261**** (p=.0002)	**-0.324****
OT	0.320**	1	0.569**	0.306**	-0.099 (p=0.165)	-0.096 (p=0.180)	-0.093 (p=0.194)
AT	0.390**	0.569**	1	0.678**	-0.102 (p=0.153)	0.139* (p=0.051)	-0.251** (p=0.0004)
TSV	0.500**	0.306**	0.678**	1	-0.255** (p=0.0003)	-0.038 (p=0.600)	-0.540**
AV (from N/S)	-0.325**	-0.099 (p=0.165)	-0.102 (p=0.153)	-0.255** (p=0.0003)	1	0.829**	0.464**
AV (Average)	-0.261** (p=.0002)	-0.096 (p=0.180)	0.139* (p=0.051)	-0.038 (p=0.600)	0.829**	1	0.339**
Air flow sensation vote	-0.324**	-0.093 (p=0.194)	-0.251** (p=0.0004)	-0.540**	0.464**	0.339**	1

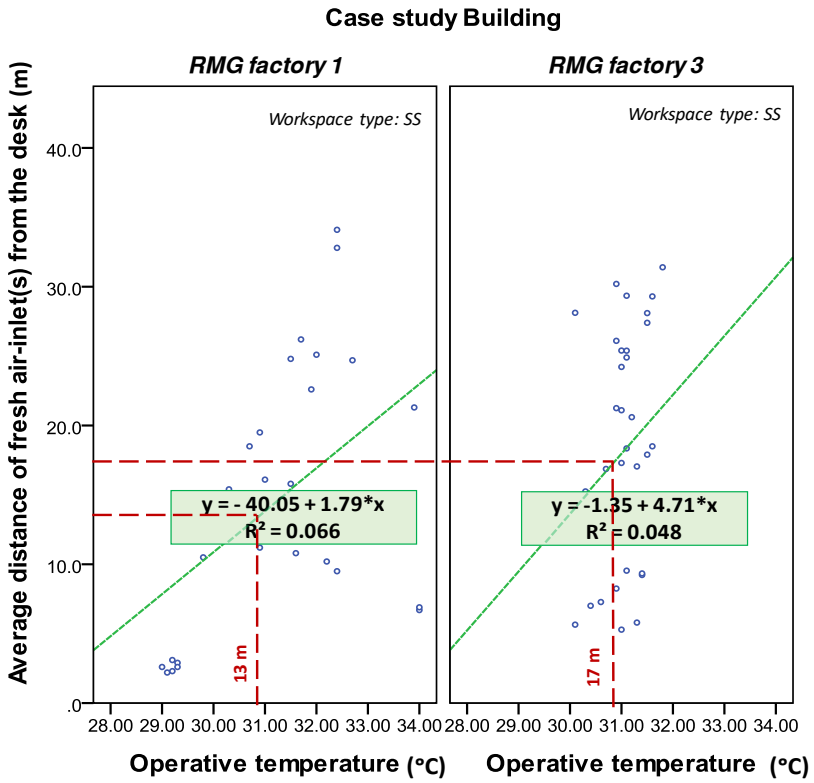
***All correlations are significant at the 0.01 level, significance p-value < 0.0001, unless otherwise stated*

AT rises and air speed falls while the distance from the ventilation inlets (i.e. windows) increases. To define the acceptable distance of ventilation-inlet, the database of OT and air speed (from north or south directions) groups were assumed as the independent variable while the distance was the dependent variable. Linear regression models (Figure 10-9) were carried out to measure the relationship between them. The linear regression equations (slopes: +1.79 and +4.71) revealed that distance of the ventilation inlet should be 13m and 17m (*RMG factory 1* and *RMG factory 3* respectively) from the workers to keep them within the comfortable OT threshold of 30.9°C for the SS (Table 10-5).

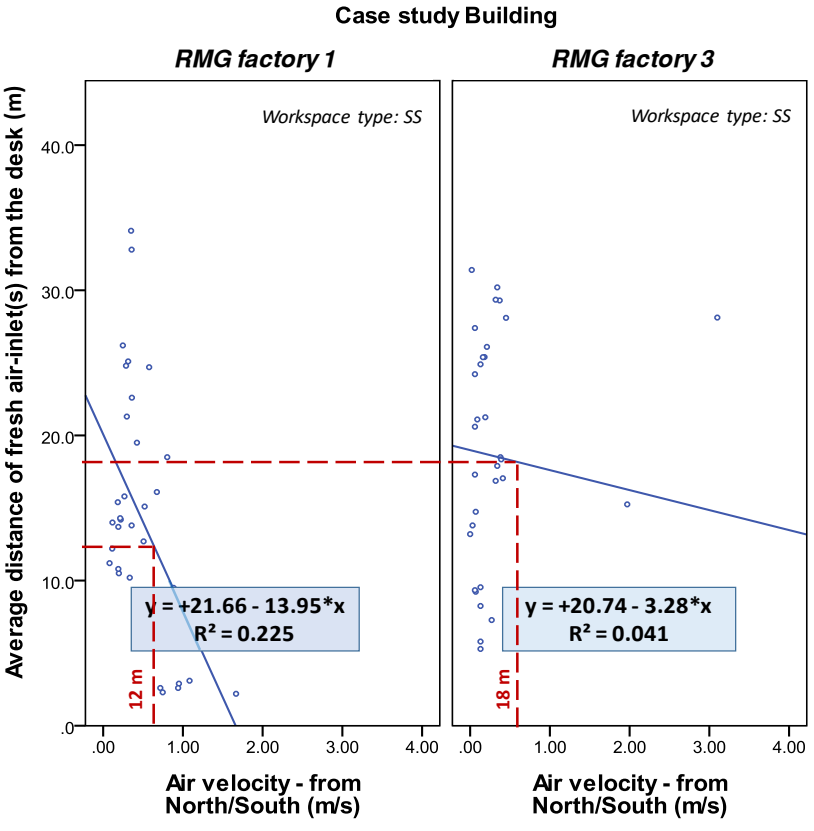
On the other hand, the regression equation (slopes: -13.95 and -3.28) revealed the distance should not exceed 12m and 18m (*RMG factory 1* and *RMG factory 3* respectively) to maintain the minimum air speed (north or south) of 0.7m/s suitable for the SS (Table 10-7) for sewing workers' workspace. The value of R^2 also represented that the significance of OT and AV-n/s within all variables that may influence to determine the required distance of the inlets.

It also can be observed that the threshold distance was relatively high (17-18m) for workspaces without ceiling fans (*RMG factory 1*), while that was relatively low (12-13m) for workspaces with ceiling fans (*RMG factory 3*). It might indicate that building can be designed with wider floor plates when there is no ceiling fans ensuring thermal comfort for the workers.

The regression analyses indicated that new ventilation inlets and outlets should be considered in these kinds of RMG buildings to improve the existing indoor thermal condition. In particular, it may be possible to ensure thermal comfort in peak hours by only maintaining air movement factor (Toe and Kubota, 2013) without a supply of cool air (cooler than the outdoor AT) from inlet windows during the warm humid season. Rest of the time of a day, personalised fan and control should be provided to elevate their comfort level, as suggested in previous research (Brager et al., 2015, Rupp et al., 2015, Nicol and Roaf, 2005, Brager et al., 2004). Moreover, the width of building floor can be reconsidered while designing the RMG factories' SS with the similar ventilation system (rule of thumb as shown in Section 3.5.1).



(a)



(b)

Figure 10-9: Scatter plot diagrams with regression lines of distance of air inlets (in meters) with OT (in °C) and AV from north/south side (in m/s)

10.8. Subjective Feedback and Workable Design Strategies

10.8.1. Common strategies based on workers' feedback

The workers from all case study buildings suffer from thermal discomfort, particularly inside the SS and FS, as described in Sections 7.8, 8.8 and 9.8. Section 10.5 and results from total six focus group discussions (Sections 7.8.2, 8.8.2 and 9.8.2) confirmed a preference for workstations located next to the windows where air speed is high, as opposed to work-stations in the middle of the floor plate where perceived air speed was negligible. They recommended providing more flexibility in operating the windows, even in the rainy seasons, and more personalised control over the operation of all type of fans. Workers should also be allowed to conduct enough adaptive measures (as mentioned in Section 10.5) to improve their thermal comfort.

10.8.2. Building designer's feedback

As mentioned in Section 5.5.7.5, informal responses regarding the design intends, occupants' comfort of and scope of improvement existing workspace were collected from the architect of the case study building-3. At the design stage, He considered the 35m wide workspace with 16 extract fans on each floor based on an theoretical estimation of horizontal air velocity and effective temperature (ET) the workers may experience at their workstations as a result of running the extract fans. However, he admitted that he had to assume the thermal comfort target, since there was no reliable standard guideline and was not aware of the effect of manoeuvring existing sliding windows on indoor thermal performance. From his previous design experience, he believed that ceiling fans are not useful for enhancing workers' thermal comfort since the airflow from ceiling fans actually hamper the main ventilation flow pattern induced by the extract fans. He also agreed with the researcher regarding the existing thermal discomfort that workers experience and saw value in improving the window configuration and ventilation strategy and reconsidering the workspace width (distance between inlet-windows and outlets) for new RMG factory buildings. He also expressed his interest to know the outcome of this research so that he can receive the scientific evidence of the existing issues and the feasible design solutions.

10.8.3. Common strategies based on factory owners' feedback

Previously in Chapters 7, 8 and 9, existing environmental condition of workspaces were investigated through a number of extensive field studies and a range applicable intervention were proposed intending to improve the existing scenarios of workspaces subject to the climatic conditions prevailing in Bangladesh. Table 10-9 provides a summary of the existing scenario of workspaces of three case study buildings and the proposed strategies to improve the existing scenario.

Table 10-9: Existing common scenarios and proposed interventions for existing three case study buildings

	Existing scenarios	Proposed interventions / improvements
i.	Ventilation operated during working hours only	Implementation of continuous day time ventilation complemented by an NTV / thermal mass strategy
ii.	Use of sliding windows with only 45% effective opening area and no solar control	Redesign of windows to increase effective opening areas and integrate solar control
iii.	Reliance on mechanical ventilation	Introduce a ventilation stack into the centre of the building to induce buoyancy driven flow
iv.	125mm thick brick masonry external wall and concrete floor plates	Changing wall, ceiling and roof design to increase thermal mass
v.	Production sections present a barrier to air flow and workers have Limited personalised control over the air flow	Segmented production area with personalised control for occupants to enhance more effective air flow to reduce MRT

Focused on the meeting agenda nos. 1 and 2 during the interviews (Section 5.5.7.4 and Appendix E-3), the owners and managing directors generally confirmed that they had received complaints about workers' thermal discomfort in the SS and FS, especially during the warm-humid seasons. They highlighted about the complex nature of indoor airflows in *RMG factory 1 and RMG factory 2* which made them difficult to understand how to resolve the ventilation issue of these workspaces. In response to this, the authorities of these two case studies increased the number of ceiling fans in the case study building. However, they claimed it did not help to reduce workers' thermal discomfort. They mentioned that they were optimistic about implementing any solutions that might lead to improvements. Owner of the *RMG factory 3* emphasised on issues of discomfort during rainy season while workers usually have to keep the

windows shut. Hence, building owners of all the case study building see value in improving the present environmental condition of workspaces and look forward to feasible solutions.

Table 10-10 illustrates the summary of their feedback at the discussion covering 'agenda 3' of the interview. Since the internal functional layout and the building façades, such as design elevations, are fixed, they face limitations in relation to make changing to their existing building. Moreover, they could only implement those changes during vacations without hampering the ongoing production process in their RMG factories. They fully agreed that it is feasible for them to immediately implement the NTV strategy, change the configuration of all windows and segment the work zones enhancing the uniform air flow if it improves workers' thermal comfort. Adding ventilation stacks, rearranging functional layout and changing construction materials can only be adopted in their future RMG buildings subject to the further evidence of the environmental benefits.

Table 10-10: Summary of factory owner feedback on proposed strategies

Proposed strategies	Factory owners' feedback on applicability of proposed strategies		
	RMG factory 1	***RMG factory 2***	***RMG factory 3***
Run full day ventilation complemented by night time ventilation (NTV)*	Yes. It is possible to arrange night time ventilation strategy. They only need to change security and management policy during the unoccupied hours ensuring the windows are open and fans are active.	Yes. It is 100% possible for them to implement.	Yes. It is absolutely possible to arrange night time ventilation strategy.
Change the configuration and type of window*	Yes. They can change the window type to increase the effective area. Relocation of the windows on the east, west and north facades of the buildings is also possible.	Yes. They are able to change the window configurations. They agreed that sliding windows have low effective opening. However, they cannot change locations of inlets.	Yes. It is possible for them to change the window configuration. They can also relocate the outlets within the limitations of the building structure.
Add ventilation stacks	No. Construction of shafts may interrupt the ongoing production inside the building. It also posed structural implications. However, it is possible for new buildings projects.	No. They cannot add ventilation stacks due to building's structural limitations. Moreover, they are not allowed to do major refurbishment as it is a rented building.	No. They cannot interrupt production process. Structurally it may not be viable. However, it is possible in new buildings.
Re-arrange functional layout with personalised control and segment zones	The layout is kind of fixed in the existing building. Hence only possible while designing new building. Segmentation of zone and personalised control over ventilation are possible.	The layout is fixed, as they got very limited allocated production spaces. Segmentation and more personalised control over airflow may be possible.	The layout is fixed. However segmentation of ventilation, particularly the isolation of ironing section, is only possible. Personalised control system may be possible.
Change construction materials	No. They are unsure about the existing structural capacity. However, it is possible for them to explore different materials in upcoming new RMG building projects.	No. It is not possible to make any changes to the existing construction material, though they are aware of hot external walls of the west facades.	No. There are structural limitations of the existing building. However, this is possible for their future building projects.

**Feasible and immediately applicable solutions, as agreed by the owners and managing directors*

As an outcome of agenda 4, Owners from *RMG factory 1* and *RMG factory 3* mentioned that they generally use a 2-year payback plan for any financial investment in their RMG factories. However, they have no particular limit on investment and any payback plan when it comes to the investment for improving the indoor environment of production spaces. Owner from *RMG factory 2* proposed their 2-year payback plan without any budget limit, since workers' health and efficiency are their priority. All of them believe any investment for workers' comfort will be naturally paid back through improved work efficiency. In the last agenda item (agenda 5), they also added that they would like to reconsider the location of inlets and outlets within their existing and new buildings. In the discussion on improving the efficiency of the existing equipment by adopting lower heat output equipment, they all mentioned that they were already in the process and might change equipment, such as sewing machine, in the future. Owner of the *RMG factory 3* raised the issue of not having viable standard they can follow to improve the present condition.

From the three interviews, it was clear that adopting NTV strategy and changing window configurations are the immediately workable strategies for all case study building. Adding ventilation stacks, rearranging functional layout with segmented ventilation and changing construction materials are less or not feasible to implement in their existing buildings. However, they can be workable solutions for new buildings.

10.9. Limitations of the Results of This Chapter

10.9.1. Implications of thermal comfort results

The environmental data monitoring and spot measurements were undertaken for around 10 days for each of three case study buildings during each season (Sections 5.5.3 and 5.5.6) assuming that the data represent a whole year's performance. Therefore, the thermal comfort guidelines, based on these data, presented in this chapter may not be representative for a whole year of thermal comfort and may need further study to apply them to other RMG factory buildings in Bangladesh. However, validated simulation studies can be undertaken and these guidelines can be used as a starting point and can be projected predicting the thermal comfort ranges for a whole year.

10.9.2. Limitation of the retrofitting measures

The following limitations of the workable solutions, presented in Section 10.8, need to be addressed before implementing them in real site:

- Increasing the effective opening of the windows may also bring polluted air, noise and dust inside the building which need further investigation.
- As stated by the building owners (Table 10-10), proposed retrofitting measures will result in disruptions to the workflows of RMG productions. For instance, installing new windows will involve closure of the workstation lanes close to window facades limiting the production process. Acknowledging these disruptions, further study is needed for phasing the retrofitting process during the factory closure time (e.g. Bank holidays, Eid holidays and during the month of low production orders) to minimise disruptions.
- Though factory owners are ready to invest any amount to adopt the improvement measures (Section 10.8.3), a detail market survey and estimation of the associate costs, such as expenses for design consultancy, local product procurement, construction labours and services, are the prerequisites before implementing any of the workable strategy. However, these estimations are beyond the scope of this research.

10.10. Summary

This chapter firstly aimed to provide a brief comparative study on thermal environment of three case study buildings and establish through statistical analyses the targeted workspaces for the factory factories' workers, such as their neutral comfort temperature, comfortable temperature range, preferred air speed and air direction at their workstations, preferred distance from the inlet, to execute specific production works during different seasons. The key finding of this chapter can be shown a follows:

- Variations in internal heat gains and resultant indoor thermal condition, such as AT, GT and MRT, in three type of production sections indicated the considerations of different thermal comfort targets (i.e. preferred AT and AV) for the workers in existing multi-storied RMG factories. The thermal comfort ranges should also be determined by three different climatic seasons, for

instance different diurnal ranges of AT and RH within a day over the site context.

- The preferred neutral temperature for the workers allowing adaptive behaviour in the CS, SS and FS were found between 25.2°C and 26°C during the cool-dry season, while those ranges were higher during the hot-dry and warm humid seasons (26.5°C - 30°C and 26.9°C - 28.9°C respectively) (Table 10-5). It was revealed that during the cool-dry and hot-dry seasons, the workers had wider adaptive temperature range (e.g. 22.7°C-29.1°C and 22.3°C -30.4°C respectively in the SS) than the warm-humid season (e.g. 28.7°C -30.9°C).
- Due to high RH and narrow comfort range during the warm-humid season, comfort condition in a workspace with high AT may only be improved by reducing GT which may depend of the elevated airflow effect.
- In these multi-storied RMG factories, workers preferred air flow from north, south and east side, while upward and downward air flows, such as from ceiling fans, were not preferable and caused increased AT.
- Though the mean values of preferred air speed for all production works were found between 0.3 to 0.5 m/s, the air speed (e.g. air flow from north or south) ranges in the CS, SS and FS were preferred as 0.4 – 1.1 m/s, 1.2 - 2.8 m/s and 2.8 – 5.8 m/s respectively (Table 10-7) to execute the specific production works comfortably.
- Sewing workers' TSVs increased and air flow sensation votes decreased with the distance of their workstations from the ventilation inlets.
- Correlation and regression analyses suggested that the workstation-distance from the inlets should be maintained from 12m to 18, for instance, 17m for *RMG factory 3* building without ceiling fans, to maintain the indoor thermal condition within the threshold point of preferred OT and air speed in the SS. This also suggests that the ceiling height to floor-plate width ratio should be maximum 1:5 to ensure effective ventilation and sufficient workflow within the workspace.
- According to the feedback from workers, better personalised control over the ventilation and airflow at their workstations, including control over fans and windows, can be considered as a workable improvement strategies.

- According to the outcome of the interview with the owners and directors of all three RMG factories, the full day ventilation with NTV strategy and changing the window configurations are the immediately implementable aiming to improve workers' thermal experience in their existing RMG factories.

The finding of this chapter can be considered as the threshold thermal conditions while designing as well as evaluating existing multi-storey RMG factory building in similar climatic context. The outcome of this chapter will also be used as design targets for parametric studies in the next chapter (Chapter 11).

CHAPTER 11. SIMULATION STUDY: EXPLORING THE BENEFITS OF WORKABLE STRATEGIES

This chapter presents a simulation study used to quantify the effects of applying a number workable strategies in an existing RMG factory building. The validation process of climate data and an IES-VE simulation model is outlined. The simulation results are compared and benefits are highlighted.

CHAPTER 11. SIMULATION STUDY: EXPLORING THE BENEFITS OF WORKABLE STRATEGIES

11.1. Introduction

As indicated by the factory owners and managing directors, it was a rational requirement to quantify the benefits of implementing the proposed strategies in existing buildings' workspaces (Section 10.8.3). In this chapter, a parametric study was undertaken to explore the likely benefits of the proposed workable solutions on the indoor environmental conditions within an existing RMG factory located in a tropical climate in order to estimate potential improvements to the comfort of their occupants.

11.2. Chapter Aim and Scope

The main aim of this chapter to provide the answer of the following sub-question of this doctoral research:

> *"To what extend are the workable design strategies beneficial in terms of improving workers' thermal comfort within the workspaces?"*

Hence, the main objectives of this chapter are to make a computer based simulated model validated with the existing scenario and explore a range of parameters associated with the workable solutions quantifying the benefits them for improvement (Section 5.6). After defining the simulation scenarios and targeted thermal environment, this chapter explores the parameters and presents the results.

11.3. Threshold Values for Workers' Thermal Comfort

Based on the results from Chapter 10, the thermal comfort condition of workspaces will be assessed based on some set criteria. The indoor environment will be evaluated targeting an AT ranges as shown in Table 11-1 where assumed mean air speed will be 0.3 m/s. Acceptable RH is below 65%. These target values will be considered while evaluating the indoor environment for various production spaces and climatic seasons through Dynamic Thermal (DT) Simulations. Preferred air velocity ranges and threshold distance will be followed, as shown in Table 11-1, in the SS for CFD simulations.

Table 11-1: Threshold values for achieving thermal comfort of the workers (source: Chapter 10)

Measurement variables and target/ranges			
Preferred Temperature in the CS, SS and FS during the three climatic seasons			
Season	**Workspace Type**	**Comfort range (°C)**	
		Lower Limit (min.)	Upper limit (max.)
Cool-dry	CS	24.1	27.5
	SS	22.7	29.1
	FS	23.1	28.5
Hot-dry	CS	25.5	31.5
	SS	22.3	30.4
	FS	28.6	31.0
Warm-humid	CS	27.7	30.0
	SS	28.7	30.9
	FS	25.4	29.1
Comfortable RH range (%):		<65%	
Preferred air velocity in the SS of RMG factory 1 during warm humid season			
Season	**Direction of air flow**	**comfortable air speed range (m/s)**	**Preferred air speed range with personalised control of airflow (m/s)**
Warm-humid	All side (average)	0.4 – 1.2	1.6 - 3.8
	East	0.8 – 2.5	0.3 – 0.6
	North/South	0.7 - 1.8	1.2 – 2.8
Maximum distance from inlets for workers with a provision of personalised control		17m	
Improvement measurement scale		Working hours within the comfort range (%)	

11.4. 3D Modelling and Initial Input Parameters

As referred in Section 5.6.3, Figure 11-1 shows the IES-VE simulation model of RMG factory-3 with the surface solar radiations. Table 11-2 summarises the input parameters applied to the model before running the in DT simulations 'ApacheSim'.

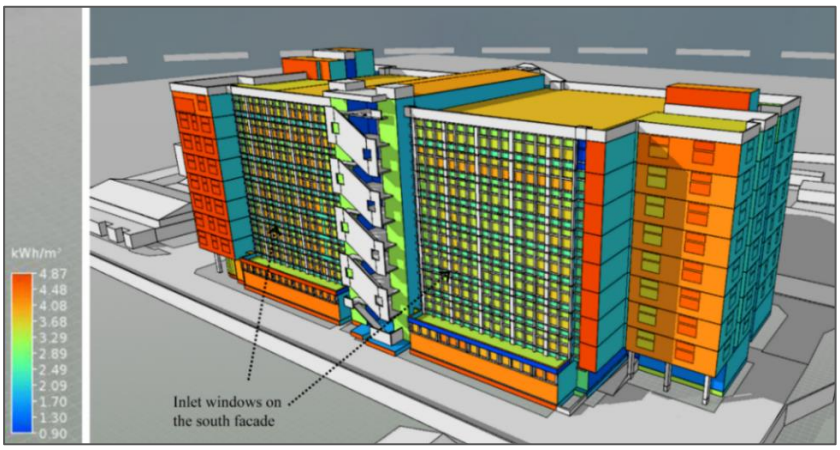


Figure 11-1: 3D model showing surface solar radiations of *RMG factory 3* in IES-VE (source: author)

Table 11-2: Fixed and variable parameters used the IES-VE model of the case study building-3

Parameters of the simulation model in IES-VE	
Weather Data	Energy Plus (.epw) formatted file calibrated with the meteorological data of Dhaka (the year 2015) and outdoor field data (2015) (explained in Section 11.5).
Calendar and working hours	Dynamic simulation for the whole year was run and results extracted for three representative months/days of the three different climatic seasons. Fridays were considered as the weekend. Daily and weekly profiles are made considering the working hours 0800-1900 and lunch break 1300-1400.
Thermal comfort	As stated in Section 11.3
Thermal aspects: fixed parameters	
Room conditions	No heating or cooling
Systems*	No HVAC or DHW system
Internal Gains	Fixed parameters as found in the field study of the existing case study building. Number of people: 216, 750, 780 in the CS, SS and FS respectively, Lighting load: 10-13.5 W/m^2, Equipment load: 16-40 W/m^2 calculated from collected equipment load and efficiency data
Air Exchanges	Infiltration: 1 Air change per hour (ACH)
	Auxiliary ventilation: 193m^3/s (CS), 193m^3/s (SS), 181m^3/s (FS) measured during the field survey in the year of 2015
Constructions: fixed parameters	
Roof	0.2m thick RCC with 13mm cement coating, U-value: 0.698 W/m^2.K, Thermal mass CM: 53.4 KJ/(m^2.K), Specific heat capacity: 840 J/(kg.K) (concrete slab) 1000 J/(kg.K) (thick plaster and cement coating)
Internal ceiling/floor	0.15m thick concrete floor with 13mm thick light plaster and cement coating, U-value: 3.224 W/m^2.K, Thermal mass CM: 136 KJ/(m^2.K), Specific heat capacity: 1000 J/(kg.K) (concrete) 1000 J/(kg.K) (plaster and cement coating)
External Walls	0.125m brickwork with medium weight plaster, U-value: 1.5188 W/m^2.K, Thermal mass CM: 195.6 KJ/(m^2.K), Specific heat capacity: 800 J/(kg.K) (brickwork) 1000 J/(kg.K) (plaster)
Glazing and frame types	Clear float 6mm glass (G-value: 0.587) with aluminium frames and recessed local shade.
Door	42mm thick Steel sliding-HF-A3 (U-value 5.617 W/m^2.K)
Local shade	RCC with light-weight plaster (U-value:2.557 W/m^2.K
Ventilation (MacroFlo): fixed parameter for existing scenario	
Opening type	Opening Category: Sliding windows on external walls with 45% openable area.
Door	Sliding door (50% effective opening)
Degree of opening (modulating profile)	The windows are considered as continuously open with 75% and 0% modulating value during daytime and night-time respectively. The doors are considered closed (0 modulating value) during unoccupied hours.
Air flow (Microflo): fixed parameters	
Boundary conditions	Imported from validated Apache model and Macroflo output
Surface heat transfer	Program-calculated
Iterations	500 (minimum)
Turbulence model	K-e
Discretisation	Upwind
Flow rates	Validated against the measured airflow rates and inlet/outlet velocities during the field study in August 2015
Stand-alone schedule	22 August 2015, 12:30

**HVAC: Heating, Ventilation and Air Conditioning; DHW: Domestic Hot*

11.5. Validation of Simulation Model

11.5.1. Weather data validation

As the first step of the validation process, Figure 11-2(a) indicates that the outdoor AT profile recorded during the field study of case study building-3 matches with meteorological data for the same period with only 3% average deviations. Figure 11-2(b) illustrates deviations between monthly average weather data and meteorological data for the years 2015, 2014 and 2013.

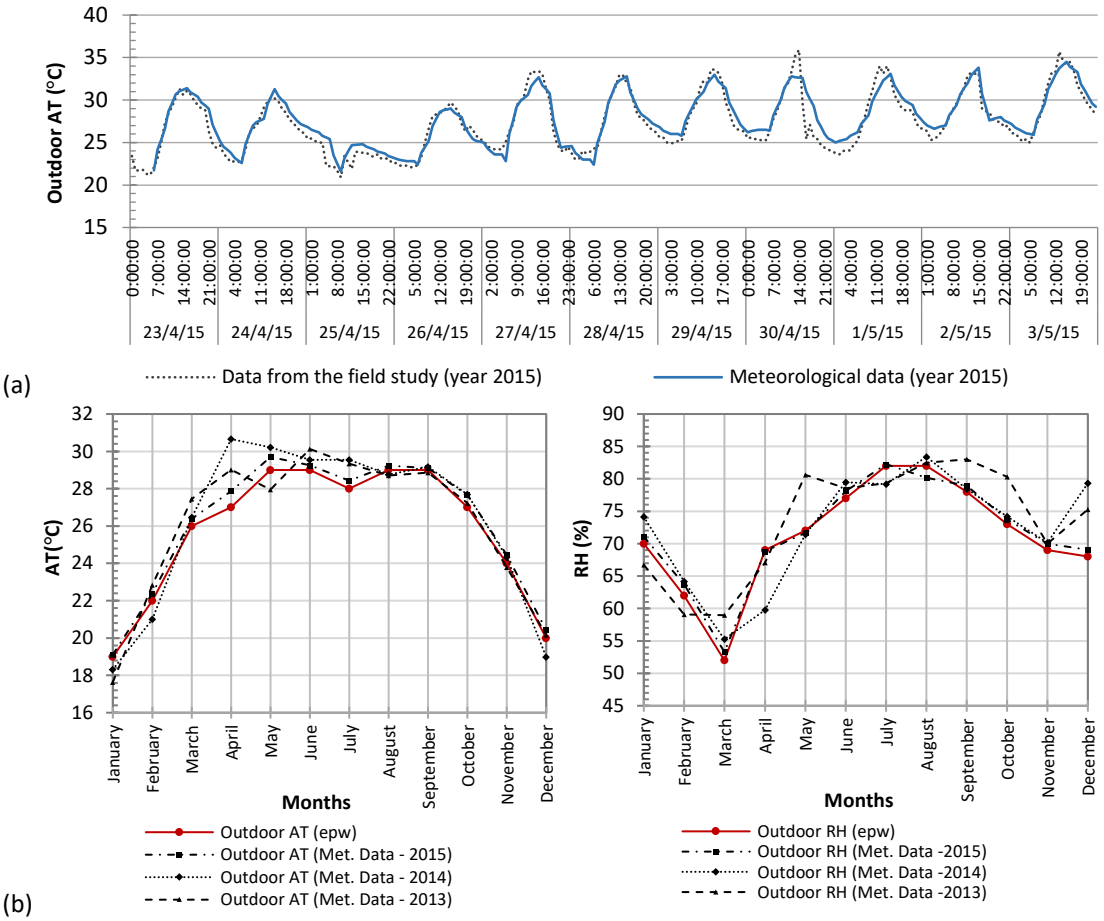


Figure 11-2: Comparison between (a) measured outdoor AT and meteorological data for Dhaka in the hottest month (b) Simulated weather data and annual meteorological data for Dhaka

11.5.2. DT model validation

Table 11-4 shows the descriptive statistics of the field measured and simulated data for the warm season. The results indicate that the simulated mean AT and mean RH values are 0.7°C higher and 2.5% lower than the measured mean values respectively. Figure 11-3 illustrates the minor deviations in daily profiles between measured and simulated AT and RH. The predicted values of the thermal environment are within the acceptable level of error (Section 4.6.2).

Table 11-3: Comparison of field-measured and simulated data during the warm season

	AT, °C (measured)	AT, °C (simulated)	RH% (measured)	RH% (simulated)
Max	34.5	36.0	84.5	83.2
Median	31.6	32.3	69.8	66.4
Mean	31.5	32.2	68.9	66.4
Min	25.1	26.0	46.6	43.7
SD	1.0	1.5	7.4	7.8
Data Count	1154	1154	1154	1154

**Here, Max: maximum, Min: minimum, SD: Standard deviation, Data Count: total number of hourly data*

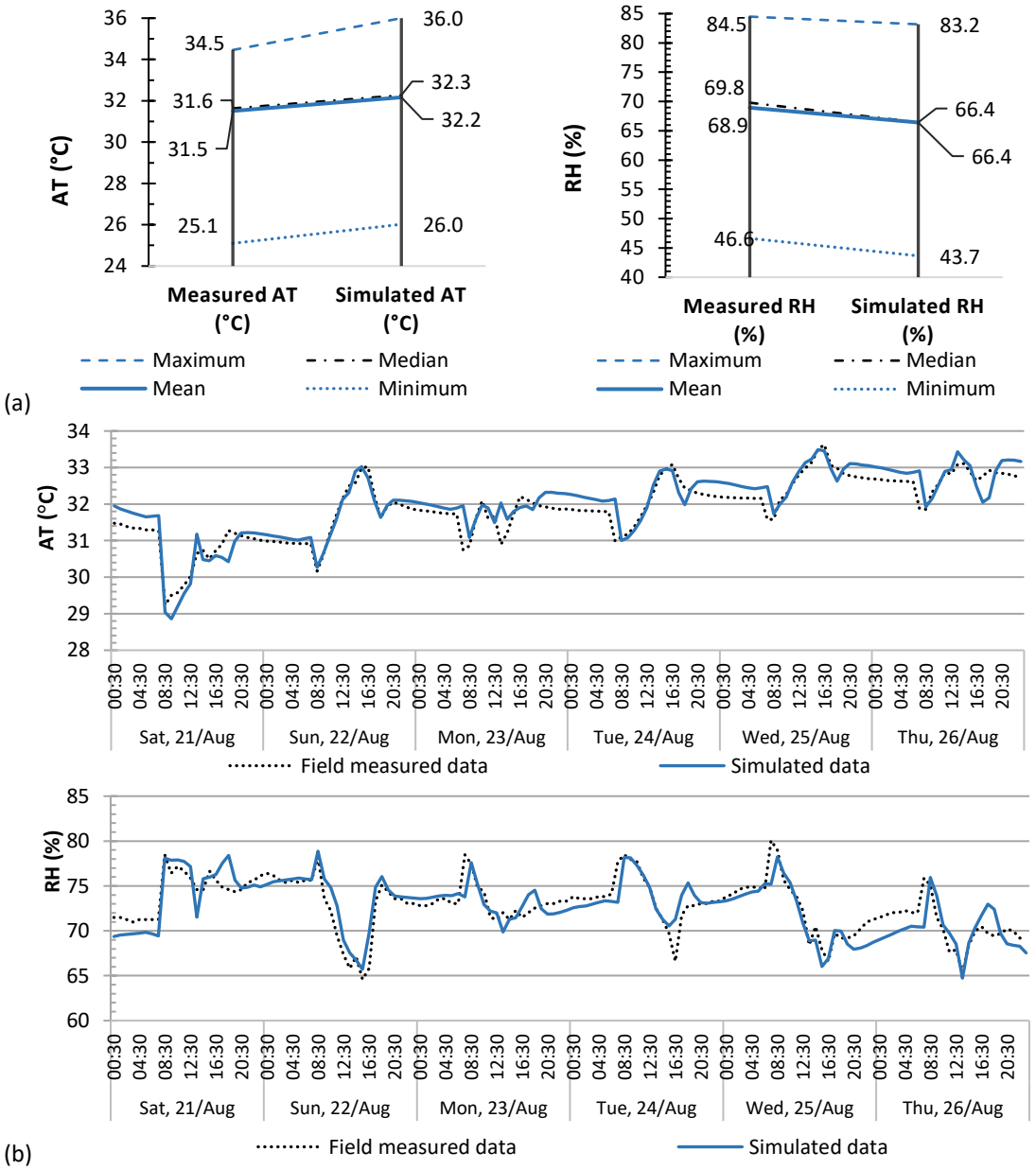


Figure 11-3: Comparison of a sample of measured and simulated data

11.5.3. CFD model validation

Figure 11-4 shows the reference grids points of the field measurements and Table 11-4 provides the comparisons between measured and CFD simulated AV data. The

validation process confirms that the simulated results are within the acceptable mean deviations of 9.9% compared with the field measurements (Section 4.6.2).

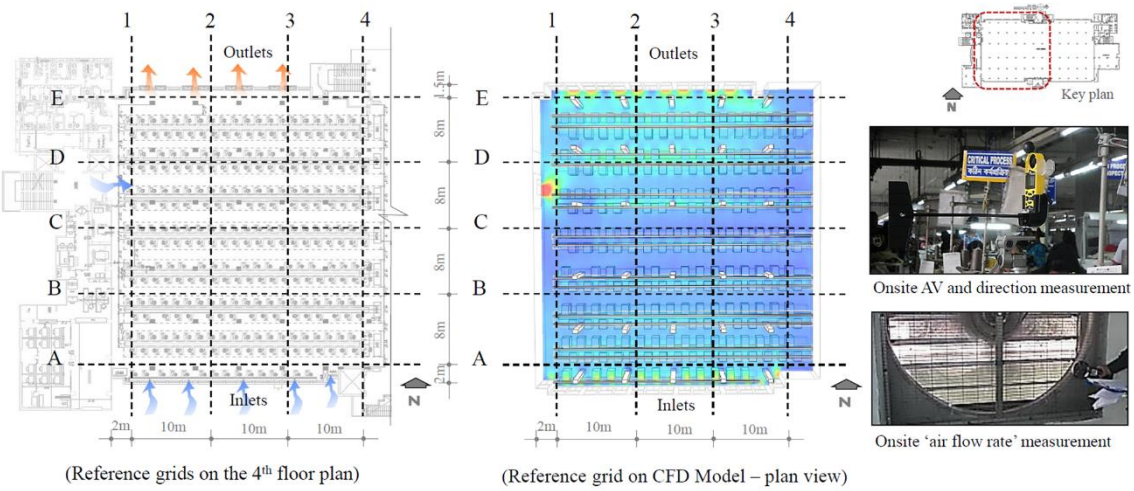


Figure 11-4: Reference grids to validate field-measured and simulated AV

Table 11-4: Comparison between field-measured* AV and simulated AV

Grid points**	AV, m/s *(source: Field measurement)*	AV, m/s *(source: CFD simulation in IES-VE)*	Deviation (m/s)	Percentage of Deviation (%)
1A	0.35	0.41	-0.06	-17.1
1B	0.18	0.25	-0.03	-13.6
1C	0.10	0.12	-0.02	-20.0
1D	0.50	0.45	0.05	10.0
1E	0.65	0.58	0.07	10.8
2A	0.52	0.45	0.07	13.5
2B	0.1	0.15	0.03	16.7
2C	0.0	0.04	-0.04	-
2D	0.35	0.43	-0.08	-22.9
2E	0.61	0.72	-0.11	-18.0
3A	0.51	0.43	0.08	15.7
3B	0.13	0.18	-0.03	-20.0
3C	0.0	0.05	-0.05	-
3D	0.35	0.48	-0.06	-14.3
3E	0.7	0.81	-0.11	-15.7
4A	0.2	0.27	-0.05	-22.7
4B	0.1	0.12	-0.02	-20.0
4C	0.0	0.03	-0.03	-
4D	0.1	0.13	-0.03	-30.0
4E	0.2	0.24	-0.04	-20.0
Mean	**0.29**	**0.32**	**-0.02**	**-9.9**
Median	**0.22**	**0.26**	**-0.03**	**-17.1**
Standard Deviation	**0.23**	**0.23**	**0.06**	**15.9**
Count (grid points)	**20**	**20**	**20**	**17**

**The field data was collected at 4th floor on 22 August 2015 at 11:00-12:30;*

***The grid points or nodes are located 1.2m above the floor level (Figure 8-6)*

11.6. Simulation Scenarios and Input Parameters

As described in Section 5.6.5, Simulation scenarios were grouped into two main categories (i.e. workable strategies type 1 and workable strategies type 2). The input variables and chosen simulation methods are presented in the Table 11-5.

Table 11-5: Chosen design strategies, Input variables and simulation methods

Strategy		Varied Input variables	Simulation Method
Workable strategies type 1	Night Ventilation Strategy	NTV	DT
	Change effective window size	Window size and design	DT and CFD
Workable strategies type 2	Improve functional layout	Arrangement of furniture within same floor area	CFD
	Add passive ventilation shaft	Shaft, inlet-outlet size of the shafts	Optivent and CFD

11.6.1. Workable strategies type-1

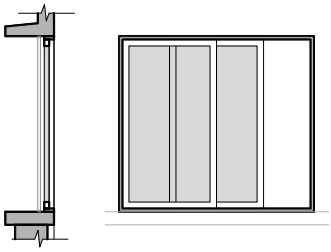
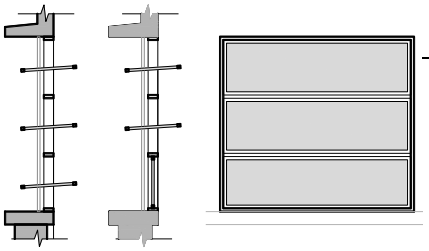
As described in Sections 10.8.3, the most feasible and immediately applicable strategies in existing RMG factory buildings were considered as follows:

- *Run full day ventilation complemented by NTV*
- *Change window type and effecting opening size*

These two solutions are categorised as 'Workable Strategy Type 1'. Based on the literature review, field evidence, worker and factory owner feedback, it was reasonable to consider changing the existing window type (i.e. sliding windows with maximum 45% effective open area) to a window type that has a higher effective opening area combined with easy operation to control the direction of air flow to avoid disruption of work. The size and modular nature of the existing windows indicate that the pivoted windows, which can maximise effective opening area, could be considered as a replacement. If designed with an appropriate arrangement of openable lights, these windows also offer flexibility to control the pattern of air flow. The window strategy and changes to fan operating hours to include break and night time operations were taken into consideration in the simulation study.

Dynamic simulations were run on the 1st floor (FS), 5th floor (SS) and 8th floor (CS). Table 11-6 shows the four simulation scenarios that were considered.

Table 11-6: Four selected simulation scenarios for thermal analysis

Simulation Scenarios	Type of inlet windows and their effective open area for air circulation	Ventilation Strategy	Simulation method
Scenario –1.A (existing scenario)	Existing sliding windows with 45% effective open area 	DTV	DT and CFD
Scenario –1.B		Continuous ventilation (DTV+NTV)	DT
Scenario – 1.C	Pivoted windows with up to 75% effective open area* 	DTV	DT and CFD
Scenario – 1.D		Continuous ventilation (DTV+NTV)	DT

**50% effective opening assumed during day time when the bottom pivoted light remains closed to avoid direct air flow over the work plane. This bottom segment is assumed to remain open during night-time and weekends.*

Scenario-1.A represents the base case study condition of the RMG building with existing sliding window type (45% effective opening) with day time ventilation (DTV) only. Scenario-1.B and scenario-1.D include the NTV driven by the exhaust fans, which were assumed to provide half of the ventilation rate present during the day. Pivoted windows with increased effective opening area (75%) were selected for scenario-1.C (which assumed DTV only) and scenario-1.D (where both DTV and NTV were assumed).

Moreover, two sets of CFD images were developed comparing the air flow patterns inside the existing SS with sliding windows and that with pivoted windows. To observe the effects of applying these two workable strategies the varied parameters were set as shown in Table 11-7.

Table 11-7: Varied simulation parameters associated with workable strategy type-1

Thermal aspect: varied parameters		
	Scenario 1.A and 1.C (Table 11-6)	Scenario 1.B and 1.D (Table 11-6)
Variation profile/calendar for auxiliary ventilation	Fans were running as DTV during working hours 0800-1900 (general 90% modulating value) with lunch break 1300-1400 (0% modulating value) varied in different climatic seasons (Appendix F-2)	Fans were running as Full day Ventilation with continuous working hours 0800-1900 (general 90% modulating value) varied in different climatic seasons. Additionally rest of the hours 80% modulating value were considered.
Ventilation (MacroFlo): varied parameters		
	Scenario 1.A and 1.B (Table 11-6)	Scenario 1.C and 1.D (Table 11-6)
Opening type	Sliding windows on external walls with 45% openable area.	Pivoted (louvre type) windows on external walls with 75% openable area.
Degree of opening (modulating profile)	For full day ventilation strategy, the windows are considered as continuously open with 50% and 75% modulating value during daytime and night-time respectively. The doors are considered closed (0 modulating value) during unoccupied hours.	

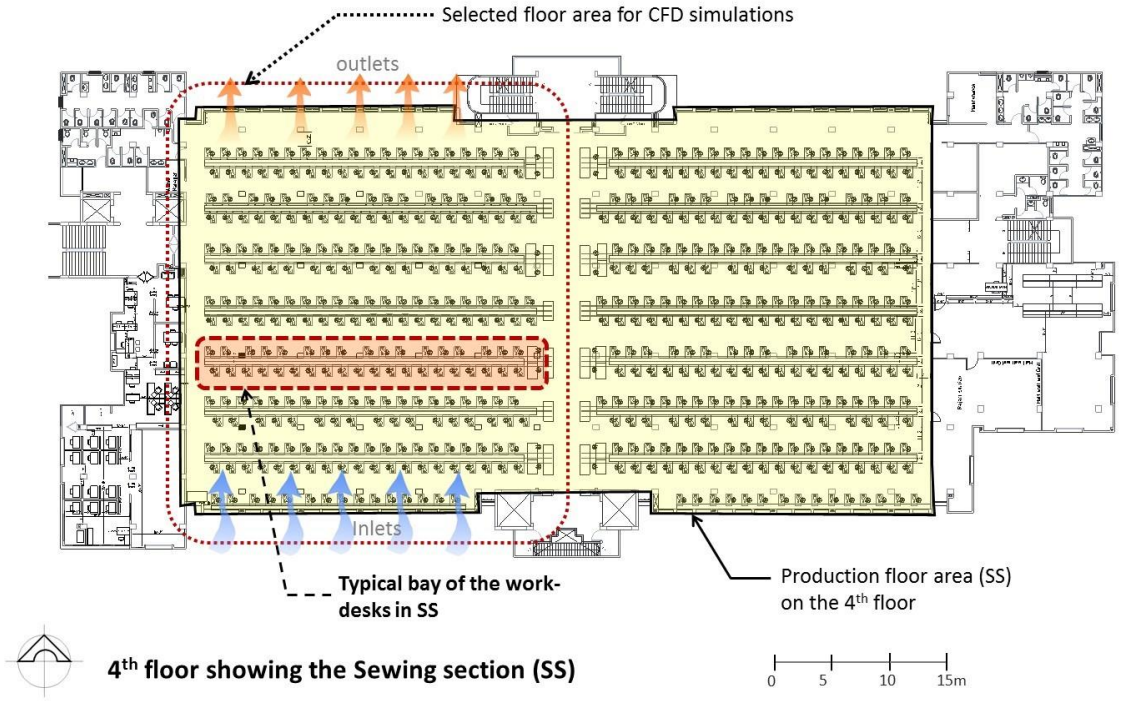
11.6.2. Workable strategies type-2

As described in Sections 10.8.3, the strategies that were less feasible to implement in the existing case study buildings but potentially more applicable to new multi-storey RMG factory buildings are categorised as 'Workable Strategies Type 2'. Among them the chosen strategies for simulation study are as follows:

- *Improve air flow by changing functional layout*
- *Add passive ventilation shaft*

11.6.2.1. Improve air flow by changing functional layout

It was observed that workers suffer from thermal discomfort due to closely allocated equipment immediately at the front or behind them. To have a closer look at the existing functional layout of the production spaces, the furniture layout of the SS in 4th floor was considered. Figure 11-5 shows the functional layout of the SS including the location of the individual workers' workstations on the 'production bay'. Section 10.6 revealed that workers also preferred to have their air flow from north and south side. However, due to obstructions of the east-west elongated production-bays the speed of the air directly entering from south inlets were eventually reduced (Figure 11-4). Hence, to enhance the air flow through the workspace, change of orientation of the production-bays to north-south could be one of options within the same floor area.



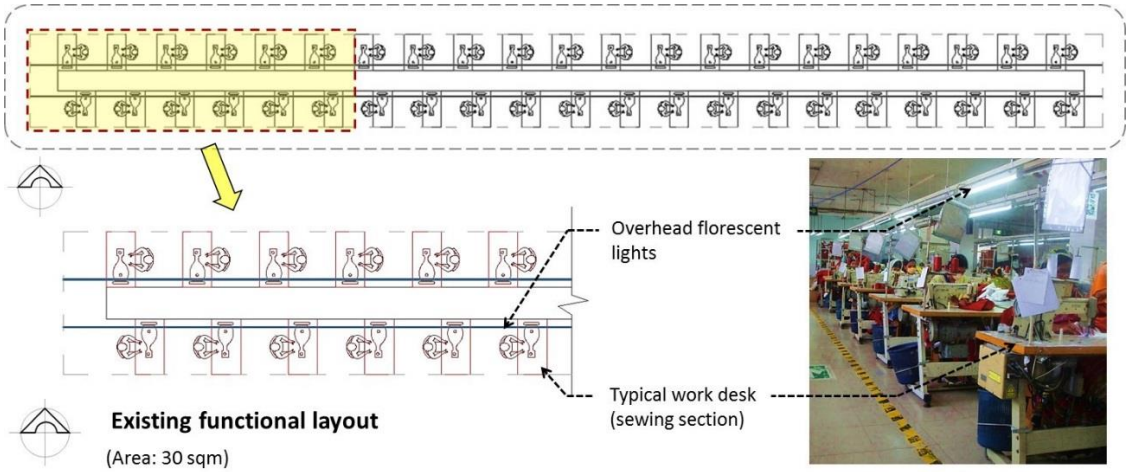


Figure 11-5: Existing functional layout of the SS on the 4th floor of the *RMG factory 3*

An existing functional area of 30m^2, keeping 2.5m^2 floor area for each sewing worker, was considered for further design development (Figure 11-5). Figure 11-6 illustrates the two proposals suggested by the author to improve the existing functional layouts. The first proposal only incorporated the change of orientation keeping the same layout. The second one not only incorporated the change of orientation, but also rearranged the desks within the bay providing the same amount of working area per sewing worker. The later proposal assumed providing more flexibility to the workers to experience the air entering through the inlets of the south side and travelling through the circulation bay.

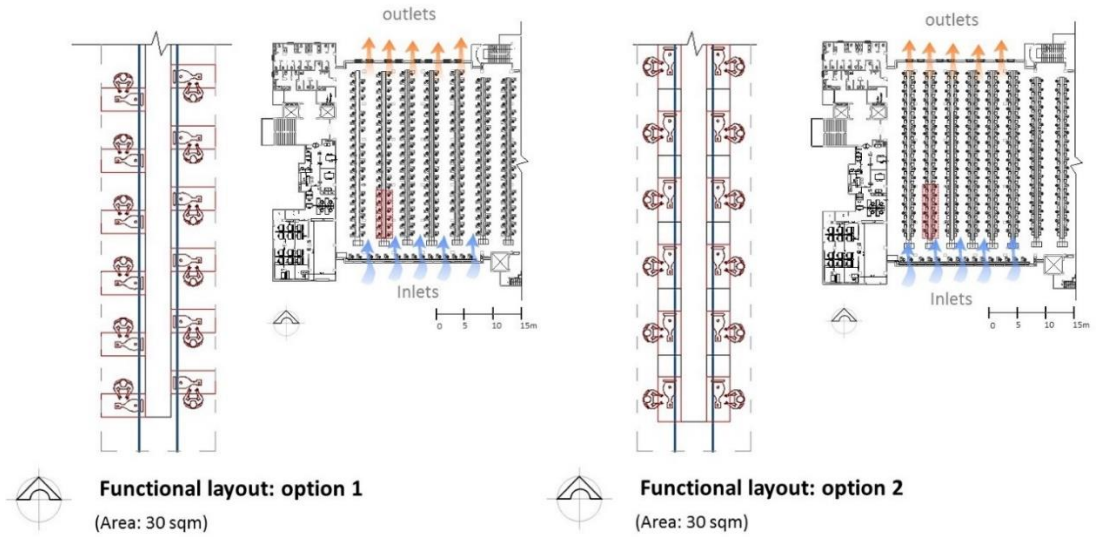
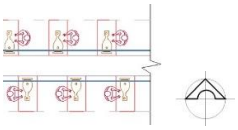
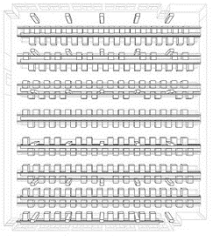
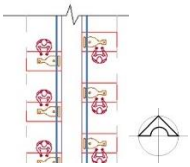
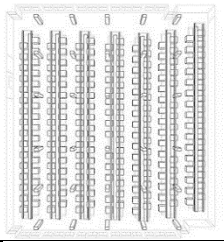
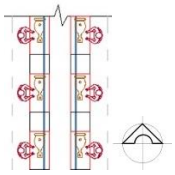
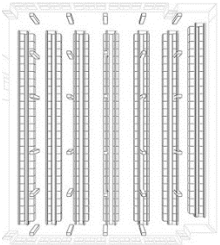


Figure 11-6: Proposed functional layouts to enhance AV inside the SS of *RMG factory 3*

Three scenarios were proposed for CFD simulations to study the benefits of the proposed layouts compared to the existing one. Table 11-8 provides an overview of the simulation scenarios and parametric model.

Table 11-8: Simulation scenarios for CFD simulations with proposed functional layouts

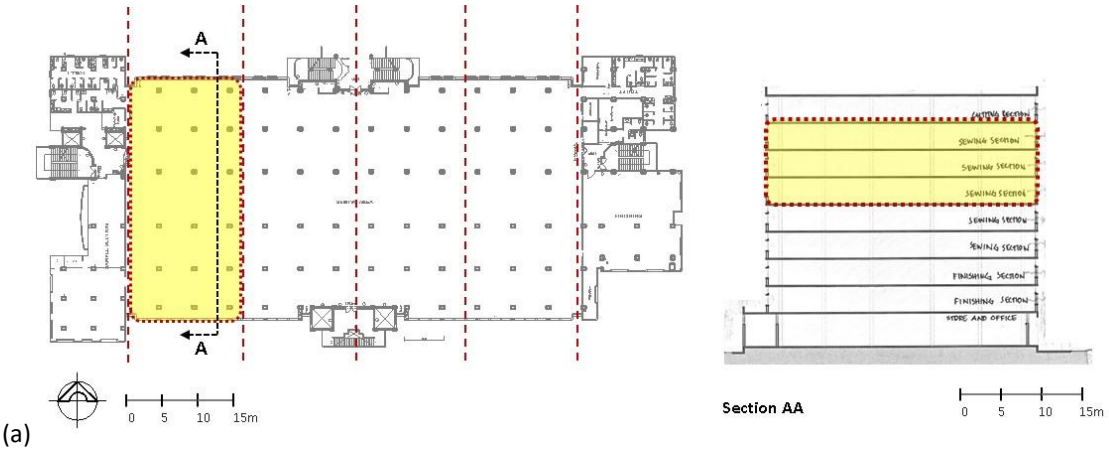
Simulation Scenarios	Functional layout type	Parameters (Component layout for CFD analysis)	
Scenario 2.A (existing scenario)	Existing functional layout of the SS 		Same boundary conditions with the components, as shown in Section 11.5.
Scenario 2.B	Proposed functional layout: *option 1* 		Same boundary conditions shown in Section 11.5, apart from changing the layout of the component following *Proposed functional layout: option 1* (Figure 11-6)
Scenario 2. C	Proposed functional layout: *option 2* 		Same boundary conditions shown in Section 11.5, apart from changing the layout of the component following *Proposed functional layout: option 2* (Figure 11-6)

For all simulation scenarios, boundary conditions of CFD models were kept same as the validated model and shown in the Section 11.5. However, the layout and shape of the components, such as heat source, surface temperature and solid boxed were varied according to proposed furniture layouts (Table 11-8). These layouts were proposed considering the limited scope of this chapter and the results would have limited applicability. Further changes can be made to these layout focusing on the functional aspect and type of sewing machines.

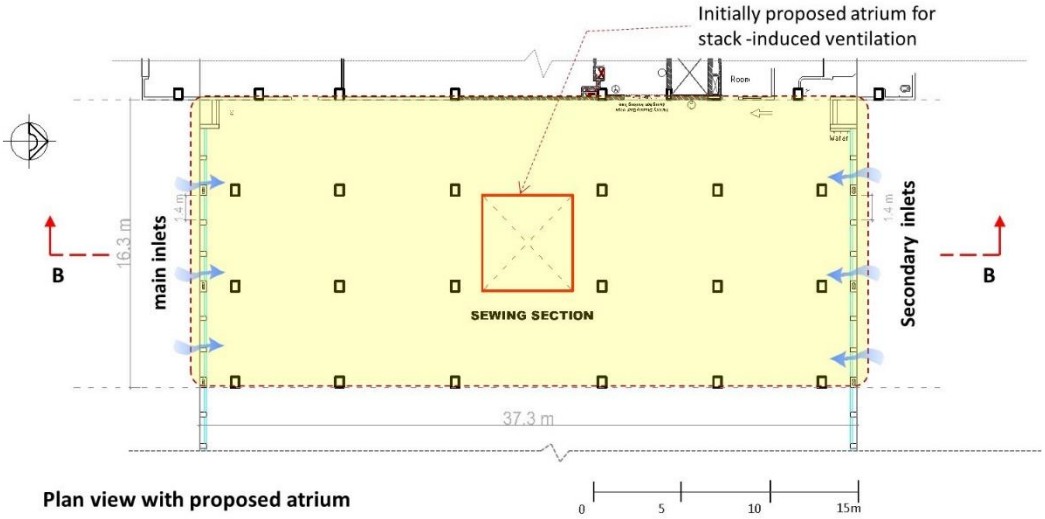
11.6.2.2. Add passive ventilation shaft

For studying the effect of adding a passive ventilation shaft in an existing RMG factory building, the parametric study was completed in two steps. Firstly a similar theoretical study on applicability of natural ventilation, as described in Section 6.7, were undertaken utilising the natural ventilation steady-state tool 'Optivent 2.0' (http://naturalcooling.co.uk/optivent.html). The main objectives of this preliminary study was to determine air flow rates and test the applicability of passive stack ventilation in *RMG factory 3* in different climatic seasons of Bangladesh. This step also more validated than the study shown in Section 6.7, since field measured data, for example mean values of indoor and outdoor AT of different climatic seasons, were used as the input data. Secondly, the IES-VE model was developed and CFD simulations were run to understand more explicitly the indoor air flow pattern inside the production floors.

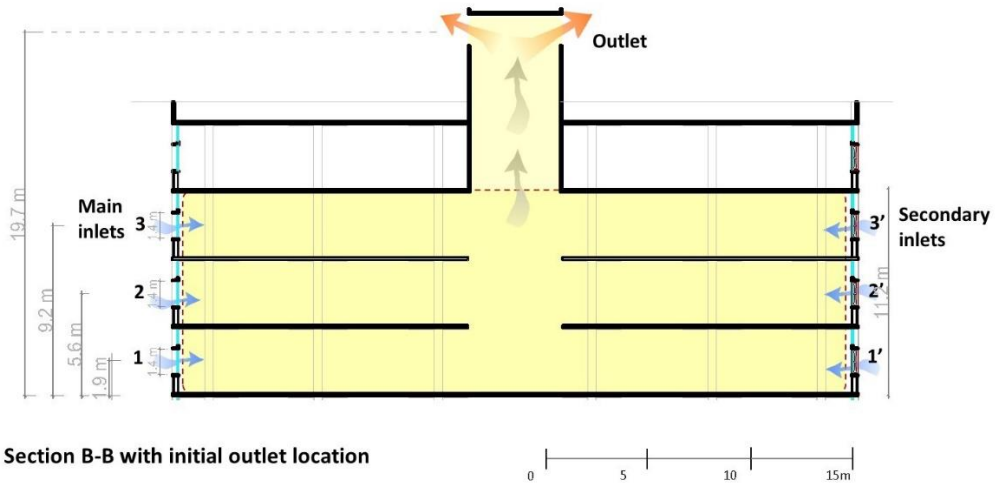
A quarter of the total SS floor areas on the top three floors (5^{th}, 6^{th} and 7^{th} floors) of *RMG factory 3* were considered for this study, as shown in Figure 11-7(a), to fit with the 'Atria (single cell)' strategy available in the 'Optivent' tool. Figures 11-7(b) and 11-7(c) illustrates the proposed atrium which was located in the centre of the demarked floor of '16.3m × 37.3m' and where areas and locations of the inlet windows on the south facade were considered same as found in the existing case study building. Simultaneously existing fixed windows on the north facade of the building was also considered as inlets. Centre of the outlet height was considered 19.7m high from the floor of 5^{th} floor and assumed as a fixed parameter.



(a)



(b)



(c)

Figure 11-7: (a) Plan and section showing considered floor areas, (b) Plan with proposed shaft and (c) Section with outlet location

Based on the data collected during field investigations and as shown in Table 11-2, all input parameters were determined for the Optivent tool. Table 11-9 shows the fixed and varied parameters, associated to this analysis. Since, the values of inlet areas and

stack height were kept constant, the only varied parameter was the ΔT which was determined by the mean indoor and outdoor AT measured during the field studies in *RMG factory 3*.

Table 11-9: Input parameters for calculation in Optivent (source: field measurement and assumptions)

Project location (fixed and varied parameters)			
Latitude (decimal degrees)	23.9		
Season	*Cool-dry*	*Hot-dry*	*Warm-humid*
Month	January	April	August
Prevailing mean outdoor temperature	21.4 °C	27.4 °C	28.4 °C
Hour	20:00		
Meteorological Wind Speed	0.5 m/s		
Terrain data	Meteorological value		
Inlet (surface) Azimuth	South facing inlet		
Air flow data input (fixed and varied parameters)			
Season	*Cool-dry*	*Hot-dry*	*Warm-humid*
Outdoor AT (T_o)	21.4 °C	27.4 °C	28.4 °C
Indoor AT (T_i)	27.4 °C	30.2 °C	30.1 °C
$\Delta T = T_o - T_i$	6 °C	2.8 °C	1.7 °C
Inlet heights of z_1, z_2 and z_3	1.9 m, 5.6 m and 9.2 m		
Outlet height z_o'	19.7 m		
Effective apertures of inlets (no. 1, 2, 3, 1', 2' and 3')	45%		
Inlet area of each side of the floor	15.7m²		
Effective apertures of outlet	65%		
Building geometry and solar gains (fixed parameters)			
Cell dimensions (section and Floor plan)	Width: 37.3m, Height: 11.2m, Roof is not exposed Length: 16.3m, Side walls are not exposed		
Construction materials properties	Glazing: Solar Transmittance Factor (0.6), Shading Proportion (5%) Wall: Surface Absorptance (0.7), U-Value (1.52 W/m²K), External Surface Transmittance (3.5 W/m²K)		
Internal Conditions (fixed parameters)			
Occupants and internal Gains	Occupants: 150 people, equipment: 40 W/m² and lighting: 13.5 W/m²		

Figure 11-8 reveals a comparative air flow rates generated by the stack induced ventilation during three climatic seasons. From this figure, it can be assumed that passive ventilation is mostly applicable in cool dry season and partially applicable in the rest of the season to achieve the required ventilation flow rate. Results also revealed that this stack ventilation can also provide adaptive thermal comfort during cool dry season without relying on auxiliary ventilation. The stack generated 42.6, 28.8 and 22.4 m^3/s of air flow rates though the outlets during the cool-dry, hot-dry and

warm-humid seasons. It also indicates that the rest of the year it can be solely used for cooling the building, particularly during night time.

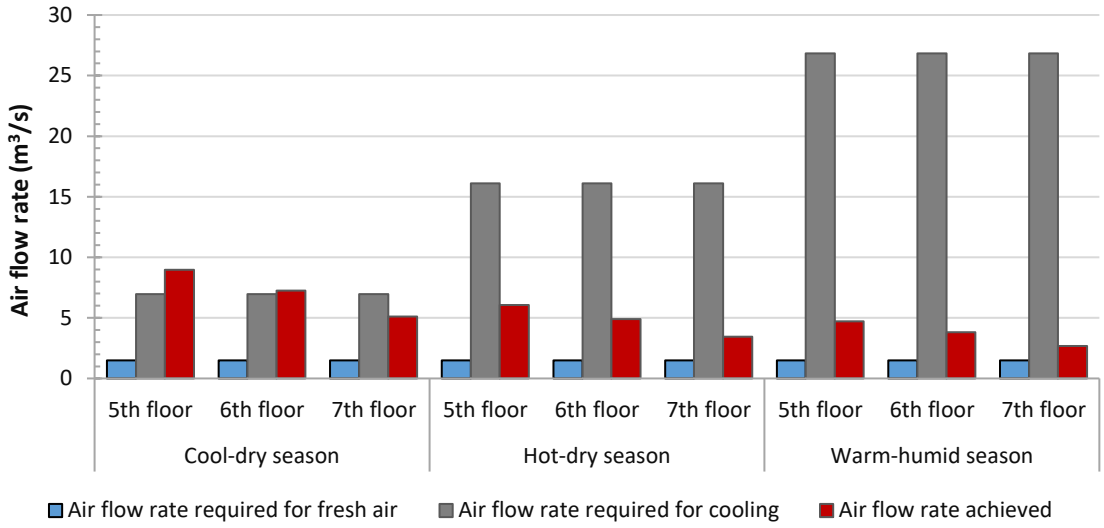


Figure 11-8: Comparison of air flow rates at inlets generated by stack induced ventilation (source: results from optivent 2.0)

To generate the air rates shown in Figure 11-8 required effective outlet area (65%) at the top of the atrium was required to be 41.8m^2 while the structural area (100%) should be 64.3m^2. Similar method, shown in Section 6.7, was used to test the physical viability of the proposed atrium. Assuming the height of the outlet as 2m, the structural length of the outlet 32.15m (i.e. 64.3m^2 / 2m = 32.2m). If the perimeter of the top of the square-shaped atrium's shaft were assumed as 32m, then the width of the atrium's top shaft can be 8m and the dimension can be '8m × 8m' . This length is also feasible to achieve considering the existing column bays are '5.4m × 6m' and can be located at the similar location shown in Figure 11-7. Since, it was a steady-state analysis considering the passive ventilation during working hours, it can be also assumed that this ventilation strategy should work during night time to naturally cooling of the building.

The results gained from the Optivent revealed that during the cool-dry, hot-dry and warm-humid seasons, average natural air speed of 0.25, 0.15 and 0.1 m/s can be maintained within the selected volume of the building with a highest air speed of 0.9 m/s. This preliminary analysis provides a certain range of justification to generate a 3D model in IES-VE to have a closer look at the stack induced air flow pattern inside these

three floors of the case study building and compare the air velocity inside the production spaces with the existing ventilation scenario. Since the functional layout of all sewing floors were same, the validated 3D model with one floor, shown in Figure 11-4, was copied along with all indoor components and generated as three floor. The demarcated floor was sliced considering the 17m threshold distance of inlets and Rule of Thumb (Table 11-1 and Section 3.5.1) and two '4m × 8m' sized ventilation stack was added guided by the results of optivent. Figure 11-9 shows the demarcated floor area and merged model in the 'MicroFlo' of IES-VE tool.

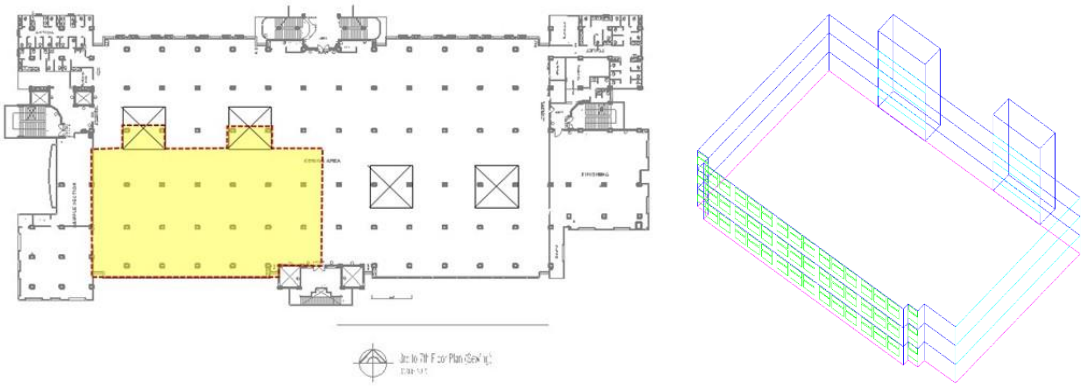
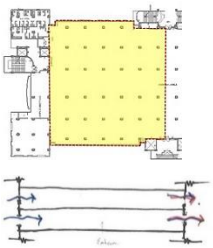
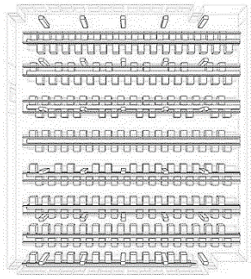
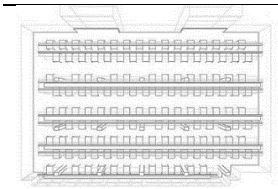
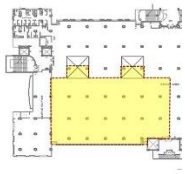
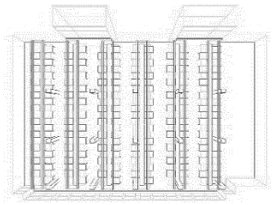
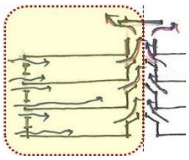
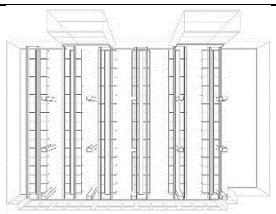


Figure 11-9: Demarcated floor area for CFD simulation and merged three SS floors with two shafts

It is an unavoidable fact that adding stack ventilation strategy in existing building reduces the available production floor area and makes a requirement of changing the existing functional layout. Based on the potentiality of arrangement of furniture efficiently and applicability of passive ventilation during both occupied and unoccupied hours, the simulation scenarios and associated parameters were selected and are shown in Table 11-10.

Table 11-10: Simulation scenarios adding passive ventilation stack for CFD simulations

Simulation Scenarios	Ventilation strategy (active/passive)	Functional layout type	Parameters (Component layout for CFD analysis
Scenario 3.A (existing scenario)	Existing active ventilation 	Existing functional layout (Figure 11-5)	
Scenario 3.B	Stack induced ventilation		
Scenario 3.C		Functional layout: *option 1* (Figure 11-6)	
Scenario 3.D		Functional layout: *option 2* (Figure 11-6)	

Since CFD simulations were run under in all case, one of the main varied parameters for scenarios 3.B -3.D were adding new 'supply' and 'extract' components in the model assigning the airflow rates of inlets and outlet found from the results of Optivent analysis. For scenarios 3C-3.D, the heat sources and components with assigned energy (Wattage) and surface temperature were reduced, as found in the field study to represent unoccupied time. The components with furniture layouts were also changed according to proposed layouts.

11.7. Benefits of Workable Strategies Type-1

11.7.1. Results from DT simulations

Figure 11-10 shows the indoor AT profiles in the SS under the four simulation scenarios. The results for scenario 1.A and scenario 1.B indicate that for changing the window

design can offer a modest reduction in indoor AT of around 0.3°C if the existing DTV only is maintained. Comparison of scenario-1.B and scenario 1.D indicates the active NTV strategy can reduce peak indoor AT by 0.8°C, 0.9°C and 1.3°C during the cool-dry, hot-dry and warm humid seasons respectively compared with the base scenario.

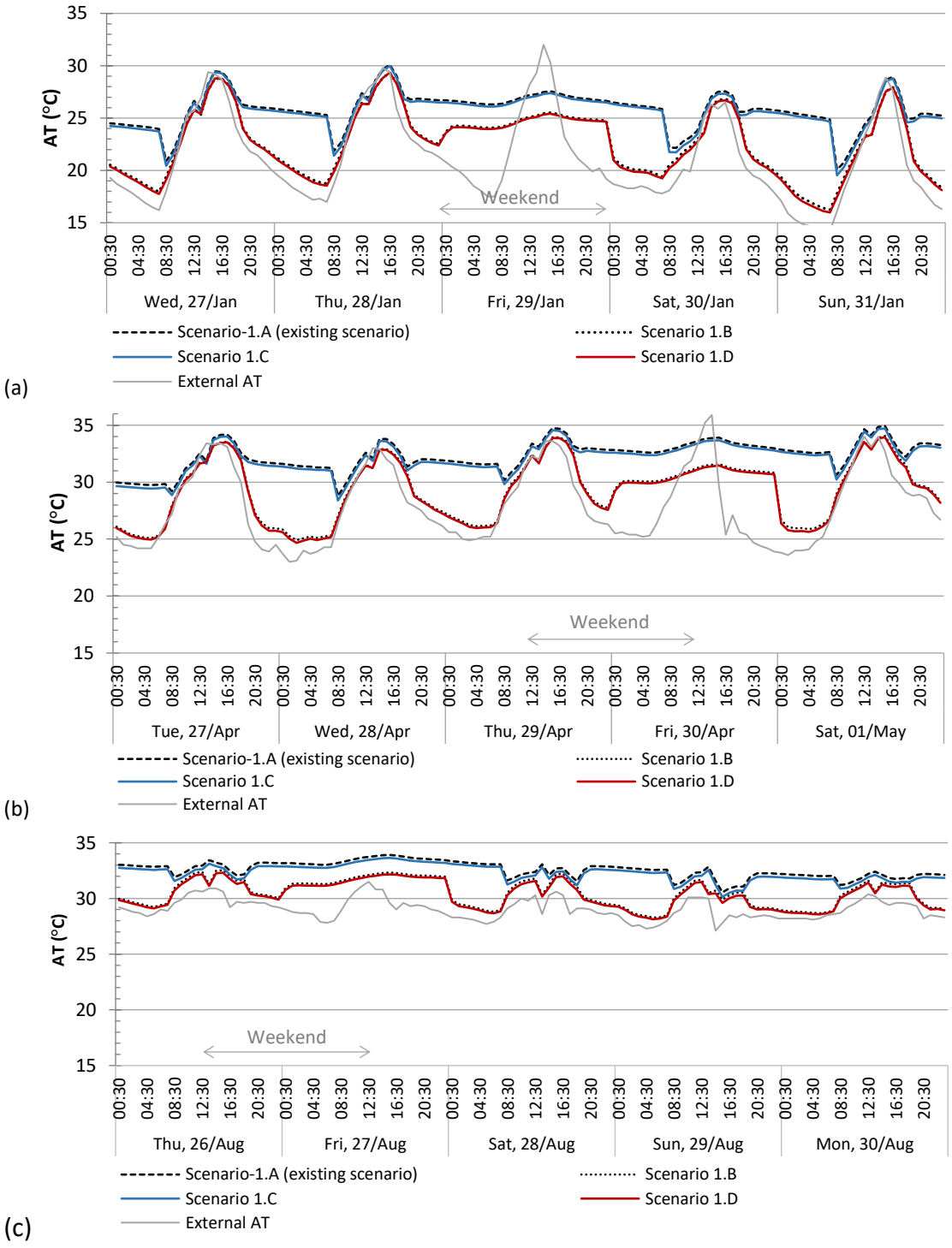


Figure 11-10: Indoor air temperature profiles of the SS during the (a) cool-dry (b) hot-dry and (c) warm-humid seasons

Looking at the annual behaviour, Figure 11-11 indicates that the active NTV strategy of scenarios 1.B and 1.D can reduce the mean temperature by about 2°C in the FS, 3°C in the SS and 1°C in the CS. Figure 11-12 indicates that modifying the configuration of the windows to provide 75% effective opening area can reduce high temperature issue by up to 15% of working hours in the FS, 12% in the SS and 2% in the CS within same season. The introduction of active NTV can increase comfortable working hours by up to 23% in the FS, 17% in the SS and 3% in the CS. It is clear from Figure 11-12 that the majority of the uncomfortable working hours fall within the warm-humid and hot-dry season and that the ventilation during the cool-dry season is negligible.

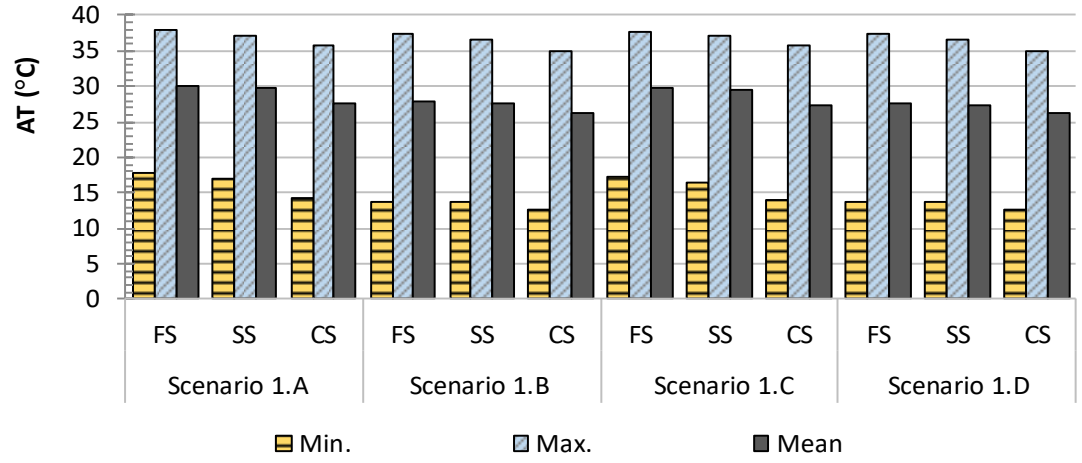


Figure 11-11: Comparison of maximum, minimum and mean annual indoor AT

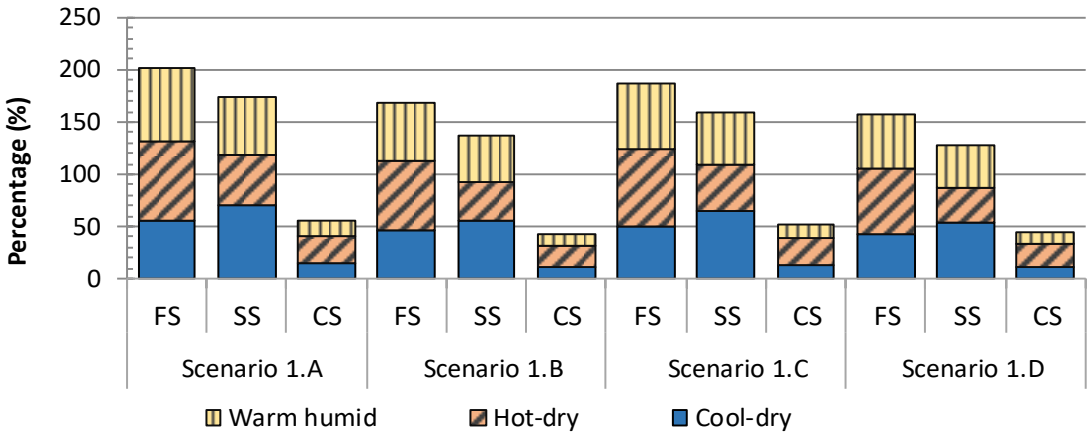


Figure 11-12: Percentage of working hours exceeding the threshold values of AT

Table 11-11 presents the annual mean values of AT, SET, MRT and RH in all production spaces for the scenarios 1.A, 1.B, 1.C and 1.D along with the percentages of working hours within the targeted ranges (Section 11.3). The data indicate that the proposed

strategies are unable to reduce the RH in production sections. However, the strategies are effective in reducing the mean values of AT, SET and MRT by up to 2.5°C and increasing the comfortable working hours up to 16.7%.

Table 11-11: Comparison of annual AT, SET, MRT and RH for comfort evaluation

Workspace	Scenario	AT		SET*		MRT		RH	
		Working hours within comfort range (%)	Mean AT (°C)	Working hours within comfort range (%)	Mean SET (°C)	Working hours within comfort range (%)	Mean MRT (°C)	Working hours within comfort range (%)	Mean RH (%)
CS (8th floor)	1.A	65.7	30.1	28.5	33.0	60.8	28.4	42.8	66.8
	1.B	66.7	26.2	29.7	32.2	67.2	27.2	38.2	72.0
	1.C	65.4	27.2	28.9	32.8	62.6	28.1	41	67.8
	1.D	66.1	26.1	29.7	32.1	67.6	27.0	37.3	72.5
SS (4th floor)	1.A	46.6	29.8	19.1	34.2	38.3	30.2	67.6	58.6
	1.B	55.0	27.5	22.9	32.8	53.6	28.0	59.1	66.9
	1.C	50.3	29.5	20.1	34.0	41.9	29.9	63.5	59.7
	1.D	56.9	27.3	23.5	32.7	55.0	27.9	56.1	67.6
FS (1st floor)	1.A	37.4	30.1	17.3	34.3	33.0	30.4	74.6	57.9
	1.B	44.8	27.8	20.6	33.0	45.6	28.3	67.2	65.9
	1.C	40.9	29.8	18.4	34.2	34.9	30.1	70.5	58.9
	1.D	47.7	27.6	21.4	32.9	47.7	28.1	63.5	66.7

**According to ASHRAE-55 (2013), RH is 50%, average air speed is below 0.1 m/s and MRT is equal to average AT with standard 'Clo' and 'met' value.*

The dynamic thermal simulation does not provide a detailed picture of the AV profile within the production spaces and as a result, further investigation is required to infer its impact on comfort. These are presented in the next section.

11.7.2. Results from CFD simulations

Figure 11-13 shows two sets of CFD images comparing the air flow patterns inside the existing SS with sliding windows and that with pivoted windows. The filled velocity contours and velocity vectors of two the images reveal that the pivoted windows with 75% effective opening allow more outdoor air move through the inlets. The new scenario provides an improved air distribution deeper inside the workspace. For instance, at least 5m plan depth, reaching the centre of the workspace, from both inlet

and outlet sides of the space, achieved 20% additional fresh air distribution. The pivoting windows also introduced a change in the pressure difference between inlets and outlets. For instance, the short air flow observed between the door in the west side and the outlets was relatively low in the second scenario (Figure 11-13). To quantify the improvement of ventilation inside the workspace, simulated data are presented in Table 11-12. These reveal that the middle zone, near the reference grids B and C, achieved higher AVs of around 0.2m/s higher than the existing scenario A.

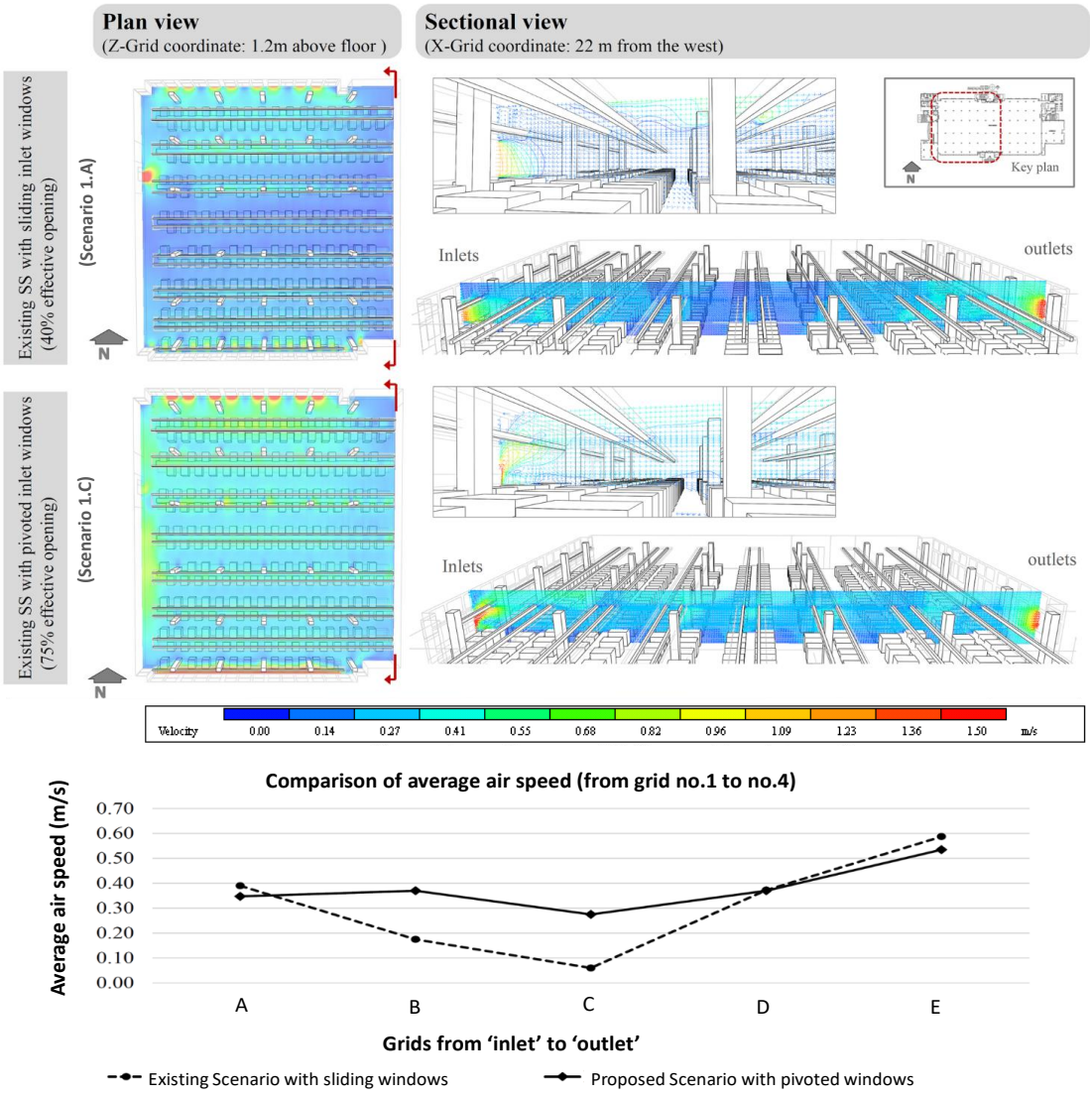


Figure 11-13: Comparison of air flow distribution and average air speed between existing and proposed scenarios

Table 11-12: Comparison indoor air speed profile between existing and proposed scenarios

	Air speed, m/s (Existing Scenario 1.A with sliding windows: 45% effective opening)					Air speed, m/s (Proposed Scenario 1.C with pivoted windows: 75% effective opening)				
Grid points	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	0.41	0.25	0.12	0.45	0.58	0.34	0.36	0.45	0.55	0.58
2	0.45	0.15	0.04	0.43	0.72	0.42	0.38	0.21	0.36	0.69
2	0.43	0.18	0.05	0.48	0.81	0.36	0.32	0.23	0.3	0.75
4	0.27	0.12	0.03	0.13	0.24	0.27	0.42	0.21	0.27	0.12
Average	**0.39**	**0.18**	**0.06**	**0.37**	**0.59**	**0.35**	**0.37**	**0.28**	**0.37**	**0.54**

A previous study conducted by Wijewardane and Jayasinghe (2008) that workers can be acclimatised by up to 3.5°C above the neutral comfort temperature and can tolerate higher temperatures if higher air velocities can be provided. Hence this additional air flow would help to improve overall thermal comfort for workers located in the centre part of the production space. It, therefore, helps to address the poor air speed issues implied in the focus group where workstations closer to the inlets/outlets were perceived as much desirable due to the higher air velocity in these areas. The air flow profiles indicate that although the pattern of flow has improved, the absolute active ventilation flow rate (193m^3/s or 68.2 ACH) is not enough to ensure the desired air speed range of 0.8-1m/s. Hence, further investigation is required to designing the ventilation strategy to ensure thermal comfort for the workers. The impact could be higher if the window-wall area ratio could be increased in this workspace subject to the careful treatment to control solar gains.

11.8. Benefits of Workable Strategies Type-2

11.8.1. Improve air flow by changing functional layout

Figure 11-14 shows three sets of CFD images comparing the air flow patterns inside the existing SS with two different furniture layouts (2.B and 2.C) along with the existing layout (2.A). The filled velocity contours and velocity vectors of two the images reveal that the new layout more outdoor air move through the inlets. The new scenario provides an improved air distribution deeper inside the workspace. For instance, at

least 5m plan depth, reaching the centre of the workspace, from both inlet and outlet sides of the space, achieved 40% and 50% additional fresh air distribution.

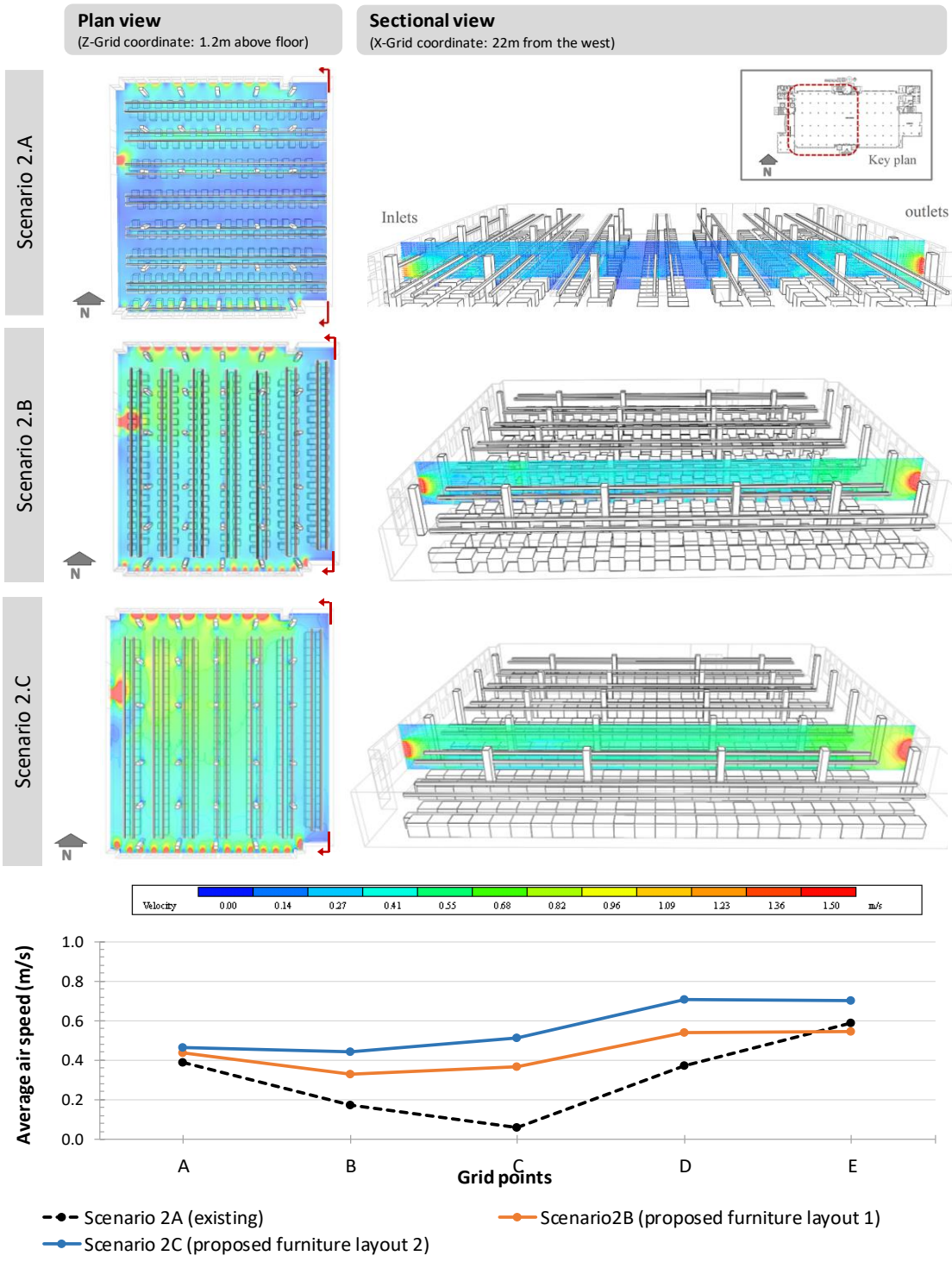


Figure 11-14: Comparison of air flow distribution and average air speed between existing and proposed scenarios

Figure 11-14 and Table 11-13 also shows the quantitative benefit of these two interventions. These reveal that the middle zone, near the reference grid C, achieved higher AVs of around 0.45m/s higher than the existing Scenario 2.A.

Table 11-13: Comparison indoor air speed profile between existing and proposed scenarios

	Air speed, m/s (Scenario 2.A: existing scenario)					Air speed, m/s (Scenario 2.B)					Air speed, m/s (Scenario 2.C)				
Grid points	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
1	0.41	0.25	0.12	0.45	0.58	0.48	0.31	0.36	0.65	0.56	0.49	0.38	0.52	0.41	0.25
2	0.45	0.15	0.04	0.43	0.72	0.45	0.3	0.35	0.58	0.58	0.48	0.45	0.55	0.45	0.15
2	0.43	0.18	0.05	0.48	0.81	0.44	0.36	0.39	0.48	0.52	0.49	0.53	0.52	0.43	0.18
4	0.27	0.12	0.03	0.13	0.24	0.38	0.35	0.36	0.44	0.53	0.4	0.42	0.45	0.27	0.12
Average	**0.39**	**0.18**	**0.06**	**0.37**	**0.59**	**0.44**	**0.33**	**0.37**	**0.54**	**0.55**	**0.47**	**0.45**	**0.51**	**0.39**	**0.18**

11.8.2. Add passive ventilation shaft

Figure 8-17 shows three sets of CFD images comparing the air flow patterns inside the existing SS (quarter part of the total floor area) with installed shaft and natural stack induced ventilation during night time. Two different furniture layouts (3.C and 3.D) along with the existing layout (3.B). The filled velocity contours and velocity vectors of two the images reveal that both existing and new layout with passive ventilation can improve the air circulation which can be used to for building cooling with utilising thermal mass. More outdoor air move through the inlets since the shaft produce natural cross ventilation. This analysis was kept qualitative. Further investigation is required to analyse this section of design (shaft design).

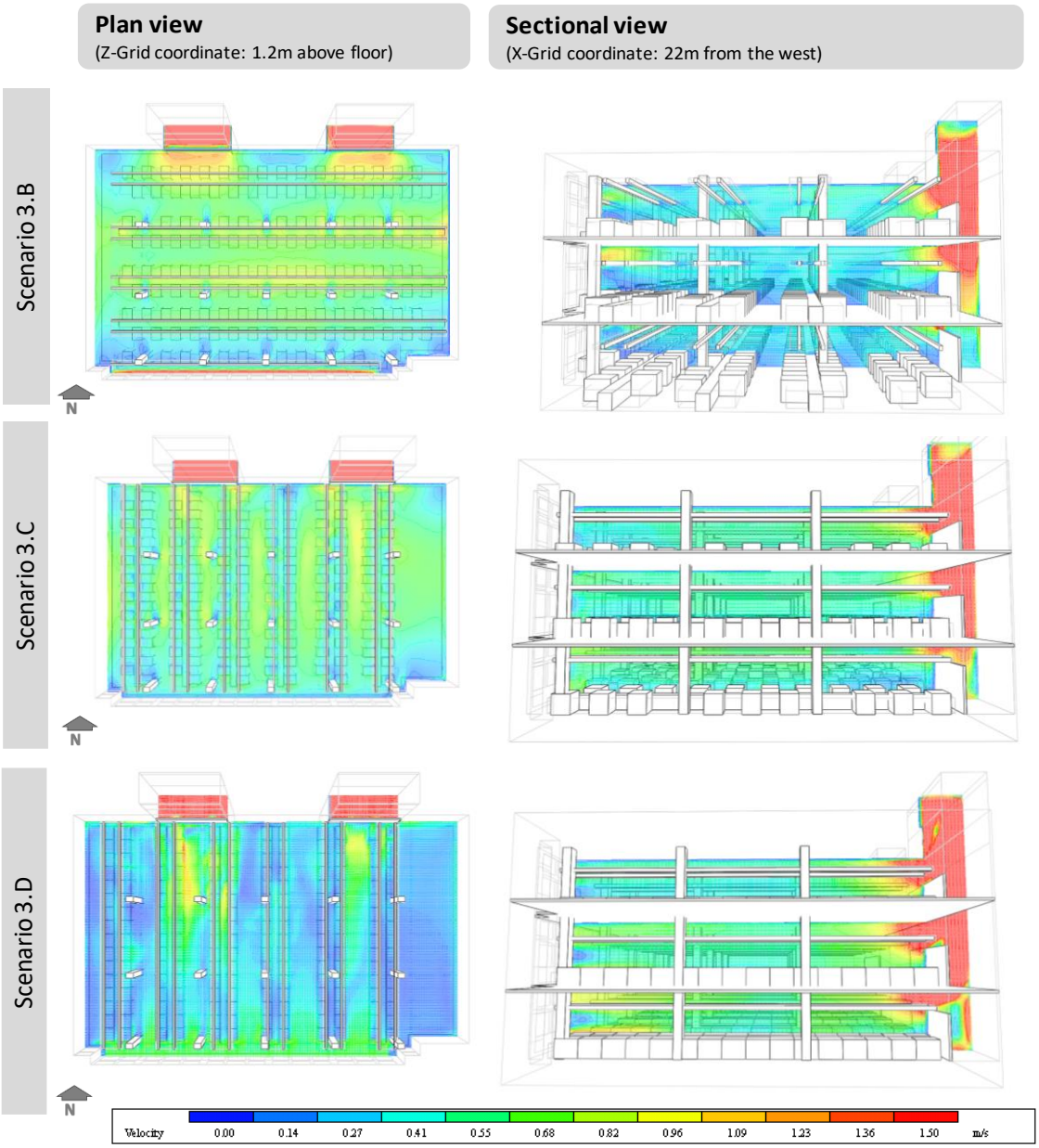


Figure 11-15: Comparison of air flow distribution and average air velocity between existing and proposed scenarios

11.9. Limitations and Implications of the Simulation Results

Considering the limitation of the methodology presented in Section 5.6.7, the following limitations of simulation results can be highlighted:

- The simulation models are validated with field data (Section 11.5). However, the results are based on short periods of simulations especially in the case of the CFD analysis and may not be accurate. They do not, therefore, represent an entire year's conditions (i.e. varied outdoor climate in the future) nor do they consider all production spaces.

- The study in chapter focused on *RMG factory 3* which is not representative of the total building stock (Section 5.6.2). As all of its production areas are located above ground level, the wind shielding offered by adjacent buildings can be ignored (Ramponi and Angelotti, 2014). As a result, the findings from this simulation study will not be fully applicable to other RMG factories with different plans, orientations and internal fan layouts. The greatest discrepancy is likely to relate to its unusual urban contexts.
- Changing the effective size of existing the windows (Section 11.6) may also bring more noise, dust and polluted air into the indoor workspaces during the day and night time. Hence, the effect of this issues on indoor air quality need further investigation and is beyond the scope of this research.
- The study within this chapter did not include all the workable strategies presented in Table 10-10, including the benefits of increasing efficiency of equipment, workers' personalised control over ventilation and changing construction materials and adding shading devices. Further simulation studies on these workable strategies should be undertaken in the future.

11.10. Summary

This chapter aimed to present the detailed simulation studies to measure the benefits of two types of workable strategies (as presented in Section 11.6) on improving existing thermal condition workspaces of the case study building-3. The key findings of this study based on field data collection and building energy simulation are:

- Changing the existing sliding windows to pivoting windows can reduce working hours with high temperature by up to 15% in the FS, 12% in the SS and 2% in the CS.
- Adopting full day ventilation can working hours with high temperature by up to 23% in FS, 17% in the SS and 3% in the CS.
- Both workable strategies were unable to improve the existing RH range annually. However, the strategies are effective in reducing the annual mean values of AT, SET and MRT by up to 2.5°C and increasing the comfortable working hours up to 16.7%.

- Changing from sliding windows to pivoting windows improve air flows in work-stations located in the central regions of production spaces, remote from ventilation inlets and outlets.
- Changing furniture and adding passive ventilation shaft can also be improvement strategies, particularly to improve the air circulation pattern inside the workspace (SS) providing additional air speed up to 0.45 m/s.

The main limitations of this study are, firstly, the results are based on short periods of simulation and may not represent an entire year's conditions nor do they consider all production spaces. Secondly, the findings may not, therefore, be applicable to other RMG factories located in denser urban areas. Thirdly, study on reducing the barriers of implementing some of the strategies was beyond the scope of work. However, the findings from this chapter are useful to present the quantifiable benefit of the improvement measures to the stakeholders of RMG sector and to promote implement the workable strategies in a real building site.

CHAPTER 12. CONCLUSIONS AND FURTHER WORK

This chapter refers back to the five research objectives and describes the key findings showing how each of the objectives was achieved in this research. It also presents limitations of the study, its original contribution to knowledge, the implications of the research to policy and practice and recommended further research arising from this research.

CHAPTER 12. CONCLUSIONS AND FURTHER WORK

12.1. Introduction

This chapter refers back to the five research objectives (as presented in Section 1.3) and briefly describes the key research findings showing how each of the research objectives was addressed in this research. It also presents limitations of the study and its original contribution to knowledge, drawing out potential implications to policy and practice. It concludes with recommendations for further research that flow from this study.

12.2. Achievement of Objectives and the Key Findings

12.2.1. Objective one

As presented in Section 1.3, the first research objective was to identify the environmental design parameters that influence the indoor thermal comfort of workspaces including the workspaces in Ready-made Garment (RMG) factories. To address this research objective, theoretical studies were undertaken reviewing literature on the research context, established principles of thermal comfort and building performance, building regulations, previous empirical research and selected precedents set in the Tropics (presented in Chapters 2 and 3).

Previous literature suggested that climate has a direct impact on the microclimate condition of a site, thermal performance of a building and the thermal comfort of building occupants. In the tropical context of Bangladesh, the key challenges buildings have to cope with are seasonal variations of climate (i.e. the cool-dry, hot-dry and warm-humid seasons), diurnal variations of air temperature (AT), solar geometry, and monsoon weather. High indoor temperature is a major issue for non-domestic buildings, such as RMG factories, where the buildings tend to be multi-storied with heavyweight construction materials and the internal heat gains are as high as the external gains during day time.

Thermal performance of workspaces within a building depends on the regulating factors of the building and the surrounding context. The key parameters include the location of the site, morphological context, micro-climate conditions in respect of daily

and seasonal variations, function of the building, building envelope and most importantly the comfort criteria for the occupants. To determine the thermal comfort of occupants, use of two types of comfort models, i.e. the heat balance model and adaptive comfort model, were suggested by previous studies.

Generally, heat gain control and provision for cooling are the key design strategies to cope with the climatic seasons, such as the cool-dry, hot-dry, hot and humid seasons, in tropical regions. Generic heat control strategies usually deal with solar heat gains, ventilation and infiltration gain and internal heat gain. To counter these, air flow (e.g. cross ventilation and stack effect), Night-time ventilation (NTV) with thermal mass, ground cooling, and evaporative cooling and dehumidification are the widely used strategies that are adopted to cool buildings and help meet occupants' physiological comfort need during working hours. A major challenge is how to integrate these strategies into existing buildings.

Literature review work and study of precedents suggested that utilising building thermal mass with NTV, effective design of ventilation inlet windows, flexible control strategies for air flow and solar radiation, stack induced passive ventilation, and effective segmentation of functional layouts are the common environmental design parameters to influence the indoor thermal comfort of RMG workspaces.

12.2.2. Objective two

The second research objective was to identify and assess the feasibility of implementing suitable passive design strategies in existing multi-storey RMG factories in Bangladesh. To address this research objective, a pilot study was designed with duel purposes: to guide the scope of principal investigation and to test the feasibility of passive design strategies in existing RMG factories.

The feasibility study (presented in Chapter 6) was undertaken within an existing multi-storey RMG factory building, located in the Dhaka region, to understand the existing working conditions within RMG factories as well as its test the applicability of one of the previously suggested design strategies in this existing building. Site and micro-climate study and environmental data indicated the potential for utilising a night-time cooling strategy to harness the heat absorbing capacity of the building fabric during

daytime to improve thermal comfort during working hours. The difference between indoor and outdoor AT was found to be as high as 14°C, which indicated the potential value of stack ventilation as a workable desgin solution. Since the floor plate of the building is ten times wider than the ceiling height and cross ventilation was not feasible, a hypothesis was made where the stack ventilation would be able to meet the required ventilation rate and meet the thermal comfort target. Further theoretical study also revealed that a stack-induced ventilation strategy incorporating a central shaft could be a viable design solution.

In addition, a questionnaire survey of 18 subjects (factory owners and directors) also revealed that they saw value in incorporating any strategy that can improve the existing working environment within RMG factories. Since this study had limitations in terms of providing sufficient field evidence and representing different climatic seasons, further field investigations targeting additional case study buildings in different site contexts drawing the three main climatic seasons in Bangladesh were suggested.

12.2.3. Objective three

The third objective of this research was to identify the common parameters that influence the thermal environment within workspaces in existing RMG factories during the climatic seasons in Bangladesh. To address this research objective, detailed field studies (presented in Chapters 7 – 9) were undertaken on three cases study buildings, i.e. *RMG factory 1*, *RMG factory 3* and *RMG factory 3*, located in the Dhaka and Chittagong regions of Bangladesh.

The site and micro-climate studies for all case study buildings indicated significant heat gain during the daylight hours affected the ventilation and thermal performance of the building during working hours due to the presence of high outdoor air temperatures. However, it was also observed that relatively low outdoor AT occurred throughout the air during night time. Monitored data revealed that the indoor air and surface temperature of workstations remained hot during unoccupied hours in all three climatic seasons due to the use of mechanical and operation of windows being limited to working hours.

Results from on-site spot measurements and a study of workers' response suggested that there is a major challenge to ensure thermal comfort at workstations during the warm-humid season. This is due to the simultaneous presence of high AT, high relative humidity (RH) and low air flow speeds. Absence of full day ventilation, including operation during night time and weekends, was found to be one of the key issues affecting the thermal environment within the existing case study buildings.

In *RMG factory 1* and *RMG factory 3,* the total effective window areas (only 45% of the structural opening area) are very low compared with existing production floor areas. The sliding windows restricted the outdoor air to flow in the workspaces, usually resulting in undesirably high airflow speeds for workstations located near windows and had a direct impact on increasing indoor AT and discomfort causing deviations of AT up to 2.5°C. Even in *RMG factory 2*, where the effective window to floor area ratio is relatively high and floor-plate width is 10m, workers claimed to face similar issues.

In all of the case study buildings, several high heat generating equipment was found across the production lines resulting in the creation of high AT across the whole production floor. Moreover, both subjective and objective data confirmed that workers having their workstations located remotely from the ventilation inlets suffer from discomfort due to simultaneously high AT and low air speed. Existing functional layouts also result in undesirable airflows at the workstations.

Thermal images from the field studies indicated that the south, west and east façades and the roof of the case study building are subject to incident solar radiation affecting the adjacent production spaces. Hence, the glazing materials, shading devices and external wall thicknesses were the major design elements that need improvement to reduce direct solar transmission and associated conductive heat gain issues.

12.2.4. Objective four

The forth objective of this research was to identify thermal comfort guidelines and workable design strategies to minimise the issues found in the previous section (Section 12.2.3) within RMG workspaces. To address this research objective, the environmental data and comfort votes collected from all field studies were compared and statistical analyses were undertaken (presented in Chapter 10).

The actual thermal comfort ranges were calculated through questionnaire survey during the three field studies representing three different climatic seasons of Bangladesh. Statistical analysis showed that the actual comfortable temperature ranges for the workers allowing sufficient adaptive behaviour in the work sections investigated cutting (CS), sewing (SS) and finishing (FS) sections were found to be between 25.2°C and 26°C during the cool-dry season, while the ranges were higher during the hot-dry and warm humid seasons (26.5°C - 30°C and 26.9°C - 28.9°C respectively). During the cool-dry and hot-dry seasons, the workers had wider adaptive temperature range than the warm-humid season. Due to high RH and narrow comfort range during the warm-humid season, the comfort condition in a workspace may only be improved by elevated airflow effect.

Statistical correlations revealed that airflows to their workstations from the north, south and east sides of the building were preferred by the workers. In contrast, airflows from above and below of their workstations (e.g. airflows from the ceiling fans) were not favoured and usually caused discomfort. Moreover, analysis results showed that the preferred air speed ranges were 0.4 – 1.1 m/s, 1.2 – 2.8 m/s and 2.8 – 5.8 m/s in the CS, SS and FS respectively, to execute the various ranges of production works. Feedback from the focus group discussions, as well as these results, indicated that workers should be provided with more personalised control over the airflow at their workstations, including control over fans and windows.

The distance between the workers' workstations and ventilation inlets should be maintained within 12m to 18m for more personalised control on their comfort avoiding the ceiling fans.

A number of strategies for improving existing case study buildings' production spaces were also proposed in Chapters 7-9. However, these strategies can only be viable if the owners of the factories see value in implementing them in the factories. The owners and managing directors enthusiastically agreed on the need to improve the thermal comfort in their existing factories and were interested in implementing any that were partially feasible and cost-effective. According to the outcome of the interviews with the owners and directors of the three case study buildings, a 24-hour ventilation strategy with NTV and changes to the window configurations were viewed as

immediately implementable strategies for improving workers' thermal experience within their existing RMG factories. They also indicated that the remaining strategies and retrofit features, such as adding ventilation shafts, rearranging the existing furniture, improving personalised control over ventilation and changing construction materials, can only be adopted in any future RMG buildings.

12.2.5. Objective five

The fifth research objective was to explore the environmental benefits of applying the workable design strategies in existing RMG factories (as presented in Section 10.8.3). To address this last objective of the research, a simulation model of case study building-3 was developed using IES-VE building energy simulation software and validated with the field data (presented in Chapter 11).

From the simulation study it was found that changing the existing sliding windows to pivoting windows (with 75% effective opening) can reduce high AT by up to 15% of working hours in the FS, 12% in the SS and 2% in the CS. Moreover, adopting 24-hour ventilation (utilising the existing thermal mass and NTV) can reduce working hours of high temperature by up to 23% in the FS, 17% in the SS and 3% in the CS during all climatic seasons. Changing to pivoting windows enhances air flows in workstations located in the central regions of production spaces, remote from ventilation inlets and outlets.

The other solutions, which were less feasible to implement in the existing case study buildings but potentially more applicable to new multi-storey RMG factory buildings (i.e. Improving air flow by changing functional layout and adding passive ventilation shafts), were also found to be beneficial to improve the air circulation in the SS providing additional air speeds up to 0.45 m/s. Integrating shafts within the existing archetype can enhance the stack induced ventilation and can partially replace the active ventilation strategy, particularly for NTV. Hence it could be anticipated that application of these strategies within the workspaces would pure beneficial in improving the workers' thermal comfort conditions in these RMG factories.

12.3. Limitations of the Study

Considering the limitations of the main research methods described in Sections 5.4.7, 5.5.9 and 5.6.7, the following key limitations of the research findings can be presented:

- Since the simulation study and field studies were conducted on a limited number of case study buildings (i.e. one and three case study buildings respectively), the findings may not be applicable to other RMG factories located in different regions of Bangladesh. Moreover, these buildings are not representative of the total building stock. In particular, the findings from this simulation study will not be fully applicable to other RMG factories with different plans and orientations or that are located in denser urban contexts.
- Time was one of the main limitations of this research. The field studies were completed within a short period of time (i.e. around 10 days for each of the three case study buildings during each season) representing the different climatic seasons of Bangladesh. Hence results, such as thermal performance of the buildings and the thermal comfort guidelines, may not be representative for a whole year.
- For collecting subjective feedback and comfort survey data, a snapshot comfort survey was undertaken due to the limited timeframe and access to the case study buildings. Sample size for these comfort survey also varied across the field-visits. This is also counted as a limitation of the study and may have impact on the results in relation to the varied sample sizes. Moreover, only three semi-structured interviews with the building owners and managing directors of the case study buildings were undertaken. Hence their feedback may not be generalised for other RMG factories. Absence of a formal interview with the architects of the building was also a limitation.
- Since the benefits of retrofitting measures were presented based on the simulation studies, the results may not be fully representative for a real site. Moreover, potential site-specific barriers of implementing the workable measures, such as issues of bringing polluted air, noise and dust inside the workspaces by increasing the effective window sizes, were not investigated.

- The research has not included an investigation and discussion of the costs and disruption associated for implementing any of the workable strategies.

12.4. Original Contribution to Knowledge and Practice

Apart from the limitations highlighted in Section 12.3, the originality of this research in terms of contribution to knowledge, policy and practice can be presented as follows:

- For the first time this research presented a body of field evidence, including both physical measurement and subjective responses from the workers, to identify the common parameters that cause issues with thermal environment of workspaces in existing RMG factories in the three climatic seasons of Bangladesh.
- This research presented new thermal comfort guidelines, including neutral temperature, preferred air temperature and operative temperature ranges for workers, in the CS, SS and FS during the three climatic seasons of Bangladesh. Moreover, preferred speeds and directions of airflows at workers' workstations in the CS, SS and FS were identified. Though these guidelines are based on the results from a limited number of case study buildings, the methodology of the study can be followed for studies in other RMG factory buildings.
- This research also identified for the first time that ceiling fans are not as effective solution to enhance the workers' thermal comfort and rather cause discomfort.
- Measuring the benefits of a number of workable strategies identified in this study, such as adding NTV strategy utilising the existing buildings' thermal mass, changing the window configuration, adding passive ventilation shafts and rearranging the furniture layout, are the novel findings that may be valid for improving the thermal comfort conditions of the case study buildings.
- The Governing bodies of Bangladesh (e.g. Ministry of Housing and Public Works), engineers, architects and academic institutions are currently undertaking further reviews to improve the existing national building code. The main agenda of the current review process is to improve the chapters of 'PART 8' of the code related to building services and to add a number of new chapters, such as refurbishment of existing buildings and green measures for new

buildings with a special section on designing RMG factories and their associated ventilation strategies. Findings from this research can be a reference for conducting extended studies and validated results can be added to the Bangladesh National Building Code.

- The researcher is developing opportunities to collaborate with the international buyers (i.e. clothing brands), BGMEA, ILO, Institutes of Architects Bangladesh (IAB) and Institutes of Engineers Bangladesh (IEB) to disseminate the research outcome to relevant stakeholders. They can, therefore, partially follow the methodology of this research for further extended study and design exercises.
- The researcher has published one journal article, four conference papers and two posters in international platforms based on this research, which represents evidence of the contribution to knowledge in academia.

12.5. Further Research

Based on the outcome of this PhD study, the following areas of further research are recommended for the future:

- Further research work should be developed by increasing the number of samples, such as more case study buildings in various site contexts and by expanding the scope of the comfort survey (e.g. increasing number of subjects, and using longitudinal comfort surveys) and by extending the scope of parametric studies to more than one building including other design parameters such as external shading devices, building form in relation to site area, archetype and contemporary green technologies for improved working condition. Further case studies can also be developed in the context of other climatic regions.
- It would be worthwhile collecting field data over a period of a whole year and evaluating the benefits of implementing the proposed strategies by measuring performance on a real site. This could increase the precision of the results and diminish the deviations between predicted and actual quantitative results on building performance and thermal comfort.

- Future research should consider the feasibility of proposed improvement strategies in terms of cost, disruption associated with retrofitting existing RMG factories and relevant site-specific barriers associated with implementing the strategies.
- A number of pilot studies could be developed focusing on the other factory buildings and a feasibility study of passive ventilation could be undertaken through experimenting in a real site.
- Future research should consider the projected future climate data and evaluate the physical viability of passive ventilation strategies in existing RMG factory.
- Emergency smoke removal is an issue in RMG factories due to their deep floor plans and consequent difficulties in extracting smoke in the event of a fire. Stack induced passive ventilation strategies may present an opportunity to quickly flush out smoke through the shafts during emergency fire incidents, an area that needs further investigation.

Future studies may focus on other environmental aspects of workspaces in RMG factories, such as indoor air quality and may also investigate the impact of workspace environment on workers' health, wellbeing and productivity.

REFERENCES

ABDULLAH, A. H. 2007. *A Study on Thermal Environmental Performance in Atria in the Tropics with Special Reference to Malaysia.* Unpublished PhD thesis, Heriot-Watt University, UK.

ABHIKRAM. 2007. *Case Study II: The TorrentResearch Centre in Ahmedabad* [Online]. Abhikram. Available: http://www.archidev.org/spip.php?article1115 [Accessed 6 May 2016].

ABSAR, S. S. 2001. Problems surrounding wages: the readymade garments sector in Bangladesh. *Journal of Labour and Management in Development,* 2**,** 1-7.

ACCORD 2013. Accord on Fire and Building Safety in Bangladesh.

ADDY, M. N., ADINYIRA, E. & KORANTENG, C. A review of research methodologies in building energy efficiency assessment. *In:* LARYEA, S. & IBEM, E., eds. 8th Construction Industry Development Board (cidb) postgraduate Conference, 10-11 February 2014 Johannesburg, South Africa. University of the Witwatersrand, 85-100.

ADEBISI, G., ONUWE, J. O. & SANI, A. M. 2015. Assessment of Biomimicry Design Concept Adoption in Architecture: Towards a Sustainable Built Environment in Nigeria. *IOSR Journal of Environmental Science, Toxicology and Food Technology (IOSR-JESTFT),* 9**,** 41-46.

AFLAKI, A., MAHYUDDIN, N., AL-CHEIKH MAHMOUD, Z. & BAHARUM, M. R. 2015. A review on natural ventilation applications through building façade components and ventilation openings in tropical climates. *Energy and Buildings,* 101**,** 153-162.

AHMED, K. S., HAQ, A. & MONIRUZZAMAN, M. 2006. Potentials of Window Design in Inducing Airchange in Still Air Condition. *PLEA2006 - The 23rd Conference on Passive and Low Energy Architecture.* Geneva, Switzerland.

AHMED, S. & RAIHAN, M. Z. 2014. Health Status of the Female Workers in the Garment Sector of Bangladesh. *Çankırı Karatekin University Journal of the Faculty of Economics and Administrative Sciences (JFEAS),* 4**,** 43-58.

AHMED, Z. N. 1987. *The Effects of Climate on the Design and Location of Windows for Buildings in Bangladesh.* Unpublished M.Phil Thesis, Sheffield City Polytechnic, UK.

AHMED, Z. N. 2011. Contextualizing International standards for compliance in Factories., . *Proceedings of PLEA 2011,.* Louvain-la-Neuve, Belgium.

AHMED, Z. N. & ROY, G. S. Ventilation Potential: Examining the Effects of Growing Densification in the Tropics. Proceedings of Clima 2007 WellBeing Indoors, 2007.

AKBARI, H. 2007. *Opportunities for Saving Energy and Improving Air Quality in Urban Heat Islands. ,* London, UK, Earthscan.

AKTHER, S., SALAHUDDIN, A., IQBAL, M., MALEK, A. & JAHAN, N. 2010. Health and Occupational Safety for Female Workforce of Garment Industries in Bangladesh. *Journal of Mechanical Engineering,* ME 41**,** 65-70.

AL-OBAIDI, K. M., ISMAIL, M. & RAHMAN, A. M. A. 2013. An innovative roofing system for tropical building interiors: Separating heat from useful visible light. *International Journal of Energy and Environment,* 4**,** 103-116.

AL-TAMIMI, N. A. M. & FADZIL, S. F. S. 2011. Thermal Performance Analysis for Ventilated and Unventilated Glazed Rooms in Malaysia (Comparing Simulated and Field Data). *Indoor and Built Environment,* 20**,** 534–542.

ALI, M. L. & ISLAM, N. 2017. Working Environment of Female Readymade Garment Workers in Bangladesh *International Academy of Management and Business Conference.* Dubai, UAE.

ALI, Z. F. 2000. *Environmental performance of the buildings designed by the modern masters in the tropics : architecture of Le Corbusier and Louis I. Kahn in India and Bangladesh.* Ph.D., Open University, UK.

ALI, Z. F. 2005. Kahn in the Tropics. *Proceedings of the International Solar Energy Society Solar World Congress.* Orlando.

ALLIANCE FOR BANGLADESH WORKER SAFETY 2016. Protecting and empowering Bangladesh garment workers (3rd annual report). Alliance for Bangladesh Worker Safety.

ALMHAFDY, A., IBRAHIM, N., AHMAD, S. S. & YAHYA, J. 2015. Thermal Performance Analysis of Courtyards in a Hot Humid Climate Using Computational Fluid Dynamics CFD Method. *Procedia - Social and Behavioral Sciences,* 170**,** 474-483.

ALWETAISHI, M. S. 2016. Impact of Building Function on Thermal Comfort: A Review Paper. *American Journal of Engineering and Applied Sciences,* 9**,** 928-945.

AMARATUNGA, D., BALDRY, D., SARSHAR, M. & NEWTON, R. 2002. Quantitative and qualitative research in the built environment: application of “mixed” research approach. *Work Study,* 51**,** 17-31.

AMOS-ABANYIE, S., AKUFFO, F. O. & KUTIN-SANWU, V. 2013. Effects of thermal mass, window size, and night-time ventilation on peak indoor air temperature in the warm-humid climate of Ghana. *Scientific World Journal,* 621095.

ARTMANN, N., MANZ, H. & HEISELBERG, P. 2008. Parameter study on performance of building cooling by night-time ventilation. *Renewable Energy,* 33**,** 2589-2598.

ASHRAE 2009. *Handbook of fundamentals,* Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc.

ASHRAE 2013. *ASHRAE Handbook: Fundamentals,* Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ATTIA, S. 2010. Building Performance Simulation Tools: Selection Criteria and User Survey. - Research Based Report. . Louvain: Université catholique de Louvain, Belgium.

AULICEMS, A. & SZOKOLAY, S. V. 2007. *Thermal Comfort*, PLEA : Passive and Low Energy Architecture International in association with Department of Architecture, The University of Queensland.

BAINBRIDGE, D. A. & HAGGARD, K. 2011. *Passive Solar Architecture: Heating, Cooling, Ventilation, Daylighting and More Using Natural Flow,* Vermont, Chelsea Green

BARAL, L. M. 2010. Comparative Study of Compliant & Non- Compliant RMG Factories in Bangladesh. *International Journal of Engineering & Technology,* 10**,** 119-131.

BARBOSA, S. & IP, K. 2016. Predicted thermal acceptance in naturally ventilated office buildings with double skin façades under Brazilian climates. *Journal of Building Engineering,* 7**,** 92-102.

BARBOSA, S., IP, K. & SOUTHALL, R. 2015. Thermal comfort in naturally ventilated buildings with double skin façade under tropical climate conditions: The influence of key design parameters. *Energy and Buildings,* 109**,** 397-406.

BAXTER, P. & JACK, S. 2008. Qualitative Case Study Methodology: Study Design and Implementation for Novice Researchers. The Qualitative Report.

BAY, J.-H. & ONG, B. L. 2006. *Tropical sustainable architecture: social and environmental dimensions,* Oxford, Architectural Press, Elsevier Ltd.

BBS 2010. Statistical Yearbook of Bangladesh -2010, Chapter 6: Energy. *In:* BANGLADESH BUREAU OF STATISTICS (ed.).

BCA 2012. Code for Environmental Sustainability of Buildings (3rd edition). Singapore: Building and Construction Authority.

BEPZA 2009. Annual Report 2008-2009. Bangladesh Export Processing Zones Authority, Dhaka, Bangladesh.

BERNARD, T. E. & HANNA, W. M. 1998. Environmental effects on WBGT and HSI using a computer simulation. *International Journal of Industrial Ergonomics,* 3**,** 103-113.

BERTHOLD, S., DANIELS, K., FISCH, M. N., HAMMANN, R. E., HEUSLER, W., KIBE, H., SHAH, A. & YACOUB, M. 2007. *plusminus20°/40°latitude: Sustainable building design in tropical and subtropical regions,* London, Schuco.

BGMEA. 2013. *Member list* [Online]. Bangladesh Garment Manufacturers and Exporters Association. Available: http://www.bgmea.com.bd/member/memberlist [Accessed 3 May 2014].

BILLÉ, R. 2010. Action without change? On the use and usefulness of pilot experiments in environmental management. *Surveys and Perspectives Integrating Environment and Society,* 3**,** 1-6.

BLAIKIE, N. 1993. *Approaches to social enquiry,* Cambridge, Polity.

BRAC EPL 2013. Bangladesh growth report 2013: strategic sales. BRAC EPL.

BRAGER, G., ZHANG, H. & ARENS, E. 2015. Evolving opportunities for providing thermal comfort. *Building Research & Information,* 43**,** 274-287.

BRAGER, G. S. & DE DEAR, R. J. 1998. Thermal adaptation in the built environment: a literature review. *Energy and Building,* 27**,** 83-96.

BRAGER, G. S., PALIAGA, G. & DE DEAR, R. 2004. Operable windows, personal control and occupant comfort. *ASHRAE Transactions,* 110 (Part 2)**,** 17-35.

BRYMAN, A. & TEEVAN, J. J. 2005. *Social research methods* Don Mills, Oxford University Press.

BUSCH, J. F. 1992. A tale of two populations: thermal comfort in air-conditioned and naturally ventilated offices in Thailand. *Energy and Buildings,* 18**,** 235-249.

BUTERA, F. M. 1998. Chapter 3- Principles of thermal comfort. *Renewable and Sustainable Energy Reviews,* 2**,** 39-66.

CAMPAIGN, C. C. 2012. Hazardous workplaces: Making the Bangladesh Garment industry safe.

CÂNDIDO, C., DE DEAR, R. & LAMBERTS, R. 2011. Combined thermal acceptability and air movement assessments in a hot humid climate. *Building and Environment,* 46**,** 379-385.

CÂNDIDO, C., DE DEAR, R. J., LAMBERTS, R. & BITTENCOURT, L. 2010. Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone. *Building and Environment,* 45**,** 222-229.

CHANG, J.-H. 2016. Thermal comfort and climatic design in the tropics: an historical critique. *The Journal of Architecture,* 21**,** 1171-1202.

CHEN, Q. 2009. Ventilation performance prediction for buildings: A method overview and recent applications. *Building and Environment,* 44**,** 848-858.

CHOWDHURY, A. K. M. M. A. 2003. Labour and Industrial Law of Bangladesh. Chittagong, Bangladesh: M. Ahmed & Co.

CHOWDHURY, S., AHMED, K. S. & HAMADA, Y. 2015. Thermal performance of building envelope of ready-made garments (RMG) factories in Dhaka, Bangladesh. *Energy and Buildings,* 107**,** 144-154.

CHOWDHURY, S. & ALAM, M. R. 2011. Design Approach of Energy Efficient Ready Made Garments Factory in View of Thermal Comfort. *International Association for Automation and Robotics in Construction (IAARC).* ISARC, Seoul, Korea.

CHOWDHURY, S., HAMADA, Y. & AHMED, K. S. 2017a. Experimental evaluation of subjective thermal perceptions for sewing activity. *Energy and Buildings,* 149**,** 450-462.

CHOWDHURY, S., HAMADA, Y. & AHMED, K. S. 2017b. Prediction and comparison of monthly indoor heat stress (WBGT and PHS) for RMG production spaces in Dhaka, Bangladesh. *Sustainable Cities and Society,* 29**,** 41-57.

CHOWDHURY, S., HAMADA, Y. & SHABBIR AHMED, K. 2017c. Indoor heat stress and cooling energy comparison between green roof (GR) and non-green roof (n-GR) by simulations for labor intensive factories in the tropics. *International Journal of Sustainable Built Environment,* 6**,** 449-462.

CHOWN, M. 2003. Building simulation as an aide to design. *the Eighth International IBPSA Conference.* Eindhoven, Netherlands.

CIBSE 2005. *Natural ventilation in non-domestic buildings: CIBSE Applications Manual AM10,* London, The Chartered Institution of Building Services Engineers.

CIBSE 2006. Environmental Design: CIBSE Guide A. London: The Chartered Institution of Building Services Engineers.

CIBSE 2013. *Environmental design: CIBSE Guide A,* Suffolk, The Chartered Institution of Building Services Engineers: The Lavenham Press Ltd.

CIBSE 2015. *Environmental design: CIBSE Guide A,* London, The Chartered Institution of Building Services Engineers.

COTESAI1. 2013. *The termite mound: A not-quite-true popular bioinspiration story. How insects bioinspire us to innovate* [Online]. Available: https://insectsdiditfirst.com/2013/09/18/the-termite-mound-a-not-quite-true-popular-bioinspiration-story/ [Accessed 3 December 2016].

COUNCIL, I. G. B. 2009. *IGBC Green Factory Building Rating System (Pilot Version),* India, Confederation of Indian Industry.

CRAWLEY, D. B., HAND, J. W., KUMMERT, M. & GRIFFITH, B. T. 2008. Contrasting the capabilities of building energy performance simulation programs. *Building and Environment,* 43**,** 661-673.

CRESWELL, J. W. 2009. *Research design: Qualitative, quantitative, and mixed methods approaches*, Sage.

CRESWELL, J. W. 2013. *Qualitative inquiry and research design: Choosing among five approaches,* Thousand Oaks, CA, Sage Publications Inc.

CUI, S., STABAT, P. & MARCHIO, D. 2013. Influence of Natural Ventilation on Solar Gains and Natural Lighting by Opening Windows. *13th Conference of International Building Performance Simulation Association.* Chambéry, France.

DAHL, R. 2013. Cooling concepts: alternatives to air conditioning for a warm world. *Environ Health Perspect,* 121**,** A18-25.

DAINTY, A. 2007. A Call for Methodological Pluralism in Built Environment Research. *The Third Scottish Conference for Postgraduate Researchers of the Built and Natural Environment (PRoBE 2007).* Glasgow, UK.

DANBY, M. 1963. *Grammar of Architectural Design with reference to the tropics,* London, Oxford University Press.

DE DEAR, R. 2004. Thermal comfort in practice. *Indoor Air,* 14**,** 32-9.

DE DEAR, R., BRAGER, G. & COOPER, D. 1997. Developing an Adaptive Model of Thermal Comfort and Preference. Berkeley, CA: Center for Environmental Design Research, University of California,.

DE DEAR, R. & BRAGER, G. S. 2001. The adaptive model of thermal comfort and energy conservation in the built environment. *Int J Biometeorol,* 45**,** 100–108.

DE DEAR, R. & FOUNTAIN, M. 1994. Field experiments on occupant comfort and office thermal environments in a hot-humid climate. *ASHRAE Transactions,* 100**,** 457-475.

DE DEAR, R., KIM, J., CANDIDO, C. & DEUBLE, M. 2015. Adaptive thermal comfort in Australian school classrooms. *Building Research & Information,* 43**,** 383-398.

DE DEAR, R. J. & BRAGER, G. S. 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings,* 34**,** 549-561.

DE DEAR, R. J., LEOW, K. G. & FOO, S. C. 1991. Thermal comfort in the humid tropics: Field experiments in air conditioned and naturally ventilated buildings in Singapore. *International Journal of Biometeorology,* 34**,** 259–265.

DE VAUS, D. A. 2001. *Research design in social research,* London, Sage.

DEAT 2009. Green Building in South Africa: Emerging Trends. Department of Environmental Affairs and Tourism.

DENZIN, N. K. & LINCOLN, Y. S. 2000. *Handbook of Qualitative Research,* Thousand Oaks, CF, Sage.

DJAMILA, H. 2017. Indoor thermal comfort predictions: Selected issues and trends. *Renewable and Sustainable Energy Reviews,* 74**,** 569-580.

DJAMILA, H., CHU, C.-M. & KUMARESAN, S. 2014. Effect of Humidity on Thermal Comfort in the Humid Tropics. *Journal of Building Construction and Planning Research,* 02**,** 109-117.

DOMAT, G., ADLER, P., DEHEJIA, R., BROWN, D. & ROBERTSON, R. 2013. Do Factory Managers Know What Workers Want? Manager- Worker Information Asymmetries and Pareto Optimal Working Conditions," Discussion Paper No. 10.: Better Work.

DOODY, O. & DOODY, C. M. 2015. Conducting a pilot study: case study of a novice researcher. *Br J Nurs,* 24**,** 1074-8.

DOOLEY, L. M. 2002. Case Study Research and Theory Building. *Advances in Developing Human Resources,* 4**,** 335-354.

DU TOIT, J. L. & MOUTON, J. 2013. A typology of designs for social research in the built environment. *International Journal of Social Research Methodology,* 16**,** 125-139.

EIA. 2017. *International Energy Outlook 2017: Chapter 6. Buildings sector energy consumption* [Online]. US Department of Energy Available:

https://www.eia.gov/outlooks/ieo/buildings.php [Accessed 18 September 2017].
ELLIS, F. P. 1953. Thermal comfort in warm and humid atmospheres: Observations on groups and individuals in Singapore. *The Journal of Hygiene,* 51**,** 386-404.
ENGINEERING TOOLBOX. 2004. *Heat Gain from Electrical Motors in Continuous Operation* [Online]. Available: https://www.engineeringtoolbox.com/electrical-motors-heat-gain-d_707.html [Accessed 30 May 2014].
ERNEST, R. & FORD, B. 2012. The role of multiple-courtyards in the promotion of convective cooling. *Architectural Science Review,* 55**,** 241-249.
FATEMI, M. N. 2012. *Study of Thermal Environment in Relation to Human Comfort in Production Spaces of Ready Made Garments Factories in the Dhaka Region.* Master of Architecture, Bangladesh University of Engineering & Technology.
FATEMI, N. 2014. *Thermal comfort in production spaces of ready-made garments Factories the context of Dhaka, Bangladesh,* Germany, LAP Lambert Academic Publishing.
FERIADI, H. & WONG, N. H. 2004. Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings,* 36**,** 614-626.
FERRARI, S. & ZANOTTO, V. 2012. Adaptive comfort: Analysis and application of the main indices. *Building and Environment,* 49**,** 25-32.
FIELD, A. 2013. *Discovering statistics using IBM SPSS Statistics,* London, Sage publications.
FIELD, A. & HOLE, G. 2006. *How to design and report experiments. ,* London, Sage publications.
FISK, W. J. 2000. Health and Productivity Gains From Better Indoor Environments and Their Relationship with Building Energy Efficiency. *Annu. Rev. Energy Environ. ,* 25**,** 537–66.
FLYVBJERG, B. 2006. Five Misunderstandings about Case-Study Research. *Qualitative Inquiry,* 12**,** 219-245.
FORD, B. 1998. Cooling Without Air Conditioning: The Torrent Research Centre, Ahmedabad, India. *Renewable Energy,* 15**,** 177-182.
FORD, B. 2010. *The Architecture & Engineering of Downdraught Cooling: A Design Sourcebook,* UK, PHDC Press.
FOUNDATION, B. A. 2013. *Accord Factory List* [Online]. Accord on Fire and Building Safety in Bangladesh. Available: http://www.bangladeshaccord.org/factories/ [Accessed March 2014 2014].
FOUNTAIN, M., BRAGER, G. & DE DEAR, R. 1996. Expectations of indoor climate control. *Energy and Buildings,* 24**,** 179-182.
FREEWAN, A. A. Y. 2014. Impact of external shading devices on thermal and daylighting performance of offices in hot climate regions. *Solar Energy,* 102**,** 14-30.
FRONTCZAK, M. & WARGOCKI, P. 2011. Literature survey on how different factors influence human comfort in indoor environments. *Building and Environment,* 46**,** 922-937.
GALVIN, J. F. P. 2016. *An Introduction to the Meteorology and Climate of the Tropics,* West Sussex, John Wiley & Sons Inc.
GIVONI, B. 1994. Building design principles for hot humid regions. *Renewable Energy,* 5**,** 908-916.

GIZ. 2017. *Promotion of social and environmental standards in the industry* [Online]. Available: https://www.giz.de/en/worldwide/14900.html [Accessed 22 July 2017].
GOB 2006. Bangladesh Labour Act 2006: act no. 42 of 2006. Ministry of Labour and Employment, Peoples Republic of Bangladesh, Government of Bangladesh.
GÖÇER, Ö., HUA, Y. & GÖÇER, K. 2015. Completing the missing link in building design process: Enhancing post-occupancy evaluation method for effective feedback for building performance. *Building and Environment,* 89**,** 14-27.
GOMM, R., HAMMERSLEY, M. & FOSTER., P. 2000. *Case Study Method: Key Issues, Key Texts,* London, Sage.
GOODFELLOW, H. D. & TAHTI, E. 2001. *Industrial Ventilation Design Guidebook,* USA, Academic Press.
GOSSAUER, E. & WAGNER, A. 2007. Post-occupancy Evaluation and Thermal Comfort: State of the Art and New Approaches. *Advances in Building Energy Research,* 1**,** 151-175.
GOURLIS, G. & KOVACIC, I. 2016. A study on building performance analysis for energy retrofit of existing industrial facilities. *Applied Energy,* 184**,** 1389-1399.
GOUVÊA, T. C., LABAKI, L. C., RUAS, Á. C. & MAIA, P. A. 2006. Thermal Comfort Evaluation: A Study in Workplaces at the Clothing Industry in Brazil. *Windsor Conference 2006: Network for Comfort and Energy Use in Buildings (NCEUB).*
GROAT, L. N. & WANG, D. 2013. *Architectural research methods,* Hoboken, Wiley.
GUERRA-SANTIN, O. & TWEED, C. A. 2015. In-use monitoring of buildings: An overview of data collection methods. *Energy and Buildings,* 93**,** 189-207.
HAIDER, M. Z. 2007. Competitiveness of the Bangladesh Ready-made Garment Industry in Major International Markets. *Pacific Trade and Investment Review,* 3**,** 3-27.
HALAWA, E., VAN HOOF, J. & SOEBARTO, V. 2014. The impacts of the thermal radiation field on thermal comfort, energy consumption and control—A critical overview. *Renewable and Sustainable Energy Reviews,* 37**,** 907-918.
HBRI 2015. Bangladesh National Building Code 2015 (draft). Housing and Building Research Institute.
HBRI & BSTI. 2006. Bangladesh National Building Code 2006. Housing and Building Research Institute, Bangladesh Standards and Testing Institution.
HEFCE 2006. Guide to Post Occupancy Evaluation. UK: University of Westminster.
HEISELBERG, P., SVIDT, K. & NIELSEN, P. V. 2001. Characteristics of airflow from open windows. *Building and Environment,* 36**,** 859–869.
HEISELBERG, P., SVIDT, K. & NIELSEN, P. V. 2011. Characteristics of airflow from open windows. *Building and Environment,* 36**,** 859-869.
HOBDAY, R. A. & DANCER, S. J. 2013. Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives. *J Hosp Infect,* 84**,** 271-82.
HONDE, T. & ALIBABA, H. Z. 2016. Green Facade as A Prototype Way Of Extending Natural Sphere In A Hyper Dense Urban Context. *International Journal of Scientific and Technology Research,* 5.
HOSSAIN, M. 2016. *Power Sector: Success and Challenges Ahead* [Online]. The Daily Asian Age. Available: https://dailyasianage.com/news/32313/power-sector-success-and-challenges-ahead [Accessed 4 June 2017].

HOSSAIN, M. M. 2011. *Study of Illumination Condition of Production Spaces With Reference To the Ready Made Garments Sector of Dhaka Region.* Master of Architecture Unpublished, Bangladesh University of Engineering & Technology.

HOSSAIN, M. M. & AHMED, K. S. 2012. Towards Performance Based Design: Scope of Using Computer Based Lighting Simulation Tool for Designing Efficient Luminaire Layout of a Production Space in the Context of Dhaka Region, Bangladesh. *26th International Conference "European Simulation and Modelling Conference" - ESM'2012.* FOM, Essen, Germany.

HUMPHREYS, M. A. 1970. A Simple Theoretical Derivation of Thermal Comfort Conditions. *Journal of the Institute ofHeating and Ventilating Engineers***,** 95–98.

HUMPHREYS, M. A., NICOL, J. F. & RAJA, I. A. 2007. Field Studies of Indoor Thermal Comfort and the Progress of the Adaptive Approach. *Advances in Building Energy Research,* 1**,** 55-88.

HUMPHREYS, M. A., RIJAL, H. B. & NICOL, J. F. 2013. Updating the adaptive relation between climate and comfort indoors; new insights and an extended database. *Building and Environment,* 63**,** 40-55.

HYDE, R. 2000. *Climate Responsive Design: a study of buildings in moderate and hot humid climates,* London, E & FN Spon, Taylor and Francis Group.

IFC 2007. Ready-made Garments: Challenges in Implementing a Sector Strategy. Dhaka: Monitor, . Dhaka: International Finance Corporation, Bangladesh.

IGBC. 2014. *IGBC Green Factory Building* [Online]. Indian Green Building Council. Available: https://igbc.in/igbc/redirectHtml.htm?redVal=showGreenFactoryBuildingnosign [Accessed 7 November 2015].

ILO 1965. Bangladesh: Factories Act, 1965 (No. 4 of 1965). *NATLEX database.* National Law of Labour, Social Security and Related Human Rights.

ILO 1998. *Improving working conditions and productivity in the garment industry: an action manual,* Geneva, International Labour Organization.

ILO. 2013. Standards and guidelines on labour statistics. [Accessed 19 October 2013].

INDRAGANTI, M. 2010. Using the adaptive model of thermal comfort for obtaining indoor neutral temperature: Findings from a field study in Hyderabad, India. *Building and Environment,* 45**,** 519-536.

INDRAGANTI, M., OOKA, R., RIJAL, H. B. & BRAGER, G. S. 2014. Adaptive model of thermal comfort for offices in hot and humid climates of India. *Building and Environment,* 74**,** 39-53.

ISLAM, M. S. & HOSSAIN, I. 2013. Bangladesh National Building Code (BNBC): Current Practice and Relevance to Future Climate Change Aspect. *CCTC 2013.*

ISMAIL, A. R., JUSOH, N., ZULKIFLI, R., SOPIAN, K. & DEROS, B. M. 2009. Thermal Comfort Assessment: A Case Study at Malaysian Automotive Industry. *American Journal of Applied Sciences,* 6**,** 1495-1501.

ISMAIL, M. & RAHMAN, A. M. A. 2012. Stack Ventilation Strategies in Architectural Context: A Brief Review of Historical Development, Current Trends and Future Possibilities. *IJRRAS,* 11**,** 291-301.

ISO 1998. *International Standard ISO 7726: Ergonomics of the thermal environment -- Instruments for measuring physical quantities,* Switzerland, International Organization for Standardization.

JAMES-CHAKRABORTY, K. 2014. Reinforced concrete in Louis Kahn's National Assembly, Dhaka: Modernity and modernism in Bangladeshi architecture. *Frontiers of Architectural Research,* 3**,** 81-88.

JAUNZENS, D., GRIGG, P., COHEN, R., WATSON, M. & PICTON, E. 2003. Building performance feedback: getting started. *BRE Environment.* BRE publications, London, UK.

JI, Y., LOMAS, K. J. & COOK, M. J. 2009. Hybrid ventilation for low energy building design in south China. *Building and Environment,* 44**,** 2245-2255.

JUSOH, N., BAKAR, R. A., ISMAIL, A. R. & ALI, T. Z. S. 2015. Computational Analysis of Thermal Building in a No-uniform Thermal Environment. *Energy Procedia,* 68**,** 438-445.

KANG, J.-H. & LEE, S.-J. 2008. Improvement of natural ventilation in a large factory building using a louver ventilator. *Building and Environment,* 43**,** 2132-2141.

KARJALAINEN, S. 2012. Thermal comfort and gender: a literature review. *Indoor Air,* 22**,** 96-109.

KARYONO, T. H. 1995. Thermal comfort for the Indonesian workers in Jakarta. *Building Research & Information,* 23**,** 317-323.

KARYONO, T. H. 2000. Report on thermal comfort and building energy studies in Jakarta - Indonesia. *Building and Environment,* 35.

KATUNSKY, D., KORJENIC, A., KATUNSKA, J., LOPUSNIAK, M., KORJENIC, S. & DOROUDIANI, S. 2013. Analysis of thermal energy demand and saving in industrial buildings: A case study in Slovakia. *Building and Environment,* 67**,** 138-146.

KAUFMAN, A., TIANTUBTIM, E., PUSSAYAPIBUL, N. & DAVIDS, P. 2004. Implementing Voluntary Labour Standards and Codes of Conduct in the Thai Garment Industry. *Journal of Corporate Citizenship,* 13.

KHAN, M. A. A. S., AHMAD, M. H. & KHAN, T. H. 2011. Indoor Thermal Condition of Factory Building in Bangladesh. *Journal of Architecture and Built Environment,* 38**,** 55-62.

KHEDARI, J., YAMTRAIPAT, N., PRATINTONG, N. & HIRUNLABH, J. 2000. Thailand Ventilation Comfort Chart. *Energy and Buildings,* 32**,** 245-249.

KOCH-NIELSEN, H. 2002. *Stay cool: a design guide for the built environment in hot climates,* London, Earthscan.

KOELMAN, O. 2004. *Biomimetic Buildings: Understanding & Applying the Lessons of Nature*, BioInspire.

KOENIGSBERGER, O. H., INGERSOLL, T. G., MAYHEW, A. & ZOKOLAY, S. V. 1973. *Manual of tropical housing and building: Part 1, Climatic design,* Longman, Longman.

KOLOKOTRONI, M. & SANTAMOURIS, M. 2007. Ventilation for Cooling. *In:* SANTAMOURIS, M. (ed.) *Building, Energy and Solar Technology: Advances in Passive Cooling.* London, UK: Earthscan.

KOTTEK, M., GRIESER, J., BECK, C., RUDOLF, B. & RUBEL, F. 2006. World Map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift,* 15**,** 259-263.

KRISHAN, A., BAKER, N., YANNAS, S. & SZOKOLAY, S. V. 2001. *Climate Responsive Architecture: A Design Handbook for Energy Efficient Buildings,* New Delhi, McGraw Hill.

KUBOTA, T., CHYEE, D. T. H. & AHMAD, S. 2009. The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia. *Energy and Buildings,* 41**,** 829-839.

KWONG, Q. J., ADAM, N. M. & SAHARI, B. B. 2014. Thermal comfort assessment and potential for energy efficiency enhancement in modern tropical buildings: A review. *Energy and Buildings,* 68**,** 547–557.

LABOWITZ, S. 2016. *New data on the number of factories in Bangladesh* [Online]. NYU Stern Center for Business and Human Rights. Available: http://bhr.stern.nyu.edu/blogs/-data-on-number-of-factories-bd [Accessed 24 January 2017].

LARYEA, S. & LEIRINGER, R. T. F. 2011. Built environment research in West Africa: current trends and future directions. *CIBW107 International Conference on Innovation and Sustainable Construction in Developing Countries.* Hanoi, Vietnam.

LAU, A. K. K., SALLEH, E., LIM, C. H. & SULAIMAN, M. Y. 2016. Potential of shading devices and glazing configurations on cooling energy savings for high-rise office buildings in hot-humid climates: The case of Malaysia. *International Journal of Sustainable Built Environment,* 5**,** 387-399.

LENG, P. C., AHMAD, M. H. B., OSSEN, D. R. & HAMID, M. 2012. Investigation of Integrated Environmental Solutions-Virtual Environment Software Accuracy for Air Temperature and Relative Humidity of the Test Room Simulations. *UMT 11th International Annual Symposium on Sustainability Science and Management.* Terengganu, Malaysia.

LI, Y. & NIELSEN, P. V. 2011. CFD and ventilation research. *Indoor Air,* 21**,** 442-53.

LIM, Y.-W. 2012. Building Modelling and Simulation for Green Building Design. *In:* AHMAD, M. H. (ed.) *Sustainability in Built Environment I.* Malaysia: ISI Publications.

LIN, T.-P., DE DEAR, R. & HWANG, R.-L. 2011. Effect of thermal adaptation on seasonal outdoor thermal comfort. *International Journal of Climatology,* 31**,** 302-312.

LIPING, W. & HIEN, W. N. 2007. Applying Natural Ventilation for Termal Comfort in Residential Buildings in Singapore. *Architectural Science Review,* 50**,** 224-233.

LIPPSMEIER, G. 1969. *Building in the Tropics,* Munchen, Callway.

LIU, P.-C., FORD, B. & ETHERIDGE, D. 2012. A Modelling Study of Segmentation of Naturally Ventilated Tall Office Buildings in a Hot and Humid Climate. *International Journal of Ventilation,* 11.

LOMAS, K. J. 2007. Architectural design of an advanced naturally ventilated building form. *Energy and Buildings,* 39**,** 166-181.

LOONEN, R. C. G. M., FAVOINO, F., HENSEN, J. L. M. & OVEREND, M. 2016. Review of Current Status, Requirements and Opportunities for Building Performance Simulation of Adaptive Facades. *Journal of Building Performance Simulation***,** 1-19.

LUM, T. 2003. Workplace Codes of Conduct in China and Related Labor Conditions. Federal Publications, Cornell University ILR School.

LUO, M., CAO, B., DAMIENS, J., LIN, B. & ZHU, Y. 2015. Evaluating thermal comfort in mixed-mode buildings: A field study in a subtropical climate. *Building and Environment,* 88**,** 46-54.

LUO, M., CAO, B., JI, W., OUYANG, Q., LIN, B. & ZHU, Y. 2016. The underlying linkage between personal control and thermal comfort: Psychological or physical effects? *Energy and Buildings,* 111**,** 56-63.

LUSH, D. & MEIKLE, J. 1988. Industrial, Retail and Service Buildings- Options for Passive Solar Design. *In:* O'SULLIVAN, P. (ed.) *Passive Solar Energy in Buildings.* London: Elsevier Applied Science Publishers.

LYNHAM, S. A. 2002. The general method of theory-building research in applied disciplines. *Advances in Developing Human Resources,* 4**,** 221-241.

MAHBOB, N. S., KAMARUZZAMAN, S. N., SALLEH, N. & SULAIMAN, R. A Correlation Studies of Indoor Environmental Quality(IEQ) Towards Productive. 2nd International Conference on Environmental Science and Technology, 2011. IACSIT Press, Singapore.

MAJUMDAR, M. 2001. *Energy-efficient Building in India* M. Majumdar.

MALLICK, F. H. 1996. Thermal comfort and building design in the tropical climates. *Energy and Buildings,* 23**,** 161-167.

MALLORY-HILL, S., PREISER, W. F. E. & WATSON, C. G. 2012. *Enhancing Building Performance,* West Sussex, John Wiley & Sons.

MAREWO, G. T. 2004. *Mathematical Modelling of Passive Cooling in Buildings.* PhD thesis, The University of Zimbabwe.

MATTHEWS, J. & NICOL., F. 1995. Thermal Comfort of Factory Workers in Northern India. *In:* NICOL, F., HUMPHREYS, M., SYKES, O. & ROAF, S. (eds.) *Standards for Thermal Comfort: Indoor Air Temperature Standards for the 21st Century.* London: E & FN Spon.

MAXWELL, F. & DREW, J. 1964. *Tropical Architecture in the dry and humid zones,* London, B.T. Batsford Limited.

MENDELL, M. J., FISK, W. J., KREISS, K., LEVIN, H., ALEXANDER, D., CAIN, W. S., GIRMAN, J. R., HINES, C. J., JENSEN, P. A., MILTON, D. K., REXROAT, L. P. & WALLINGFORD, K. M. 2002. Improving the Health of Workers in Indoor Environments: Priority Research Needs for a National Occupational Research Agenda. *American Journal of Public Health,* 92**,** 1430-1440.

MENG, J. 2015. *The Green Building Museum of Hangzhou – Feel China's Greenest Building in Zero Distance.,* China, China Development Gateway.

MINISTRY OF HOUSING OF GOVT. OF BANGLADESH 2008. Building Construction Act: Dhaka Mohanagar Imarot Nirman Bidhimala, Bangladesh Gazette. Ministry of Housing of Govt. of Bangladesh,.

MISHRA, A. K. & RAMGOPAL, M. 2013. Field studies on human thermal comfort — An overview. *Building and Environment,* 64**,** 94-106.

MISHRA, A. K. & RAMGOPAL, M. 2015. An adaptive thermal comfort model for the tropical climatic regions of India (Koppen climate type A). *Building and Environment,* 85 134-143.

MORAN, D. S., PANDOLF, K. B., SHAPIRO, Y., HELED, Y., SHANI, Y., MATHEW, W. T. & GONZALEZ, R. R. 2001. An environmental stress index(ESI) as a substitute for the wet bulb globe temperature (WBGT). *Journal of Thermal Biology,* 26**,** 427–431.

MOSTOFA, S. & LAU, B. Louis I. Kahn's climate responsive strategies in the tropics: a case study on National Parliament Building, Bangladesh. 36th International

Conference on Passive and Low Energy Architecture (PLEA): Cities, Buildings, People: Towards Regenerative Environments, 2016 Los Angeles, USA.
MRIDULA, S. M. & KHAN, K. A. 2009. Working Conditions and Reproductive Health Status of Female Garments Workers of Bangladesh, Study Report, Bangladesh Occupational Safety. Dhaka: Health and Environment Foundation.
N. BAKER 2013. Natural Ventilation: Stack Ventilation. The Royal Institute of British Architects.
NAP. 2010. *Executive Summary by 'The National Academies Press'* [Online]. National Academies Press. Available: http://www.nap.edu/openbook.php?record_id=11233&page=1 [Accessed 2 December 2013].
NAZ, F. 2008. Energy Efficient garment factories in Bangladesh. *PLEA 2008 – 25th Conference on Passive and Low Energy Architecture.* Dublin.
NGUYEN, A. T., REITER, S. & RIGO, P. 2014. A Review on Simulation-Based Optimisation Methods Applied to Building Performance Analysis. *Applied Energy* 113**,** 1043–1058.
NICOL, F. 2004. Adaptive thermal comfort standards in the hot–humid tropics. *Energy and Buildings,* 36**,** 628-637.
NICOL, F. & ROAF, S. 2005. Post-occupancy evaluation and field studies of thermal comfort. *Building Research & Information,* 33**,** 338-346.
NICOL, J. F. & HUMPHREYS, M. A. 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings,* 34**,** 563-572.
O'BRIEN, W. & GUNAY, H. B. 2014. The contextual factors contributing to occupants' adaptive comfort behaviors in offices – A review and proposed modeling framework. *Building and Environment,* 77**,** 77-87.
OAKLEY, D. 1961. *Tropical houses: a guide to their design,* London, B. T. Batsford Ltd.
ODUYEMI, O. & OKOROH, M. 2016. Building performance modelling for sustainable building design. *International Journal of Sustainable Built Environment,* 5**,** 461–469.
OLIVIA, G.-S. & CHRISTOPHER, T. A. 2015. In-use monitoring of buildings: An overview and classification of evaluation methods *Energy and Buildings,* 86**,** 176–189.
OPOKU, A., AHMED, V. & AKOTIA, J. 2016. Choosing an appropriate research methodology and method. *In:* AHMED, V. (ed.) *Research Methodology in the Built Environment: A Selection of Case Studies.* Oxon: Routledge.
OROSA, J. A. & OLIVEIRA, A. C. 2011. A new thermal comfort approach comparing adaptive and PMV models. *Renewable Energy,* 36**,** 951-956.
PARSONS, K. 2006. Heat stress standard ISO 7243 and its global application. *Industrial Health,* 44**,** 368–379.
PAUL-MAJUMDER, P. 2003. *Health status of the garment workers in Bangladesh*, Bangladesh Institute of Development Studies.
PAUL-MAJUMDER, P. & BEGUM, A. 2000. The Gender Imbalances in the Export Oriented Garment Industry in Bangladesh, Working Paper Series No. 12. *Policy Research Report On Gender and Development, Poverty Reduction and Economic Management Network.* The World Bank Development Research Group.
PAUL-MAJUMDER, P. & BEGUM, A. 2006. *Engendering Garment Industry: the Bangladesh Context,* Dhaka, The University Press Limited.

PEETERS, L., DE DEAR, R., HENSEN, J. & D'HAESELEER, W. 2009. Thermal comfort in residential buildings: Comfort values and scales for building energy simulation. *Applied Energy,* 86**,** 772-780.

PERETTI, C. & SCHIAVON, S. 2011. Indoor environmental quality surveys. A brief literature review. *International conference Indoor Air 2011.* Dallas: Centre for the Built environment, UC Berkeley.

PRAJONGSAN, P. & SHARPLES, S. 2012. Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts. *Building and Environment,* 50**,** 104-113.

PRIANTO, E. & DEPECKER, P. 2003. Optimization of architectural design elements in tropical humid region with thermal comfort approach. *Energy and Buildings 35 (2003)* 35**,** 273–280.

PROKAUSHALI SANGSAD LIMITED 2007. Identification of eco-Efficiency Measures for the Readymade Garments Factories in Bangladesh. Working paper no-2. Bangladesh: GTZ Progress.

PROSSER, C. L. 1958. *Physiological adaptation,* Washington DC, American Physiological Society.

PROVERBS, D. & GAMESON, R. 2009. Case Study Research. *In:* KNIGHT, A. & RUDDOCK, L. (eds.) *Advanced Research Methods in the Built Environment.* West Sussex: John Wiley & Sons.

RACE, G. L. 2006. KS6 CIBSE Knowledge Series – Comfort. London: The Chartered Institution of Building Services Engineers.

RAHMAN, M., BHATTACHARYA, D. & MOAZZEM, K. G. 2007. Bangladesh's Apparel Sector in Post-MFA Period A Benchmarking Study on the Ongoing Restructuring Process. Dhaka, Bangladesh: Centre for Policy Dialogue (CPD), Bangladesh.

RAINA, J. & JENNINGS, P. 2013. Accord on Fire and Building Safety in Bangladesh.

RAJA, I. A., NICOL, J. F., MCCARTNEY, K. J. & HUMPHREYS, M. A. 2001. Thermal comfort: use of controls in naturally ventilated buildings. *Energy and Building,* 33**,** 235-244.

RAJAPAKSHA, U. & HYDE, R. 2012. Barriers to and opportunities for advanced passive cooling in sub-tropical climates. *Architectural Science Review,* 55.

RAMPONI, R. I. G. & ANGELOTTI, A. 2014. Influence of the Urban Environment on the Effectiveness of Natural Night-Ventilation of an Office Building. *Energy and Buildings,* 78**,** 5–34.

RAMSEY, J. D., BURFORD, C. L., BESHIR, M. Y. & JENSEN., R. C. 1983. Effects of Workplace Thermal Conditions on Safe Work Behaviour. *Journal of Safety Research,* 14**,** 105-114.

RAVINDU, S., RAMEEZDEEN, R., ZUO, J., ZHOU, Z. & CHANDRATILAKE, R. 2015. Indoor environment quality of green buildings: Case study of an LEED platinum certified factory in a warm humid tropical climate. *Building and Environment,* 84**,** 105-113.

RENNIE, D. & PARAND, F. 1998. *Environmental Design Guide for Naturally Ventilated and Daylit Offices,* London, BRE Press.

RIJAL, H. B., TUOHY, P., HUMPHREYS, M. A., NICOL, J. F., SAMUEL, A. & CLARKE, J. 2007. Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings,* 39**,** 823-836.

RIJAL, H. B., YOSHIDA, H. & UMEMIYA, N. 2002. Investigation of the thermal comfort in Nepal. *international symposium: Building research and sustainability of the built environment in the tropics.* Jakarta–Indonesia:.

ROBERTSON, M. M., HUANG, Y. H., O'NEILL, M. J. & SCHLEIFER, L. M. 2008. Flexible workspace design and ergonomics training: impacts on the psychosocial work environment, musculoskeletal health, and work effectiveness among knowledge workers. *Appl Ergon,* 39**,** 482-94.

ROCHE, P. L. & MILNE, M. 2004. Effects of window size and thermal mass on building comfort using an intelligent ventilation controller. *Solar Energy,* 77.

ROYAPOOR, M. & ROSKILLY, T. 2015. Building model calibration using energy and environmental data. *Energy and Buildings,* 94**,** 109-120.

RUPP, R. F., VÁSQUEZ, N. G. & LAMBERTS, R. 2015. A review of human thermal comfort in the built environment. *Energy and Buildings,* 105**,** 178-205.

SABET, D. M. & TAZREEN, A. 2013. Building construction laws and their enforcement: Looking beyond Rana Plaza. *Current Events Analysis Series.* The Center for Enterprise Society (CES).

SAFETY, T. A. F. B. W. 2013. *Alliance Factory Profile, November 15, 2013* [Online]. Available: www.afbws.org [Accessed December 2013 2013].

SANTAMOURIS, M. 2005. *Natural ventilation in the urban environment: Assessment and design,* London, Earthscan/Routledge.

SANTAMOURIS, M. & ASHIMAKOPOULOS, D. 1996. *Passive Cooling of Building,* London, James and James (Science Publisher) Ltd.

SANTAMOURIS, M. & KOLOKOTSA, D. 2013. Passive cooling dissipation techniques for buildings and other structures: The state of the art. *Energy and Buildings,* 57**,** 74-94.

SARKAR, M. Q. & AKTER, N. 2008. Environmental, Health, and Safety Guidelines for Small and Medium Enterprises of BRAC Bank Limited. *Research Monograph Series No. 37* [Online].

SARVIMAKI, M. 2018. *Case Study Strategies for Architects and Designers: Integrative Data Research Methods,* New York, Taylor & Francis.

SATTRUP, P. A. 2012. Architectural Research Paradigms: an overview and a research example. Technical University of Denmark.

SCHIAVON, S., HOYT, T. & PICCIOLI, A. 2014. Web application for thermal comfort visualization and calculation according to ASHRAE Standard 55. *Building Simulation,* 7**,** 321-334.

SCHWEIKER, M., BRASCHE, S., BISCHOF, W., HAWIGHORST, M. & WAGNER, A. 2013. Explaining the individual processes leading to adaptive comfort: Exploring physiological, behavioural and psychological reactions to thermal stimuli. *Journal of Building Physics,* 36**,** 438-463.

SCHWEIKER, M. & WAGNER, A. 2015. A framework for an adaptive thermal heat balance model (ATHB). *Building and Environment,* 94**,** 252-262.

SHAJAHAN, A. 2012. *An Investigation of Indoor Thermal Comfort Range for Rural House of Dhaka Region.* Unpublished M.Arch Thesis, BUET.

SHAJAHAN, A. & AHMED, Z. N. 2016. Indoor thermal comfort evaluation of naturally ventilated rural houses of Dhaka region, Bangladesh. *32nd international PLEA 2016 conference.* USA.

SHARMA, M. R. & ALI, S. 1986. Tropical Summer Index - A Study of Thermal Comfort of Indian Subjects. *Building and Environment,* 21**,** 11-24.

SHAVIV, E., YEZIORO, A. & CAPELUTO, I. G. 2001. Thermal mass and night ventilation as passive cooling design strategy. *Renewable Energy,* 24**,** 445-452.

SIMONS, B., KORANTENG, C., ADINYIRA, E. & AYARKWA, J. 2014. An Assessment of Thermal Comfort in Multi Storey Office Buildings in Ghana. *Journal of Building Construction and Planning Research,* 2**,** 30-38.

SINGH, M. K., MAHAPATRA, S. & ATREYA, S. K. 2010. Thermal performance study and evaluation of comfort temperatures in vernacular buildings of North-East India. *Building and Environment,* 45**,** 320-329.

Ali. 2007. *Dhaka - Landmarks and Points of Interest* [Online]. SkyscraperCity. Available: http://www.skyscrapercity.com/showthread.php?t=143280&page=25 [Accessed 2 November 2016].

STEINISCH, M., YUSUF, R., LI, J., RAHMAN, O., ASHRAF, H. M., STRUMPELL, C., FISCHER, J. E. & LOERBROKS, A. 2013. Work stress: its components and its association with self-reported health outcomes in a garment factory in Bangladesh-Findings from a cross-sectional study. *Health Place,* 24**,** 123-30.

STRACHAN, P., SVEHLA, K., HEUSLER, I. & KERSKEN, M. 2016. Whole model empirical validation on a full-scale building *Journal of Building Performance Simulation,* 9**,** 331-350.

SUSANTI, L., HOMMA, H. & MATSUMOTO, H. 2011. A naturally ventilated cavity roof as potential benefits for improving thermal environment and cooling load of a factory building. *Energy and Buildings,* 43**,** 211-218.

SUSANTI, L., HOMMA, H., MATSUMOTO, H., SUZUKI, Y. & SHIMIZU, M. 2008. A laboratory experiment on natural ventilation through a roof cavity for reduction of solar heat gain. *Energy and Buildings,* 40**,** 2196-2206.

SUSANTI, L., HOMMA, H., MATSUMOTO, H., SUZUKI, Y. & SHIMIZU, M. 2010. Numerical simulation of natural ventilation of a factory roof cavity. *Energy and Buildings,* 42**,** 1337-1343.

SZOKOLAY, S. V. 1991. *Climate, Comfort and Energy, Design of Houses for Queens-land Climates Architectural Science Unit*, Architectural Science Unit, The University of Queensland, St. Lucia, Qld.

SZOKOLAY, S. V. 2008. Introduction to Architectural Scinece:The Basis of Sustainable Design. 2nd edition ed. Oxford: Elsevier Ltd.

TARIQ, T. 2014. *Investigation of Perception of Thermal Condition of Naturally Ventilated Classroom Environment during Warm Periods in Dhaka.* Unpublished MArch Thesis, BUET.

THOMAS, L. & BAIRD, G. Post-occupancy evaluation of passive downdraft evaporative cooling and air-conditioned buildings at Torrent Research Centre, Ahmedabad, India. Australian and New Zealand Architectural Science Association Annual Conference-Challenges for Architectural Science in Changing Climates, 2006. 97-104.

TOE, D. H. C. & KUBOTA, T. 2013. Development of an adaptive thermal comfort equation for naturally ventilated buildings in hot–humid climates using ASHRAE RP-884 database. *Frontiers of Architectural Research,* 2**,** 278-291.

TRIANTAFYLLOU, G. N. & TSONIS, A. A. 1994. Assessing the ability of the Köppen System to delineate the general world pattern of climates. *Geophysical Research Letters,* 21**,** 2809-2812.

TURPIN-BROOKS, S. & VICCARS, G. 2006. The development of robust methods of post occupancy evaluation. *Facilities,* 24**,** 177-196.

TYLER, H., STEFANO, S., ALBERTO, P., DUSTIN, M. & KYLE, S. 2013. CBE Thermal Comfort Tool. Center for the Built Environment, University of California Berkeley.

TYMKOW, P., TASSOU, S., KOLOKOTRONI, M. & JOUHARA, H. 2013. *Building Services Design for Energy Efficient Buildings*, Routledge.

UNEP 2007. Buildings and climate change: status, challenges and opportunities. United Nations Environment Programme.

VENUGOPAL, V., CHINNADURAI, J. S., LUCAS, R. A. & KJELLSTROM, T. 2015. Occupational Heat Stress Profiles in Selected Workplaces in India. *International Journal of Environmental Research and Public Health,* 13.

VESELÝ, M. & ZEILER, W. 2014. Personalized conditioning and its impact on thermal comfort and energy performance – A review. *Renewable and Sustainable Energy Reviews,* 34**,** 401-408.

WANG, H. & ZHAI, Z. 2016. Advances in building simulation and computational techniques: A review between 1987 and 2014. *Energy and Buildings,* 128**,** 319-335.

WIJEWARDANE, S. & JAYASINGHE, M. T. R. 2008. Thermal comfort temperature range for factory workers in warm humid tropical climates. *Renewable Energy,* 33**,** 2057-2063.

WILSON, J. R. & CORLETT, N. 2005. *Evaluation of Human Work,* Boca Raton, CRC Press, Taylor and Francis Group.

WINEFSKY, H. R. & TENNEY, J. A. 2002. Preserving the Garment Industry Proviso: Protecting Acceptable Working Conditions within the Apparel and Accessories Industries. *Hofstra Law Review,* 31**,** 587-631.

WINTER, J. 1970. *Industrial architecture: a survey of factory building,* London, Studio Vista.

WMO. 2017. *Frequently Asked Questions (FAQs)* [Online]. World Meteorological Organization. Available: http://www.wmo.int/pages/prog/wcp/ccl/faqs.php [Accessed 12/03/2017].

WONG, D. C., MOSKOWITZ, P. A. & AFZALI-ARDAKANI, A. 2003. System and method for controlling workspace environment. Google Patents.

WONG, N. H. & KHOO, S. S. 2003. Thermal comfort in classrooms in the tropics. *Energy and Buildings,* 35**,** 337–351.

WONG, N. H., TAN, E., GABRIELA, O. & JUSUF, S. K. 2016. Indoor Thermal Comfort Assessment of Industrial Buildings in Singapore. *Procedia Engineering,* 169**,** 158-165.

WONG, S.-C. & ABE, N. 2014. Stakeholders' perspectives of a building environmental assessment method: The case of CASBEE. *Building and Environment,* 82**,** 502-516.

WORLD-BANK. 2017. *Bangladesh* [Online]. The World Bank Group. Available: https://data.worldbank.org/country/bangladesh [Accessed 21 August 2017].

WYON, D. P. 1974. Thermal aspects of the environment in buildings. *Journal of Architectural Research,* 3**,** 12-17.

YANG, L., YAN, H. & LAM, J. C. 2014. Thermal comfort and building energy consumption implications – A review. *Applied Energy,* 115**,** 164-173.

YANG, W. & ZHANG, G. 2008. Thermal comfort in naturally ventilated and air-conditioned buildings in humid subtropical climate zone in China. *International Journal of Biometeorology,* 52**,** 385-398.

YAU, Y. & CHEW, B. 2012. A review on predicted mean vote and adaptive thermal comfort models. *Building Services Engineering Research and Technology,* 35**,** 23-35.

YAU, Y. H. 2008. A Preliminary Thermal Comfort Study in Tropical Buildings Located in Malaysia. *International Journal of Mechanical and Materials Engineering (IJMME),* 3**,** 119-126.

YIN, R. K. 2018. *Case Study Research and Applications: Design and Methods,* Thousand Oaks, CA, Sage.

ZAINAL, Z. 2007. Case study as a research method. *Jurnal Kemanusiaan,* 5**,** 1-6.

ZARZAR, K. M. & GUNEY, A. 2008. *Understanding Meaningful Environments: Architectural Precedents and the Question of Identity in Creative Design,* The Netherlands, IOS Press.

ZHAO, Q., ZHAO, Y., WANG, F., WANG, J., JIANG, Y. & ZHANG, F. 2014. A data-driven method to describe the personalized dynamic thermal comfort in ordinary office environment: From model to application. *Building and Environment,* 72**,** 309-318.

ZOHIR, S. C. & PAUL-MAJUMDER, P. 2008. *Garment Workers in Bangladesh: Economic, Social and Health Condition,* Dhaka, Bangladesh Institute of Development Studies.

APPENDICES

Appendix A

Study of five precedents:

Appendix A-1. The handloom workspaces at Demra:

The 400 years old traditional handloom workspaces, one storey mixed-used buildings are located at Noapara, Demra, 13 km away from the Dhaka city. The climate of the region is tropical -Aw (Figure 2-2). The area of a typical workspace is 20m^2 and WFR is 1: 3.4. The openings are located on the south, east and north facades.

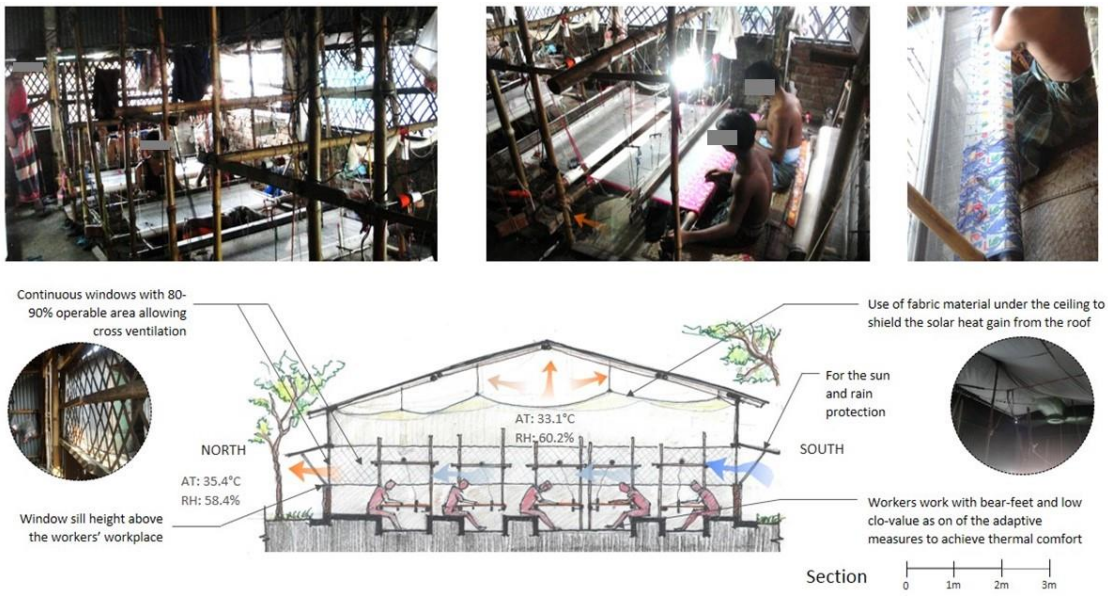


Figure A-1. Environmental design strategies of handloom workspaces (source: field visit, year 2015)

The building is naturally ventilated with occasional or no use of ceiling fans. The workers tend to gain their thermal comfort through contact of their partial body and feet to the ground and utilising opening at 0.6m sill height for air flow on the upper part of the body (Figure A-1). It was found that the users of the building additionally use NTV as a partial strategy during their night time work in warm seasons by keeping their windows fully open unless raining. Each window also has a continuous shading device (Figure A-1) made of metal sheets for rain and solar control. The major learning from these handloom workspaces is the strategies workers traditionally adopted to gain their thermal comfort by ensuring cross ventilation, keeping their body near to the ground surfaces, 80-90% effective windows and use of fabric material to protect from the conductive heat gain of the roof.

<u>Appendix A-2.</u> National Parliament Building at Dhaka:

The national parliament building of Bangladesh, designed by Architect Louis I Kahn and commissioned in 1962 (James-Chakraborty, 2014), is located at Dhaka metropolitan. The climate of the region is tropical -Aw (Figure 2-2). The central zone of the building contains the main assembly hall attach with eight light and air shafts in its perimeter as the middle zone. Workspaces are located at the outer. The main feature of this zone is the screen walls (Figure A-2) with large geometric form of openings. The building has also designed with thick precast concrete materials in response to hot climatic context of Bangladesh.

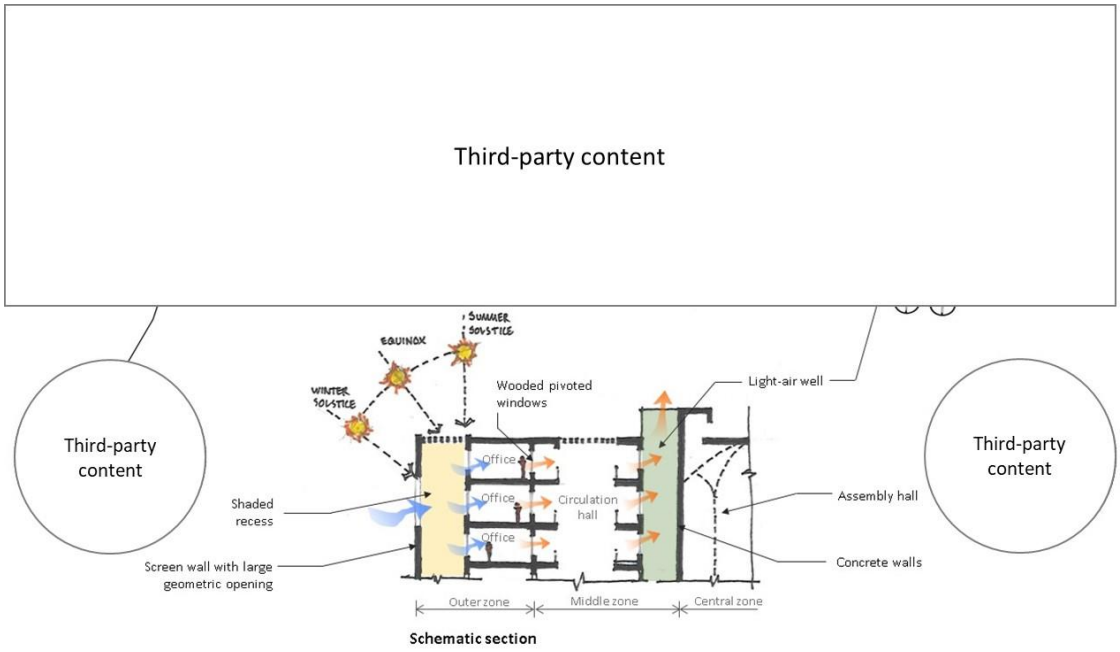


Figure A-2. Environmental design strategies of National Assembly Building and its workspace-block (Source: SkyscraperCity 2007, Ali 2000: page 276, Ali 2005: page 3, Wikipedia Commons, James-Chakraborty 2014 and drawn by the author)

Ali (2005) showed that ventilation courts and large inlet-outlets played a significant role for natural ventilation and comfortable environment inside this building (Figure A-2). Mostofa and Lau (2016), supported by DT simulation modelling, showed that thermal comfort can be achieved in the assembly hall in 31.6% of the year by adopting only the natural ventilation. The outer zone, that is vulnerable to outdoor climate, can be a free running space with natural ventilation for only 5.54% of the year. The study concluded with the statement that the central zone was found to be reasonably comfortable due to the air shaft and the thermal buffer offered from surrounding zones. From a field study, Ali (2000) also found the AT inside the assembly hall was steadily between 26.1°C and 26.9°C while that of the outside was 20.1°C - 32.6°C during the month of April. These studies indicated the building performed by utilising thermal mass and natural ventilation through air-shafts.

Appendix A-3. Torrent research building at Ahmedabad

Torrent research building is located on the fringe area of Ahmedabad, India where the climate is tropical savannah – Bsh (Figure 2-2) with hot dry summers (Ford, 2010). The total 19700m^2 area of this three storied laboratory building, built in the year of 2000, comprises a central administrative zone with six wings (Figure A-3). The Passive Downdraught Evaporative Cooling (PDEC) was applied in the 70% of the building including laboratories and administrative buildings for mainly cooling in the hot-dry season (Ford, 1998). Air is pulled in through 4m by 4m wind-catching towers with motorised louvres on the top (Dahl, 2013). The stack shafts are placed both on the external sides of the buildings to flush out the indoor air (Thomas and Baird, 2006, Abhikram, 2007). Use of thermal mass was also noticed in this building by using reinforced concrete frames and hollow concrete blocks (Abhikram, 2007).

During the hot-dry summer season, the natural ventilation strategies can be observed where stack induced natural ventilation is utilised with the evaporated cool air from the central towers (Figure A-4). An NTV strategy is also adopted where the stack induced air flow is in reverse pattern. However, during the warm-humid season, they have to use ceiling fans.

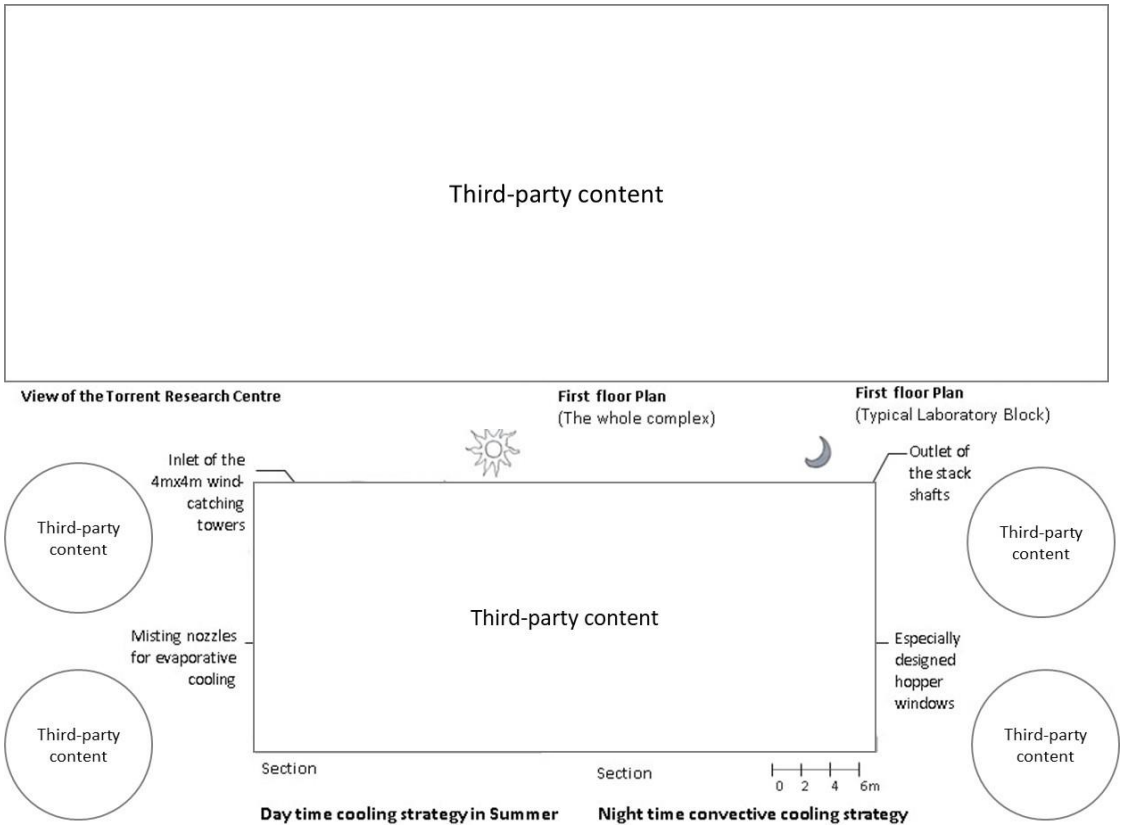


Figure A-3. Ventilation design strategies of Torrent Research Centre (source: Ford et al. 2010, Dahl 2013, Abhikram 2007 and drawn by the author)



Figure A-4. Season-wise ventilation design strategies (source: Zaveri and Patel, Abhikram 2007)

During the cool-dry winter, daytime stack induced passive ventilation strategy is practiced (Abhikram, 2007). In reference to Majumdar (2001), 29-30°C of AT was achieved inside this building with the maximum fluctuation of 4°C while outside AT was 43-44°. A post-occupancy study revealed that occupants were adequately comfortable (Abhikram, 2007).

Appendix A-4. Eastgate Centre at Harare:

The East-gate centre, built in 1995, is located at Harare city, Zimbabwe. The climate of the region is Subtropical highland - Cwb (Figure 2-2) with moderate sunny, warm days and cool nights (Adebisi et al., 2015). It consists of two linear-shaped building blocks with a central atrium covered by a glazed roof (Marewo, 2004). The total dimension of this 9 storied building is '140mx70m' while the width of the atrium is 16m (Chown, 2003).

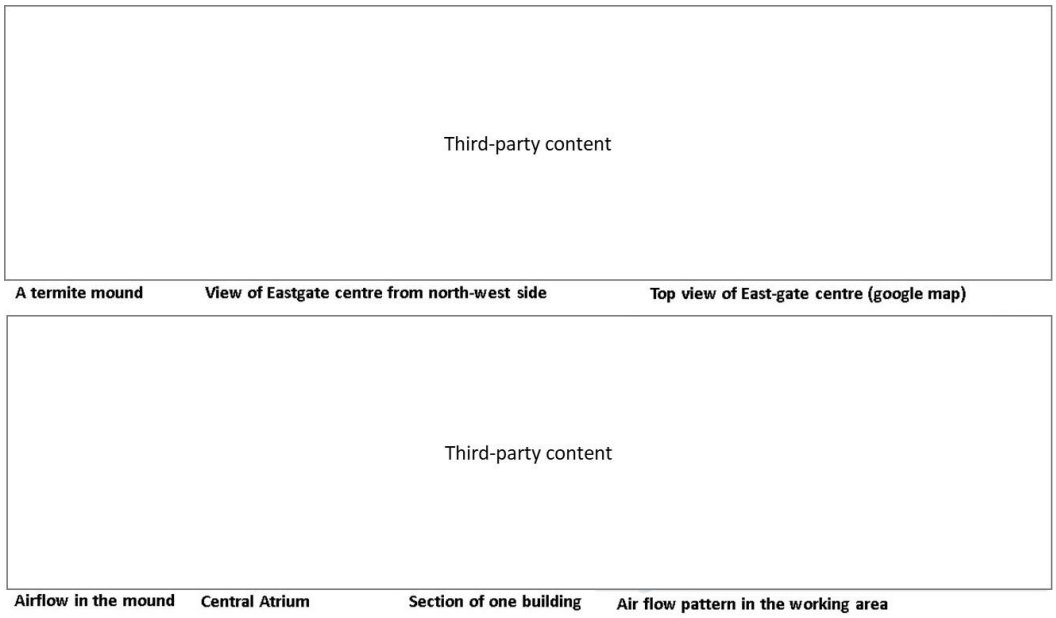


Figure A-5. Ventilation design strategy of Eastgate centre inspired from termite mound (sources: Cotesai 2013; Pearce's official website, Honde & Alibaba 2016: page 5 and google map)

As shown in Figure A-5, Passive ventilation strategy was adopted to cool the building during hot seasons and to keep the internal environment thermally stable with AT between 18-23.8°C (Koelman, 2004, DEAT, 2009, Adebisi et al., 2015). The building was oriented such a way it avoid the strong direct sun from east and west side (Chown, 2003). The building was built with masonry mass to cool down the building during night-time and help to absorbs day time heat gain (Dahl, 2013, Marewo, 2004). Central ventilation shafts and 48 nos. of round shaped chimneys on the top of the buildings are integrated to flash out the internal hot air by buoyancy-driven convection (Marewo, 2004). Marewo (2004) and Chown (2003) also mentioned about running the high number of fans during night time while using low velocity fans at day time (Figures A-6 and A-7). Chown (2003) showed that up to 4.5°C reduction of AT was obtained during occupied hours at office spaces while the outdoor diurnal swing was 10°C.

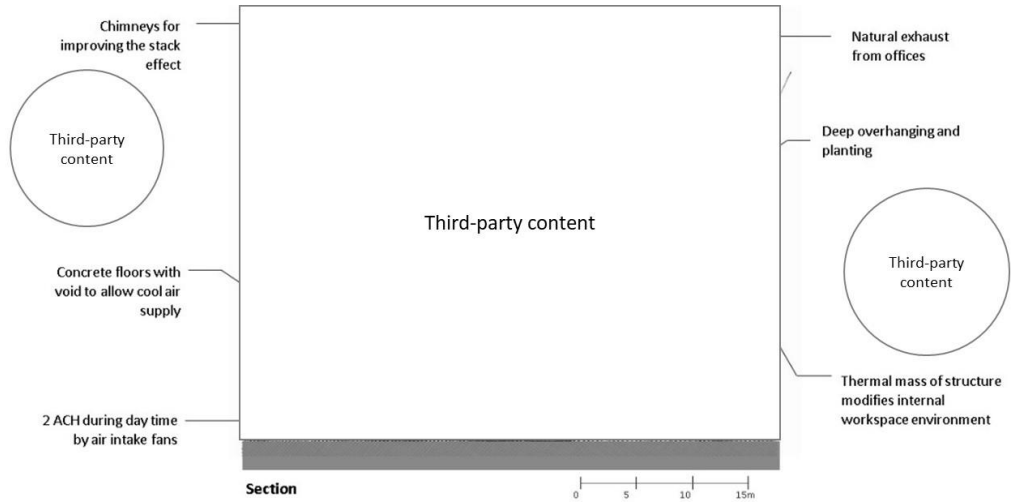


Figure A-6. Overall environmental design strategies (sources: http://smartwave.altervista.org/eastgate-centre/ and Pearce's website, edited by the author)

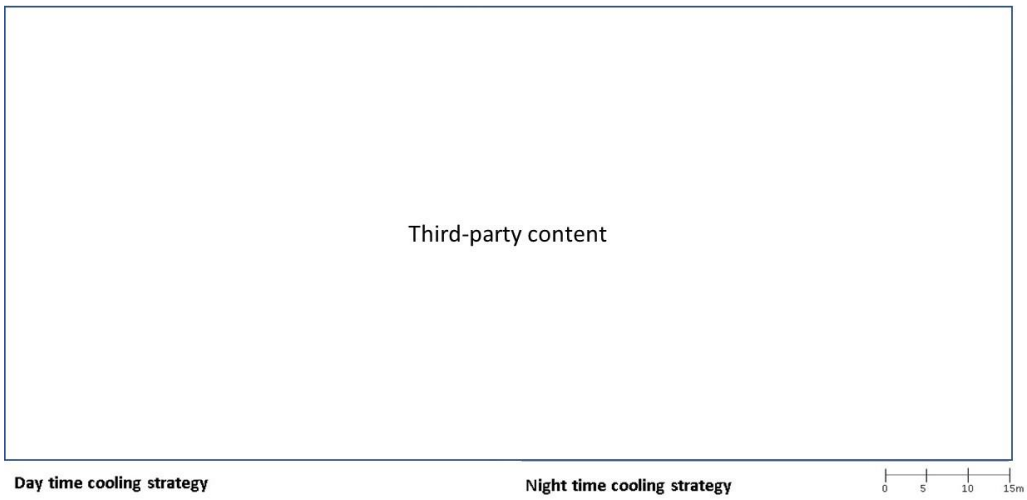


Figure A-7. Ventilation design strategies during day and night (source: Pearce's website)

Appendix A-5. Workspaces of Green Building Museum at Hangzhou:

The Green building museum, built in 2009, is located at Hangzhou in south China. The climate of the region is humid Subtropical- Cfa (Figure 2-2) with warm humid summers and mild winters. It covers a ground area of 1348sqm with the 4679sqm of total floor areas. Ji et al. (2009) showed that the floor below ground level serves as the source of fresh air for passive ventilation. The stack shafts are attached to this floor and workspace areas in upper floor to supply the fresh air. The used air is flashed out though the central light-well and then top stack-outlets. Segmented ventilation and different air flow in at least 11 spaces per floor was found to ensure thermal comfort. As shown in Figure A-8, Hybrid ventilation and double glazing with low-emissivity glass are incorporated to ensure the thermal comfort of the occupants (Ji et al., 2009). . Ji et al. (2009) showed that by incorporating NTV continuously, the indoor temperature was kept at 28°C while outdoor temperature raised above 32°C. However, in the hottest day, passive ventilation was not sufficient to reduce AT and demanded mechanical cooling.

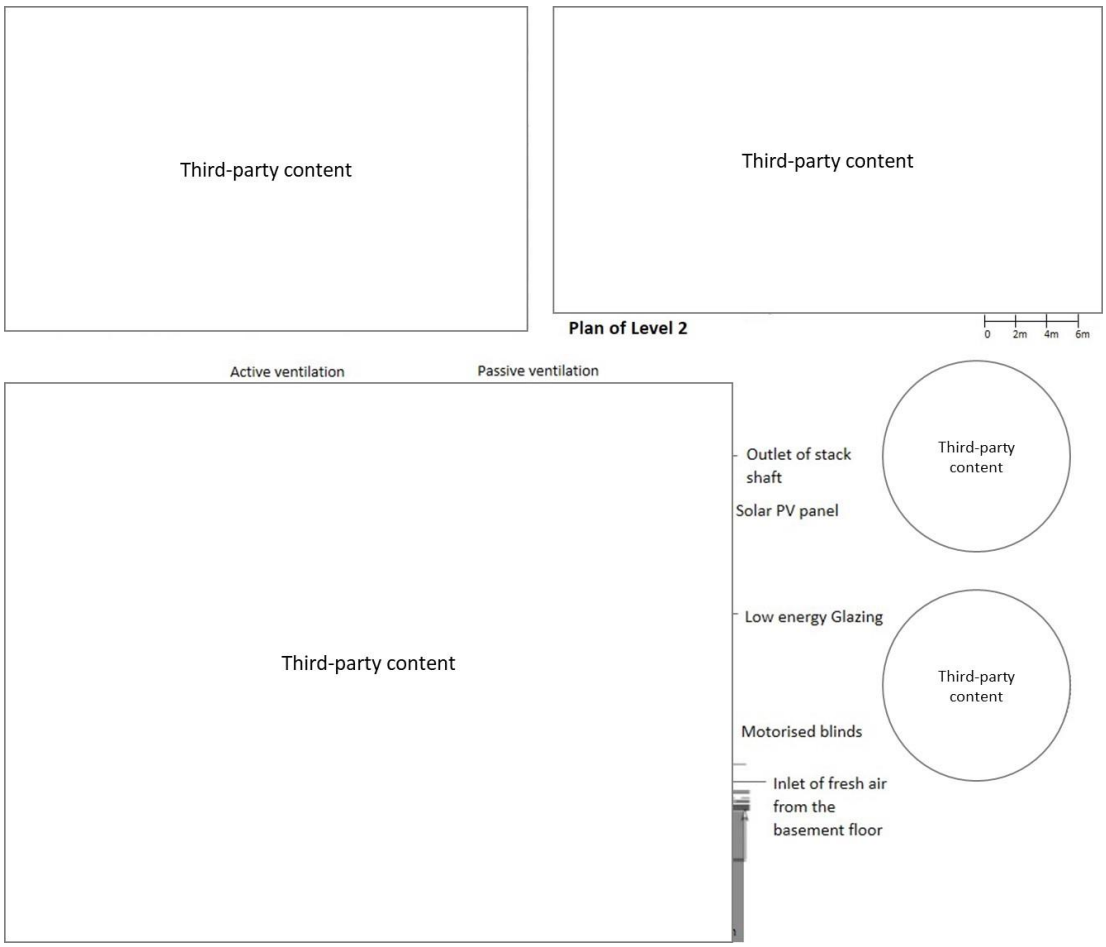


Figure A-8. Environmental design strategies of Green Building Museum (source: Meng 2015; Ji et al 2009 and Gigabase's website, edited by the author)

Appendix B

Reference Letters and Ethical approvals

<u>Appendix B-1.</u> Reference Letter-1 for field studies:

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA
Faculty of Engineering
Department of Architecture & Built Environment
University of Nottingham
University Park
Nottingham NG7 2RD
United Kingdom

Tel: (0115) 9513156
Email: brian.ford@nottingham.ac.uk

October 8th 2014

To whom it may concern

I am writing to introduce Md Mohataz Hossain, who is a student registered at the University of Nottingham for the full time course leading to the degree of PhD Architecture (student no: 4179566). His studies with us began on 1st October 2013 and is expected to complete by 30 September 2016. Mohataz is pursuing his PhD research under my supervision, and his research focuses on improving ventilation conditions in the workspace environment, with special reference to existing multi-storied ready-made garment (RMG) factories in Bangladesh.

During his research, Mohataz will conduct an extensive field study in Bangladesh which may include data logging, on-site spot measurements, questionnaire surveys and focus group discussions among the workers in the RMG factories. He also intends to interview the owner/managing directors of the same factories. The recorded data will be used for academic purposes only, while maintaining privacy of the data and of all involved in accordance with the University of Nottingham data storage policy. Subsequent publication of anonymised data will only take place with agreement from the businesses involved.

I would greatly appreciate your assistance and support, and if necessary provide official permission in favour of Mohataz, so that he can conduct his field survey which is so fundamental to his research . If you need any further information you can contact me by email: brian.ford@nottingham.ac.uk

Yours sincerely,



Professor Brian Ford RIBA FRSA
Chair in Bio-Climatic Architecture

<u>Appendix B-2.</u> Reference letter-2 for field study:

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA
Faculty of Engineering
Department of Architecture & Built Environment
University of Nottingham
University Park
Nottingham NG7 2RD
United Kingdom

Tel: (0115) 84 67542
Email: benson.lau@nottingham.ac.uk.

28 July 2015

To whom it may concern

I am writing to introduce Md Mohataz Hossain, who is a student registered at the University of Nottingham for the full time course leading to the degree of PhD Architecture (student no: 4179566, passport no: AA9634103). His study with us began on 1st October 2013 and is expected to complete by 30 September 2016. Mohataz is pursuing his PhD research under my supervision, and his research focuses on improving ventilation conditions in the workspace environment, with special reference to existing multi-storied ready-made garment (RMG) factories in Bangladesh.

During his research, Mohataz will conduct an extensive field study in Bangladesh from the 1st of January 2015 till October 2015 which may include data logging, on-site spot measurements, questionnaire surveys and focus group discussions among the workers in the RMG factories. For his field study, Mohataz will be travelling with the following 'scientific instruments' which are the properties of the University of Nottingham to record field data for academic purposes only.

Sl no.	Product Code	Description of the product/instrument	Quantity (no.)
01	TGU 4500	Tinytag Ultra 2: Indoor temperature data logger	20
02	TGU 4510-PK-RS	Tinytag Ultra 2: Internal & external temperature data logger with	02
03	PB-5001-1M5	Probe for Tinytag Ultra 2 temperature data loggers	02
04	TV-4505	Tinytag View 2: Temperature and Relative Humidity logger with display and accompanying probe	03
05	K4600BT – 0846B	Kestrel® 4600 pocket heat stress tracker with compass (Yellow colour)	01
06	KVANE - 0791	Kestrel® Portable Vane Mount	01
07	78195	Stanley TLM165 Distance Measurer: Laser Distance measuring instrument	01
08	0560 4170	Testo 417 - Vane Anemometer Testo 417 - Vane Anemometer With integrated 100 mm vane	01
09	0632 3153	Testo 315-3 - CO/CO2 monitor	01
10	DL7030N	Digital Light meter	01
11	FLIR E60bx	FLIR Thermal Imaging Camera	01

I would greatly appreciate your assistance and support in favour of Mohataz so that he can carry the mentioned scientific instruments to conduct his field survey which is so fundamental to his research. If you need any further information you can contact me by email: benson.lau@nottingham.ac.uk.

Yours sincerely,



Benson Lau
Course Director, MArch Environmental Design,
Architect/Lecturer,
Institute of Architecture, Faculty of Engineering

<u>Appendix B-3.</u> Reference letter-3 for field study:

Bangladesh Garment Manufacturers & Exporters Association

MD. SHAHIDULLAH AZIM
VICE - PRESIDENT

BGA/Admin/2014/35215

30 December 2014

To:

Chairman / Managing Director

- [redacted] Savar, Dhaka.
- [redacted] Chittagong
- [redacted] Dhaka-1216
- [redacted] Narayangan
- [redacted] Gazipur, Dhaka
- [redacted] Joydebpur, Gazipur, Dhaka.
- [redacted] Dhaka

Subject: To extend all support to conduct survey in your garment factories

Dear Colleagues ,

Mr Md Mohataz Hossain, Assistant Professor, Department of Architecture, Bangladesh University of Engineering & Technology (BUET) is pursuing his doctoral research on **"Improving ventilation condition of workspace environment with special reference to existing multi-storied Ready-made Garment (RMG) factories in Bangladesh"** in the University of Nottingham, UK.

He may be extended all possible support when he visits your factories/premises.

Sincerely yours,

[redacted]

Vice President

Copy to: Mr Md Mohataz Hossain, Assistant Professor, Department of Architecture, Bangladesh University of Engineering & Technology (BUET), Dhaka-1000, Bangladesh.

BGMEA Complex, 23/1 Panthapath Link Road, Karwan Bazar, Dhaka-1215, Bangladesh, Tel : +88-02-8140310-20
Fax : +88-02-8140322-23, info@bgmea.com, www.bgmea.com.bd, www.garmentworker.com.bd, www.bgmeajobs.com.bd

<u>Appendix B-4.</u> Approval letter-1 for online questionnaire study:

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator (Jo Deeley) from a University of Nottingham email address, or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name Md Mohataz Hossain

Reviewed by:

Name [redacted]

Signature (paper based only) .....

Date .....30/4/2014.....

- ■ Approval awarded - no changes required
- ☐ Approval awarded - subject to required changes (see comments below)
- ☐ Approval pending - further information & resubmission required (see comments)
- ☐ Approval declined – reasons given below

Comments:

Would like to thank the applicants for a clear and comprehensively completed application.

Please note:

1. The approval only covers the participants and trials specified on the form and further approval must be requested for any repetition or extension to the investigation.
2. The approval covers the ethical requirements for the techniques and procedures described in the protocol but does not replace a safety or risk assessment.
3. Approval is not intended to convey any judgement on the quality of the research, experimental design or techniques.
4. Normally, all queries raised by reviewers should be addressed. In the case of conflicting or incomplete views, the ethics committee chair will review the comments and relay these to the applicant via email. All email correspondence related to the application must be copied to the Faculty research ethics administrator.

Any problems which arise during the course of the investigation must be reported to the Faculty Research Ethics Committee

Appendix B-5. Approval letter-2 for questionnaire and focus group discussions:

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator (Jo Deeley) from a University of Nottingham email address, or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name **MdMohataz Hossain,**

Reviewed by:

Name [redacted]

Signature (paper based only) .....

Date .....18/12/14.....

- ☐ Approval awarded - no changes required
- ■ Approval awarded - subject to required changes (see comments below)
- ☐ Approval pending - further information & resubmission required (see comments)
- ☐ Approval declined – reasons given below

Comments:

Applicant should include a clause in the participant information sheets along the lines of - 'participation in this study does not affect a person's individual job role and individual responses given during the studies will be anonymised and will not be passed onto company representatives in a way in which the participant can be identified'. The reason for this inclusion is that the applicant should provide a bit more reassurance to the participants that this study does not affect their employment.

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Please note:

1. The approval only covers the participants and trials specified on the form and further approval must be requested for any repetition or extension to the investigation.
2. The approval covers the ethical requirements for the techniques and procedures described in the protocol but does not replace a safety or risk assessment.
3. Approval is not intended to convey any judgement on the quality of the research, experimental design or techniques.
4. Normally, all queries raised by reviewers should be addressed. In the case of conflicting or incomplete views, the ethics committee chair will review the comments and relay these to the applicant via email. All email correspondence related to the application must be copied to the Faculty research ethics administrator.

Any problems which arise during the course of the investigation must be reported to the Faculty Research Ethics Committee

<u>Appendix B-6.</u> Approval letter-3 for semi-structured interview:

Ethics Committee Reviewer Decision

This form must be completed by each reviewer. Each application will be reviewed by two members of the ethics committee. Reviews may be completed electronically and sent to the Faculty ethics administrator (Jo Deeley) from a University of Nottingham email address, or may be completed in paper form and delivered to the Faculty of Engineering Research Office.

Applicant full name Md Mohataz Hossain

Reviewed by:

Name

Signature (paper based only) .....[redacted].....

Date .....30/07/2015.....

- [x] Approval awarded - no changes required
- [ ] Approval awarded - subject to required changes (see comments below)
- [ ] Approval pending - further information & resubmission required (see comments)
- [ ] Approval declined – reasons given below

Comments:

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Please note:

1. The approval only covers the participants and trials specified on the form and further approval must be requested for any repetition or extension to the investigation.
2. The approval covers the ethical requirements for the techniques and procedures described in the protocol but does not replace a safety or risk assessment.
3. Approval is not intended to convey any judgement on the quality of the research, experimental design or techniques.
4. Normally, all queries raised by reviewers should be addressed. In the case of conflicting or incomplete views, the ethics committee chair will review the comments and relay these to the applicant via email. All email correspondence related to the application must be copied to the Faculty research ethics administrator.

Any problems which arise during the course of the investigation must be reported to the Faculty Research Ethics Committee

Appendix C

<u>Appendix C-1.</u> Data loggers used for the environmental data (Pilot Study)





The HOBO U30-NRC Weather Station is our most rugged data logging system that can be easily reconfigured and adapted to a wide variety of applications. Up to 15 channels of environmental data can be measured and recorded, and later analyzed with HOBOware® Pro software.

Key Features:

- All electronics are housed within a rugged double-weatherproof, tamper-proof enclosure
- Set up is quick and easy with plug-and-play sensors
- Fast data offload via USB
- Optional analog inputs with sensor excitation
- Includes relay that can be activated on user-defined alarm conditions

Environment:

The U30-NRC Data Logger is for use in Indoor and Outdoor environments

**Source: http://www.onsetcomp.com/products/kits/U30-nrc-sys-a*

(Source: Hossain 2011)

<u>Appendix C-2.</u> Name, measuring range and accuracy of the instruments used during the main field studies

Model number and name of the instruments	Number of instruments used	Illustration	Range of the instrument	Accuracy of the instrument
Tinytag Ultra 2: TGU-4500 (Indoor temperature data logger)	20		-25 to +85°C / 0 to 95% RH	Better than ±0.5°C / Better than 0.3% RH
Tinytag Ultra 2: TGU 4510 (Internal and external temperature data logger with PB-5001-1M5 probe)	2		-40 to +85°C (internally mounted)/ -40 to +125°C (external probe)	Better than ±0.4°C (internally mounted)/ Better than ±0.35° when used with PB-5001
Tinytag View 2: TV-4505 (Temperature and Relative Humidity logger with display and accompanying probe)	3		-25 to +85°C / 0 to 100% RH	Better than ±0.35°C with probe/ Better than 0.3% RH (±3.0% RH at 25°C)
Kestrel® 4600 pocket heat stress tracker with compass and (KVANE – 0791 Kestrel® portable vane mount)	1+(2)	 	AV: 0.6 to 60 m/s, Direction: 0 to 360°, Crosswind, headwind, tailwind: 0.6 to 60 m/s, T: -45 to +125°C, GT: -10 to +55°C, 0.1 RH: 0 to 100%	AV: ±3% of reading or ±0.1m/s, Direction: ±5°, Crosswind, headwind, tailwind: ±5%, T: ±1°C, GT: ±1.4°C, WBT: ±0.8 °C, RH: ±3%
Testo 417 - Vane Anemometer With integrated 100 mm vane	1		0 to +50 °C / +0.3 to +20 m/s	±0.5 °C/ ±(0.1 m/s +1.5% of mv)
Testo 315-3 - CO/CO2 monitor	1		-10 to +60 °C/ CO: 0 to 100 ppm/ CO_2: 0 to 10.000 ppm	±0.5 °C/ CO: ±3 ppm (0 to 20 ppm), ±5 ppm (>20 ppm) CO_2: ±300 ppm (0 to 4.000 ppm), ±8% of mv (4.000 to 6.000 ppm)
Raytek minitemp MT4: Infrared Thermometer	1		T: -18 to 400°C (Distance to target up to 1.5m)	±2%, or ±2°C whichever is greater
FLIR E60bx: FLIR Thermal Imaging Camera	1		T: -20°C to +120°C	±2°C or ±2% of reading
Stanley TLM165 Distance Measurer: Laser Distance measuring instrument (for distance/area/volume calculation)	1		0.1m to 50m	± 1.5mm

(Source: Specifications and official data sheets)

Appendix D

Online Questionnaire Survey Documents:

Online Questionnaire Survey (Stakeholder's Feedback)

The University of Nottingham
UNITED KINGDOM · CHINA · MALAYSIA

(Improving ventilation condition of the work-space environment with special reference to existing ready-made garment factories in Bangladesh)

The details of the survey is stated as below **if you want to know more** about its objective. Otherwise, **Please go to** the **next section** for the **11 questions**.

Before starting, participant should know that:
1. Participation is voluntary, they can withdraw at any point, without giving a reason why
2. They do not have to answer any question they do not wish to, without giving a reason why
3. All data will be treated anonymously.
4. The data will be used for academic publication(s) and conference(s).
If they have any questions, please contact the researcher via email to: mdmohataz.hossain@nottingham.ac.uk]

Objective: The main purpose of this study is to improve the ventilation condition of work-space environment with special reference to the existing Ready-Made Garment (RMG) factories in Bangladesh. In this stage of the research, we are conducting a 'pilot study' and interested to identify feasibility of natural ventilation approach that may improve the ventilation condition inside the existing labour intensive production spaces of Garment factory buildings in terms of energy efficiency, indoor air quality, workers' comfort and potentially emergency smoke removal in context of Bangladesh. Moreover, previous evidences significantly suggest that improved environmental conditions in factories also result in higher productivity of the workforce. Hence, the additional purpose of the study is to improve the workers' productivity through improving indoor ventilation condition.

Sample and population: 50-100 persons (stakeholders) from 50-100 member companies have been randomly selected from the official website of 'Bangladesh Garment Manufacturers and Exporters Association' (BGMEA). Total population of the sample stakeholders is about 700 according to the 'selection criteria' which are as follows:

o Managing director or owner of registered member company of BGMEA as stated in BGMEA official website (http://www.bgmea.com.bd/search/membersresult#.UzwAXfldXxI)

o The company must also be enlisted as a member company under the 'Accord on fire and building safety in Bangladesh' (http://www.bangladeshaccord.org/wp-content/uploads/Accord-Public-Disclosure-Report-1-April-2014.pdf) and/or 'Alliance for Bangladesh Worker safety' (http://www.bangladeshworkersafety.org/factory-information/factory-lists) as stated in official websites.

o The member company also must have at least one 'multi storied' ready-made garment (RMG) factory building in Bangladesh

The above selection criteria have been formulated considering relevancy to this pilot-study topic and availability of official contact information or data.

Duration: The online questionnaire survey includes 11 questions with multiple choices of answers and will take not more than 10 minutes for each participant. All the questionnaire surveys are expected to be conducted within three months.

Equipment and Procedures: The entire questionnaire survey will be conducted online by using researcher's email address and written feedbacks will be collected from the participants through secured webpage anonymously .

Recruitment: The recruitment will be developed randomly by personal invitation through emails to the stakeholders (managing director or owner), selected according to the stated criteria in the sample section.

Compensation: Stakeholder's participation is totally voluntary. However, on request, a copy of the findings will be provided to the participant in a format of 'paper/journal publication' or Phd thesis at the end of researcher's PhD study.

Confidentiality: Electronic data will be stored anonymously on Md Mohataz Hossain's password protected computer and email address for 3-4 years from the date of any publication arising from this work and thereafter his supervisor's computer to a total of 7 years as per policy of the University of Nottingham. If any online feedbacks or consent pages are printed to hard copies, these will be also stored in a locked cabinet in Mohataz's office at the University of Nottingham for 3-4 years from the date of any publication arising from this work and thereafter his supervisor's office to a total of 7 years as per policy of the university. The documents will be destroyed approximately 7 years after in accordance with the university of Nottingham data storage policy.

Relevant Definitions

Stakeholder: A person or group that may or may not own significant shares in a company but affected by or having an interest in its operations. The person or group may also take or influence major decisions for the company's welfare and productivity.

RMG Factory: It refers to Ready-made Garment factories where worker labour in the production spaces of garments factory buildings all day long.

Production space: By RMG production, the researcher has meant to refer the three main sections of a RMG factory, Cutting, Sewing and finishing.

Kilowatt per hour: It is the unit of electrical energy consumption, which is commonly used to generate monthly electricity bill from the Power development board.

Emergency smoke removal system: It refers to any efficient system that can quickly extract trapped smoke inside the deep-planned building during any major or minor unexpected fire hazard.

Passive ventilation strategy: It is an alternative of mechanical ventilation where natural ventilation is promoted. In addition, it is actually a building design approach that may generate naturally induced air flow within the building space (even in deep-plan or large spanned buildings).

Energy Efficiency: Any efficient design or approach that consume minimum or nil electric energy.

Refurbishment the existing RMG building: Refurbishment of existing building refers here adding or altering any building

elements such as, cutting holes in the floors and adding ventilation shafts, changing w indow size, shading devices etc.

Please take a few moments to complete this Stakeholder's feedback survey.

Participant ID [A unique ID or code assigned by researcher]

01. Do the RMG production spaces of your company use ceiling and mechanical exhaust fans?

○ Yes ○ No

02. What is the approximate 'monthly average electrical energy consumption' (in unit of 'Kilowatt per hour') of your company's RMG factory building?*

○ below 1000KWh ○ 1000-2000KWh ○ above 2000KWh
○ Out of my knowledge

03. How much approximate annual electricity bill that your company usually pays for the RMG factory?*

○ Below 2,00,000 Taka ○ From 2,00,000 to 5,00,000 Taka
○ Above 5,00,000 Taka ○ Out of my knowledge

04. Do you know that mechanical fans in production space consume a significant amount of energy?*

○ Yes ○ No

05. Do your company's RMG production spaces have any emergency smoke removal system?*

○ Yes ○ No

06. In what extent do you know that natural ventilation strategy may improve the indoor environmental performance, workers' productivity and save energy consumption of the RMG building?*

	1 (Out of my knowledge)	2	3	4	5 (Very well known to me)
Knowledge about Natural Ventilation Strategy	○	○	○	○	○

07. In what extent may your company be interested to adopt passive strategy in existing building, if your company's production spaces do not need to use mechanical ventilation system inside the building?*

	1 (may not like to do)	2	3	4	5 (very much like to do)
Interest to adopt passive strategy	○	○	○	○	○

08. In what extent may your company do any refurbishment in the existing building (such as adding ventilation shafts, changing window size, etc.) and/or reshuffle functions within the building, if it improves the existing ventilation condition in terms of workers' comfort (hence, productivity), indoor air quality, energy efficiency and emergency smoke removal system?*

	1 (Not interested)	2	3	4	5 (Very much interested)
Interest to do any refurbishment	○	○	○	○	○

09. How much money may your company like to invest to implement above effective refurbishment in your existing building?*

○ Below 5,00,000tk ○ 5,00,000-10,00,000 Taka ○ Above 10,00,000tk
○ Not applicable

10. Within what period may your company expect to get the 'invested amount' returned through saving the energy after successful completion of above refurbishment in the existing building?*

○ Below 2 years ○ 2-5 years ○ Above 5 years ○ Not applicable

11. What would be the most critical issue for your company in implementing the above refurbishment in the RMG factory building?*

○ Investment of money ○ Construction issue ○ Indoor functional layout
○ Other issue (please state in two words)

Submit

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Participant Consent Form

Project title: Improving ventilation condition of the work-space environment with special reference to existing ready-made garment factories in Bangladesh

Participant ID *[researcher to complete]:* 1043

Researcher's details: **Md Mohataz Hossain,** PhD Student
BW4A, Sustainable research Building,
Architecture, Climate and Environment research group
Faculty of Engineering, University of Nottingham,
Nottingham NG7 2RD, UK
Email: mdmohataz.hossain@nottingham.ac.uk

1. I confirm that I have read and understand the information sheet for the above study.
2. I understand that my participation is voluntary and that I am free to withdraw at any time during the online survey, without giving a reason.
3. I understand that my information will be used by the researcher involved in the project for PhD thesis, academic publications and conferences. I understand that my data will be anonymised.
4. I understand that the information (hard copies and electronic copy) will be kept in accordance with the university of Nottingham data storage policy.
5. I agree to take part in the above study

[redacted]	21 May 2014	[redacted]
Name of the Participants	*Date*	*Electronic Signature*
MD MOHATAZ HOSSAIN	07 May 2014	[redacted]
Name of the Researcher	*Date*	*Electronic Signature*

Appendix E

Appendix E-1. Questionnaire survey and spot measurement forms:

Thermal Comfort Study (Part 1: measured and observed data)

Building case no.		**Building Floor**		**Date**	
Survey Time	Start time:		End time:		
Location of the participant	*(number of the respondent is located in the floor plan)*				
Distance from the nearby window(s)		**Distance from the ceiling fan (if running)**		**Distance from the fan switch**	
Main Activity name	Cutting ☐	Sewing ☐	Finishing ☐	Other ☐	

Participant Information

Participant ID *[assigned by the researcher]*				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Work experience in this factory	1-6 Months ☐	7-12 months ☐	> 12 months ☐	---------- months

Environmental Data (onsite spot measurement)

Position from floor	**0.1 m**	**0.6 m**	**1.1 m**	**Position from floor**		**0.1 m**	**0.6 m**	**1.1 m**
AT (°C)				RH (%)				
GT (°C)				WBT (°C)				
CO_2 level (ppm)				Air velocity (m/s) Direction from (+/-)	South/North			
CO level (ppm)					West/East			
Other parameter (if relevant):					Down/Up			
Light level (lux) at work plane				Volumetric flow rate (m^3/h) (if relevant)				
Outdoor AT (°C)				Outdoor RH (%)				

Observations

Clothing type				
Short sleeve T-shirt	Full Sleeve Short T-shirt	Full pant	Cotton Fotua	Other:
Cotton Salwar Kameez	Sharee	Sandal	Shoe-socks	

Colour and material of the cloth				
Cloth Material	1.	2.	3.	4.
Colour of the cloth	1.	2.	3.	4.

Activity level							
Immediate last Activity before the survey	Walking	Running	Eating	Sewing	Ironing	Cutting	Other (specify)
Occupant's activity level (during the survey)	Sewing	Ironing	Cutting	Seated	Standing	Reclining	Other (specify)

Provision of control					
Provision of regulating window	Yes ☐	No ☐	Ceiling fan (On/Off)	On ☐	Off ☐
Provision of regulating fan(s)	Yes ☐	No ☐	Windows with a curtain or without a curtain?	Yes ☐	No ☐
Window open (Approximate %)			Curtain open (approximate % of opening)		

Thermal Comfort Study (Part 2: workers' subjective feedback)

Questionnaire survey on thermal comfort

How are you feeling with your workspace environment at the moment?

Thermal sensation (ASHRAE scale)	Cold -3	Cool -2	Slightly cool -1	Neutral 0	Slightly warm +1	Warm +2	Hot +3
Humidity	Very dry -3	Dry -2	Slightly dry -1	Perfect 0	Slightly humid +1	Humid +2	Very humid +3
Air flow sensation	Very low -3	low -2	Slightly low -1	Perfect 0	Slightly high +1	High +2	very high +3
Freshness of air (Bedford scale)	Absolute stale -3	Very stale -2	slightly stale -1	Neutral 0	Quite fresh +1	Very fresh +2	Absolute fresh +3

How comfortable are you feeling with your workspace environment at the moment?

General comfort scale	Uncomfortable			Not sure*	Comfortable		
Thermal sensation	-3	-2	-1	-	+1	+2	+3
Humidity	-3	-2	-1	-	+1	+2	+3
Airflow	-3	-2	-1	-	+1	+2	+3
Freshness of air	-3	-2	-1	-	+1	+2	+3

What kind of improvement do you suggest at your workspace at the moment?

Thermal preference: Change in the temperature (McIntyre scale)	Prefer cooler	Much cooler +2	Slightly cooler +1	Prefer no change 0	Prefer warmer Slightly warmer -1	Much warmer -2
Change of humidity	Prefer drier	Much drier +2	Slightly drier +1	Prefer no change 0	Prefer more humid Slightly humid -1	Much humid -2
Change of Airflow	More Ventilation	Much less air flow +2	A bit less air flow +1	No change 0	Less ventilation A bit more air flow -1	Much more air flow -2

What do think of the overall acceptability of the existing thermal environment?

Overall thermal acceptability assessment **	**Not Acceptable**			Not sure*	**Acceptable**		
	-3	-2	-1	-	+1	+2	+3

What action do you undertake while feeling uncomfortable in terms of thermal sensation?

Increasing the speed of the fan (or on/off)	Opening the window	Closing the window /curtain	Reducing activity	Tying up hair	Changing the dress	Changing posture	Other (specify)

** 'Not sure' is only added to these answer sheets to provide workers with having the flexibility of choice to say 'not sure' vote if they are actually not sure about experience. This will also be used crosscheck with other set in the future.*

***Though the answer is originally sought to vote either 'not acceptable' or 'acceptable', the additional divisions (i.e. '-3, -2, and -1' or +'1, +2 and +3') in each side are provided for statistical cross-tabulation purpose.*

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অংশগ্রহণকারীর সম্মতি পত্র / Participant Consent Form

(প্রশ্নমালা জরিপ/ Questionnaire Survey)

প্রকল্প শিরোনাম: বাংলাদেশে বিদ্যমান পোশাক কারখানার কাজের পরিবেশের বায়ুচলাচল অবস্থার উন্নতি করা

গবেষকের বিবরণ: মো: মোহতাজ হোসেন, পিএইচডি ছাত্র
স্থাপত্য, জলবায়ু ও পরিবেশ গবেষণা গ্রুপ
প্রকৌশল অনুষদ, নটিংঘাম ইউনিভার্সিটি
নটিংঘাম, এন.জি.৭৩.এন.এ., ইউ. কে.
ইমেইল: mdmohataz.hossain@nottingham.ac.uk
ফোন: +৪৪৭৭৮৩৬৭৪৯৪২, +৮৮০১৭১১০৫০৭৬২

১. আমি তথ্য শীট যে বুঝেছি তা নিশ্চিত করছি
২. আমি বুঝলাম যে, আমার অংশগ্রহণ স্বেচ্ছাকৃত এবং আমি কোন কারণ প্রদান ছাড়াই জরিপ এবং গ্রুপ আলোচনার যে কোনো সময়ে নিজেকে প্রত্যাহার করতে পারি
৩. আমি বুঝলাম যে, আমার তথ্য অসনাক্তনীয় করা হবে যা আমার কর্মসংস্থান বাধাগ্রস্ত করবে না এবং যা গবেষকের পিএইচডি থিসিস, একাডেমিক প্রকাশনা এবং সম্মেলন-এ ব্যবহার করা হবে
৪. আমি বুঝলাম, আমার সকল তথ্য নটিংঘাম বিশ্ববিদ্যালয় তথ্য সংগ্রহের নীতি অনুযায়ী সংরক্ষণ করা হবে
৫. আমি উপরের গবেষণায় অংশ নিতে সম্মত হলাম

[redacted]	18.01.2015	[redacted]
অংশগ্রহণকারীর নাম	*তারিখ*	*স্বাক্ষর*
মো: মোহতাজ হোসেন	18.01.2015	[redacted]
গবেষকের নাম	*তারিখ*	*স্বাক্ষর*

অংশগ্রহণকারীর কোড *(গবেষক দ্বারা সম্পন্ন করার জন্য)*: 2077

<u>Appendix E-2.</u> Focus group discussion forms:

Focus Group Discussion on Thermal Comfort

researcher should emphasise to the participants in the group that:

1. *Participation is voluntary, they can withdraw at any point, without giving a reason why*
2. *They do not have to answer any question they do not wish to, without giving a reason why*
3. *All data will be treated anonymously.*
4. *The data will be used for academic publication(s) and conference(s).*

If they have any questions, please invite them to ask the researcher now]

Building case no.		**Location of discussion**		**Date**	
Discussion Time	Start time:		End time:		
Focus Group No:		**Type of Focus Group:**			
Number of group members	Male:		Female:		

Objective: The main purpose of this study is to gather garment factory workers' feedback, in detail manner, on how much they are comfortable with their existing workspace environment in terms of temperature, humidity, air velocity and freshness of the air with their expected changes, if required. The possible adaptive measures they take to make themselves comfortable will also be collected in detail through discussions. These detail feedbacks of the workers will be analysed, cross checked with the questionnaire survey, to establish the required ventilation target for workers' thermal comfort in the garment factories in Bangladesh.

Sample and population: 2 groups x 3 case studies = 6 groups. Each group will consist of 6-9 workers. Hence total is 36-54 representative workers. The criteria of forming the focus group in each case study buildings are as follows:

Group type one: Male and female, Located near to the windows and at least two representatives from different production workers (cutting, sewing and ironing workers), minimum 1 year work experience in the casestudy building and stratified random selection.

Group type two: Male and female, Located far from the windows and at least two representatives from different production workers (cutting, sewing and ironing workers) minimum 1 year work experience in the case study building and stratified random selection.

Duration: Each focus group discussion will take from 50 minutes to maximum 1 hour. All the focus group discussions will be conducted within January -October 2015 according to workers' convenient schedule.

Equipment and Procedures: The focus group discussion will be conducted after working hours at a convenient room inside the case study building. This document will be used to lead the group discussion and collecting information.

Recruitment: The recruitment will be developed randomly with a personal invitation at the beginning of the working time by distributing the invitation letter and getting their consent at their desk later.

Compensation: Participation is totally voluntary. However, the researcher will provide them with with a 'Prize bond of Taka 300/-' (or equivalent gift) along with a small souvenir (i.e. key ring) as a token of appreciation.

Confidentiality: Paperwork will be stored in a locked cabinet in Mohataz's office for 4 years from the date of any publication arising from this work and thereafter in his supervisor's office until 7 years. Electronic data will be stored anonymously on Mohataz's password protected computer for 4 years from the date of any publication arising from this work and thereafter on his supervisor's computer to a total of 7 years. The documents will be destroyed approximately 7 years after in accordance with the university of Nottingham data storage policy.

Participant Information

[Some information will be collected from the worker's information chart beside the desk or asking them personally aftergetting their consent. However, no name or identity will be recorded anywhere in this document.]

Participant (no. 01) ID *[A unique IDs or codes assigned by the researcher]*				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 02) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 03) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 04) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 05) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 06) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**

Participant (no. 07) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**
Participant (no. 08) ID				
Gender	Male ☐	Female ☐	**Age**	
Height			**Weight**	
Main Activity name	Cutting ☐	Sewing ☐	Ironing☐	Other ☐
Work experience	1 year ☐	2 years ☐	More than 2 years ☐	N/A ☐
Location of the participant	(The floor plan will be attached)			
Distance from the window		**Distance from ceiling fan**		**Distance from fan switch**

Explanation

[The researcher will explain that this is a focus group discussion session, a bit informal, with semi-structured questions (1-7 band scales and further comment options). The researcher will explain the definitions for the correct understanding of questions. Thereafter, the participants will discuss with 24 semi-structured questions. The participant will be asked how much they are comfortable with their existing workspace environment in terms of temperature, humidity, air velocity and freshness of the air with their expected changes and adaptive measures. The discussion will be in three main sections on three seasons on Bangladesh and concluding section at the end]

Relevant Definitions

[Provide participants with the following definitions. Explain that they can ask to have these repeated at any time. Answer any questions they may have.]

RMG Factory: It refers to Ready-made Garment factories where worker labour in the production spaces of garments factory buildings all day long.

Production space: By RMG production, the researcher has meant to refer the three main sections of a RMG factory, Cutting, Sewing and finishing.

Workspace environment: The environment of the work desk (of cutting, sewing and ironing desks) and immediate surroundings in terms of thermal comfort.

Thermal comfort and sensation: Thermal comfort is a subjective response, and is defined as the state of your mind that expresses satisfaction with the existing thermal environment.

Thermal sensation: In terms of bodily sensations, thermal comfort can be regarded as a scale of sensation from hot through 'warm, slightly warm, neutral, slightly cool and cool' to cold.

Humidity: Relative Humidity of the air affects as moisture content of the air is related to wetness of skin, which in turns affects comfort sensation.

Air flow: Air flow within a space is important, as it supplies fresh air, removes accumulated heat and moisture next to the body, and provides mixes of air to avoid thermal stratification.

Cool-dry season: From December till February (3 Months of a year)

Hot-dry season: From March till May (3 Months of a year)

Warm-humid season: From June till November (6 Months of a year) which consists of both monsoon and post-monsoon seasons.

Main Questions and discussion topics

[Participants will be asked to vote for the thermal comfort issues in various seasons of the year with sharing their own experience and feedback. To make the discussion environment more informal, the research may ask and may be asked by the workers relevant question. The researcher will audio record the discussion and note the answers of the questions]

Discussion section one: Cool-dry season (Dec-Feb)

01. According to your own experience, which are the major issues that may have impact on your thermal sensation in your workspace environment in this particular season?

02. Please elaborate it in terms of different time of the working hours within a typical day.

03. What are the immediate adaptive actions do you undertake to resolve those issues?

04. Please comment on your thermal comfort experience in terms of different time of the working hours within a typical day.

05. According to your opinion what changes in your workspaces would improve the exiting condition during this season?

Discussion section two: Hot-dry season (Mar-May)

06. According to your own experience, which are the major issues that may have impact on your thermal sensation in your workspace environment in this particular season?

07. Please elaborate it in terms of different time of the working hours within a typical day of this season.

08. What are the immediate adaptive actions do you undertake to resolve those issues?

09. Please comment on your thermal comfort experience in terms of different time of the working hours within a typical day.

10. According to your opinion what changes in your workspaces would improve the exiting condition during this season?

Discussion section three: warm-humid season (Jun - Nov)

11. According to your own experience, which are the major issues that may have impact on your thermal sensation in your workspace environment in this particular season?

12. Please elaborate it in terms of different time of the working hours within a typical day.

13. What are the immediate adaptive actions do you undertake to resolve those issues?

14. Please comment on your thermal comfort experience in terms of different time of the working hours within a typical day of this season.

15. According to your opinion what changes in your workspaces would improve the exiting condition during this season?

Discussion Section four: Concluding remarks

Please provide any other comments to help us understand your overall feedback rating on present ventilation condition in your working environment. Please feel free to add more topics.

[The researcher will thank all the participants for their time]

End of the focus group discussion

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অংশগ্রহণকারীর সম্মতি পত্র / Participant Consent Form

(ফোকাস গ্রুপ আলোচনা / Focus group discussion)

প্রকল্প শিরোনাম: বাংলাদেশে বিদ্যমান পোশাক কারখানার কাজের পরিবেশের বায়ুচলাচল অবস্থার উন্নতি করা

গবেষকের বিবরণ: মো: মোহতাজ হোসেন, পিএইচডি ছাত্র
স্থাপত্য, জলবায়ু ও পরিবেশ গবেষণা গ্রুপ
প্রকৌশল অনুষদ, নটিংঘাম ইউনিভার্সিটি
নটিংঘাম, এন.জি.৭৩.এন.এ., ইউ. কে.
ইমেইল: mdmohataz.hossain@nottingham.ac.uk
ফোন: +৪৪৭৭৮৩৬৭৪৯৪২, +৮৮০১৭১১০৫০৭৬২

১. আমি তথ্য শীট যে বুঝেছি তা নিশ্চিত করছি।

২. আমি বুঝলাম যে, আমার অংশগ্রহণ স্বেচ্ছাকৃত এবং আমি কোন কারণ প্রদান ছাড়াই জরিপ এবং গ্রুপ আলোচনার যে কোনো সময়ে নিজেকে প্রত্যাহার করতে পারি।

৩. আমি বুঝলাম যে, আমার তথ্য অসনাক্তনীয় করা হবে যা আমার কর্মসংস্থান বাধাগ্রস্ত করবে না এবং যা গবেষকের পিএইচডি থিসিস, একাডেমিক প্রকাশনা এবং সম্মেলন-এ ব্যবহার করা হবে।

৪. আমি আমাদের আলোচনার সময় অডিও রেকর্ড এবং ছবির তোলাতে আমার সম্মতি দিচ্ছি।

৫. আমি বুঝলাম যে, আমার সকল তথ্য নটিংঘাম বিশ্ববিদ্যালয় তথ্য সংগ্রহের নীতি অনুযায়ী সংরক্ষণ করা হবে।

৬. আমি উপরের গবেষণায় অংশ নিতে সম্মত হলাম।

[redacted]	20.01.2015	[redacted]
অংশগ্রহণকারীর নাম	তারিখ	স্বাক্ষর
মো: মোহতাজ হোসেন	20.01.2015	[redacted]
গবেষকের নাম	তারিখ	স্বাক্ষর

অংশগ্রহণকারীর কোড *(গবেষক দ্বারা সম্পন্ন করার জন্য)*: 22005

Appendix E-3. Semi-structured interview forms:

Interview with Managing Director and Owner of the Garment Factories

(Semi-Structured)

Introduction:

The main objective of this interview is to gather feedback from the owner or managing directors of the case study buildings (garment factories) about their perception and interest in improving the present ventilation condition of the factories production spaces through enhancing the natural ventilation. In addition, opinions on the practical viability of the implementing the proposed ventilation strategies will be collected from the concerned authority including expected financial benefits, workers wellbeing and quality workspaces. Through gathering the detail feedback, the information will be used for the doctoral research and propose both physically and practically viable ventilation strategies for improving the present thermal condition of the workspaces. The interview may take 30 minutes to maximum 1 hour.

Main agenda:

1. Present ventilation condition of workspaces
2. Future improvement plan (if any)
3. Implementing some proposed ventilation strategies
4. Interest of investment and expected benefits
5. Additional feedback (if any)

Agenda 1: Present ventilation condition of workspaces

Could you please describe about the present ventilation condition and evaluate its performance inside the production floors of your garment factory building? Do you consider the benefits of natural ventilation? *(Probes: ventilation system, workers' thermal comfort, different production sections, strategy and performance in different climatic seasons, emergency smoke removal, energy expenditure, advantages and drawbacks)*

Agenda 2: Future improvement plan (if any)

Do you think the present ventilation condition of the workspace of your RMG factory needs any improvement? If yes, do you have any plan to improve or change the present in near future? *(Probes: inlet/outlet windows, building refurbishments, fans, workspace rearrangement)*

Agenda 3: Implementation of some proposed ventilation strategies

Could you please explain your company's interest and/or limitations on implementing the following proposed ventilation strategies and refurbishments in your production spaces?

- **Night-time ventilation**
- **Changing the configuration and location of the windows**
- **Adding ventilation shaft(s)**
- **Re-arranging the functional layout**
- **Change of external (i.e. walls, roof) building material**

(Probes: financial issue, physical, building itself, official permissions etc.)

Agenda 4: Interest of investment and expected benefits

Could you please provide a brief idea about your any investment plan and expected benefits to improve present workspaces' ventilation condition? *(Probes: Investment budget, payback plan, expected financial benefit; say 1% productivity improvement, Commercial benefits)*

Agenda 5: Additional feedback (if any)

Do you like to add any further comment related to this discussion and the overall agenda?

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Participant Consent Form

(Semi-structured interview)

Project title: Improving ventilation condition of the work-space environment with special reference to existing garment factories in Bangladesh

Researcher's details: **Md Mohataz Hossain,** PhD Student
Architecture, Climate and Environment research group
Faculty of Engineering, University of Nottingham,
Nottingham NG7 2RD, UK
Email: mdmohataz.hossain@nottingham.ac.uk
Phone: +447783674942, +8801711050762

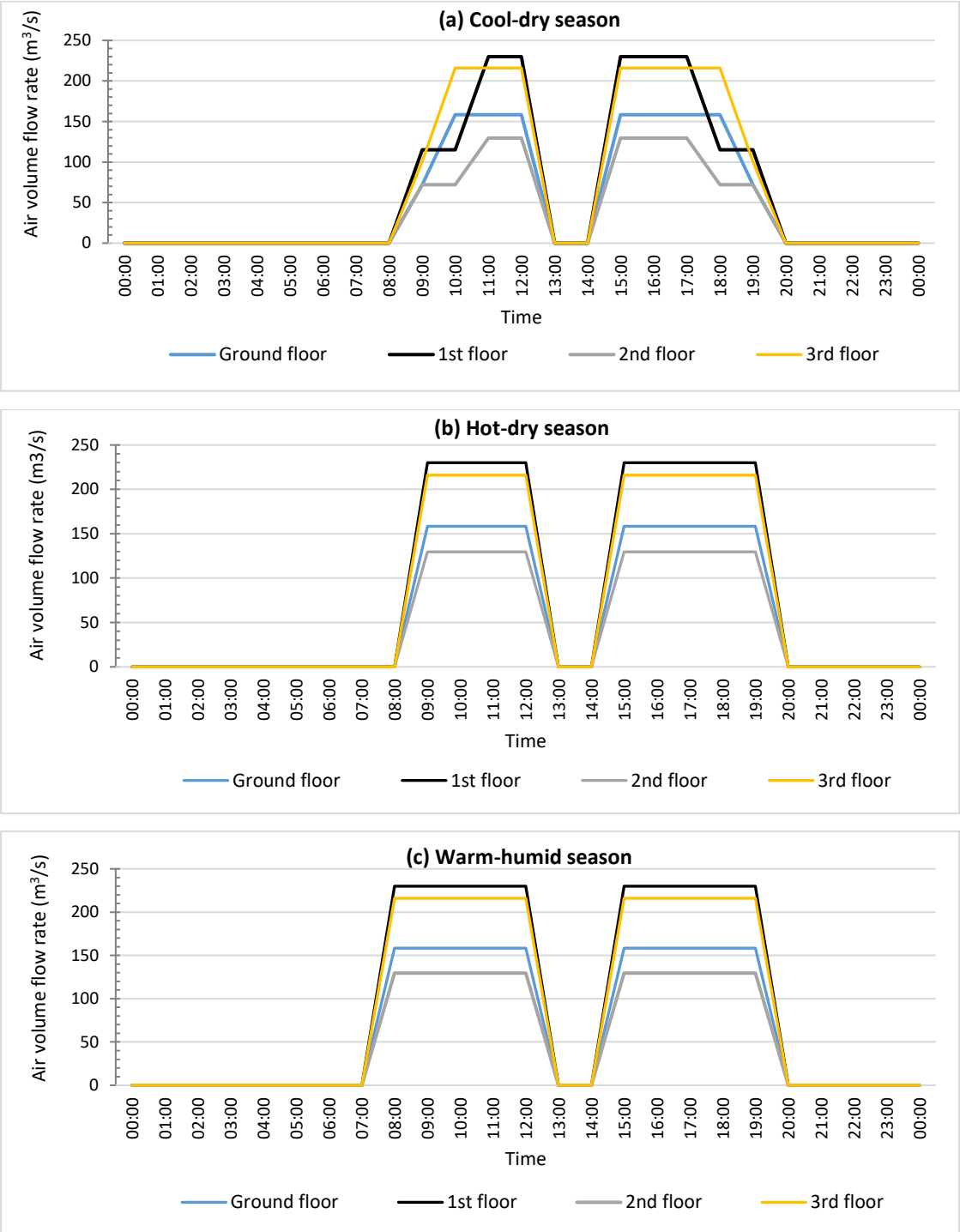
1. I confirm that I have read and understand the information sheet for this study.
2. I understand that my participation is voluntary and that I am free to withdraw at any time during the interview without giving a reason.
3. I understand that my information will be anonymised and will be used by the researcher in his PhD thesis, academic publications and conferences.
4. I understand that the information (hardcopy or any recorded audio) will be stored in accordance with the university of Nottingham data storage policy.
5. I agree to take part in the above study.

[redacted]	12.08.15	[redacted]
Name of the Participants	*Date*	*Signature*
MD MOHATAZ HOSSAIN	12 Aug 2015	[redacted]
Name of the Researcher	*Date*	*Signature*

Participant Code *{researcher to complete}*: A001

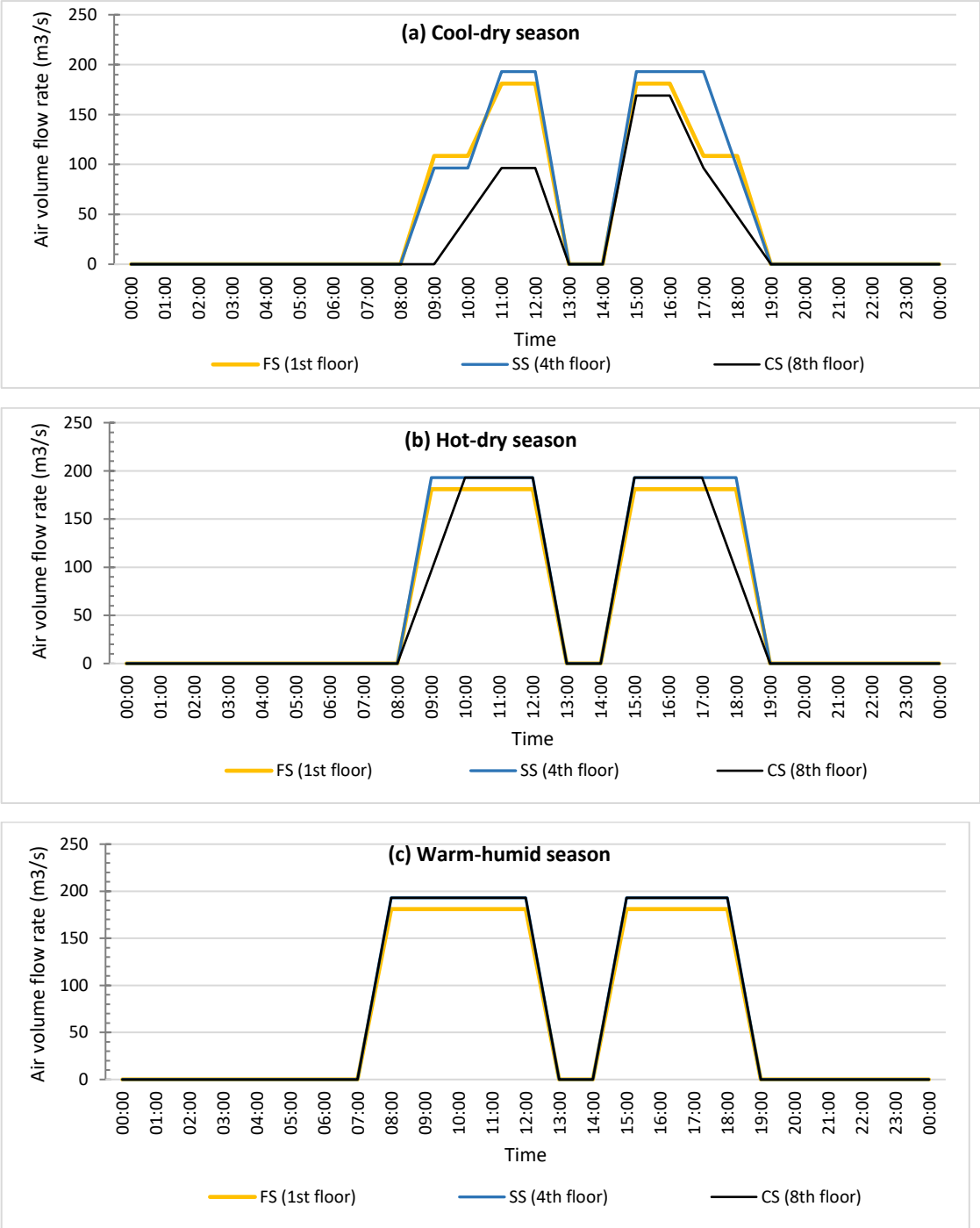
Appendix F

<u>Appendix F-1.</u> Daily schedule of active ventilation and AVFR in *RMG factory 1*:



(Source: measured in RMG factory 1 during the field surveys, year 2015)

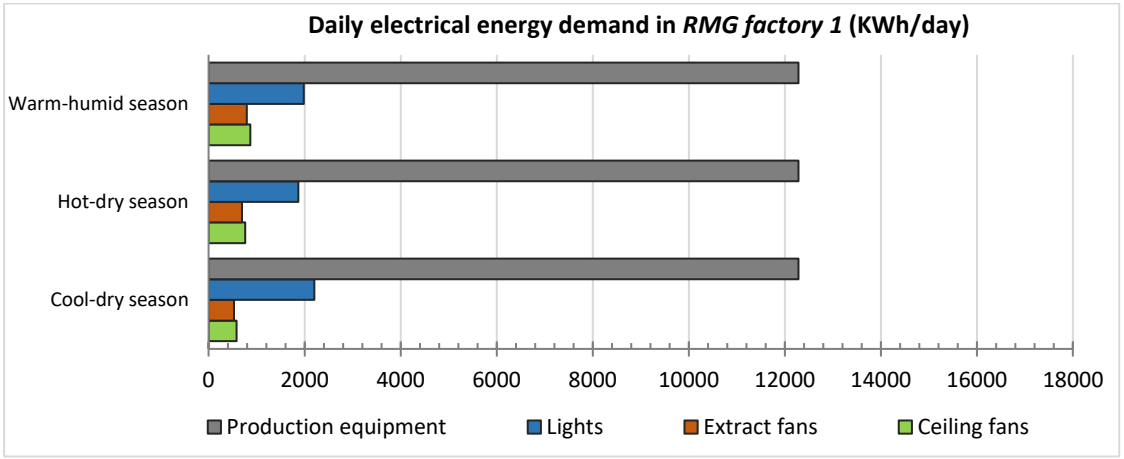
<u>Appendix F-2.</u> Daily schedule of active ventilation and AVFR in *RMG factory 3*:

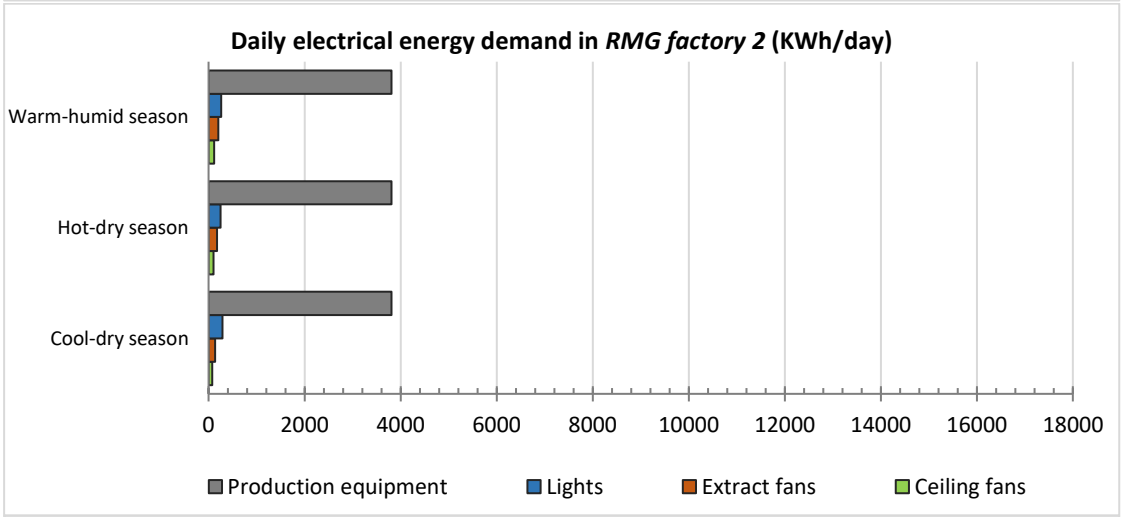


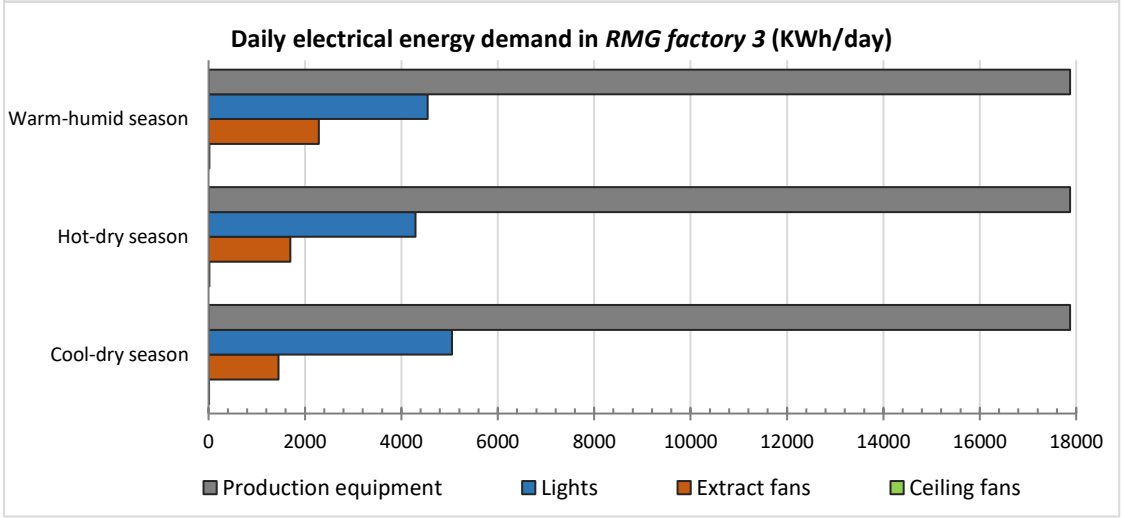
(Source: measured in RMG factory 3 during the field surveys, year 2015)

Appendix G

Daily electrical energy demand of production spaces:



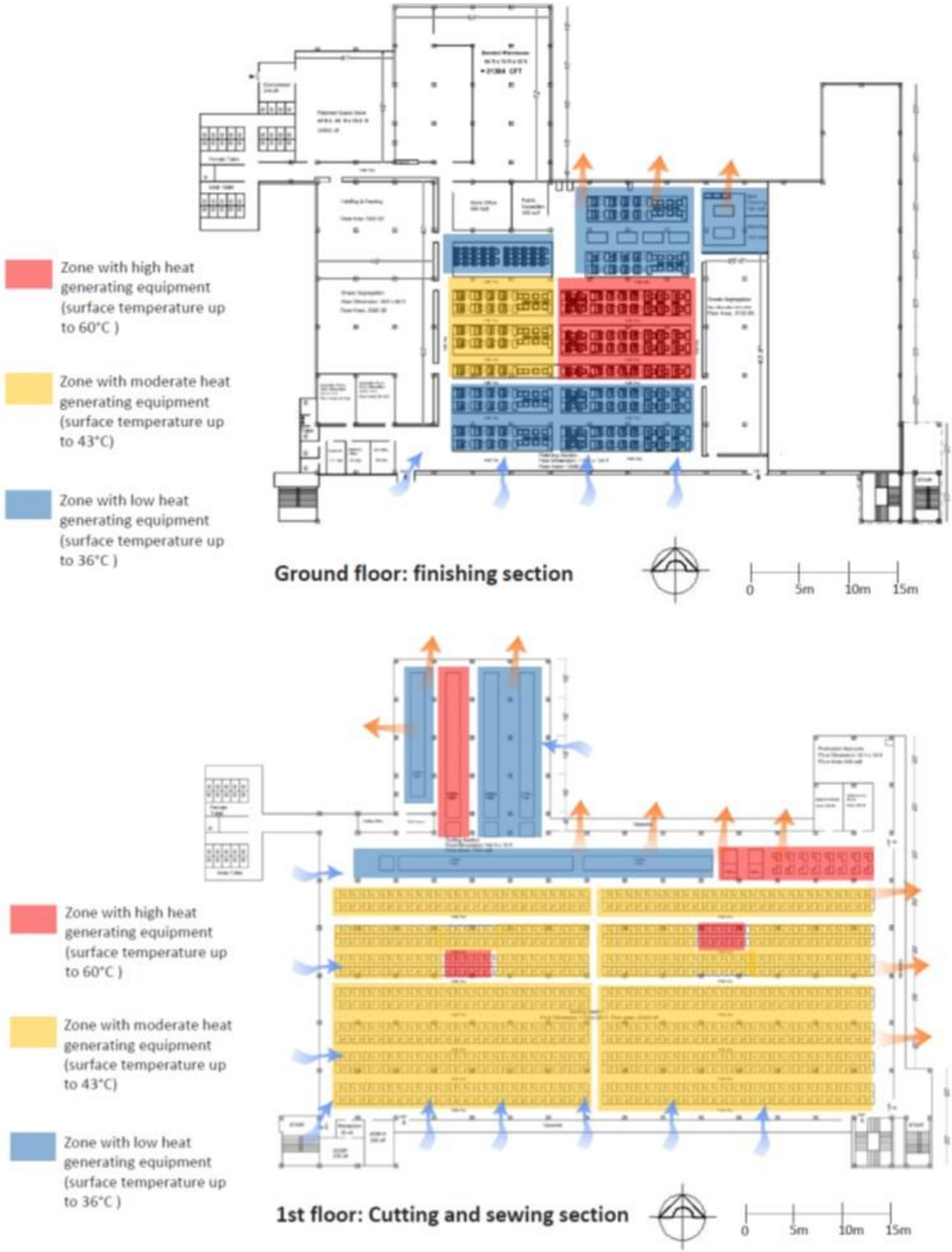




(Source: Monthly energy bills, specification of equipment and estimation by the author)

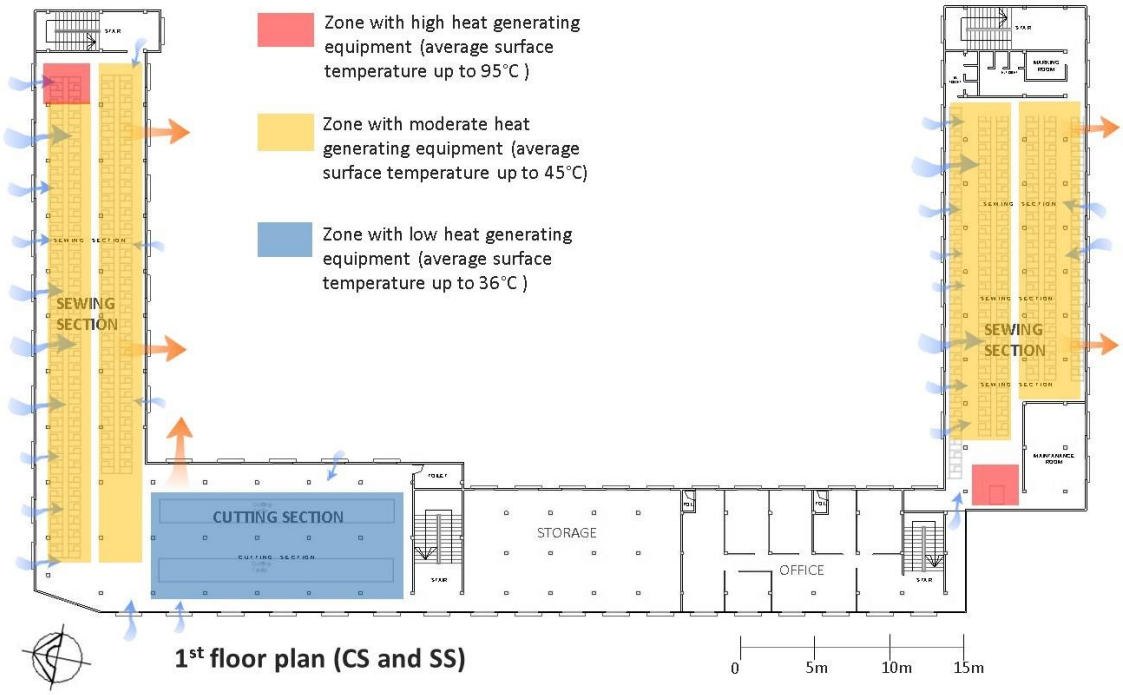
Appendix H

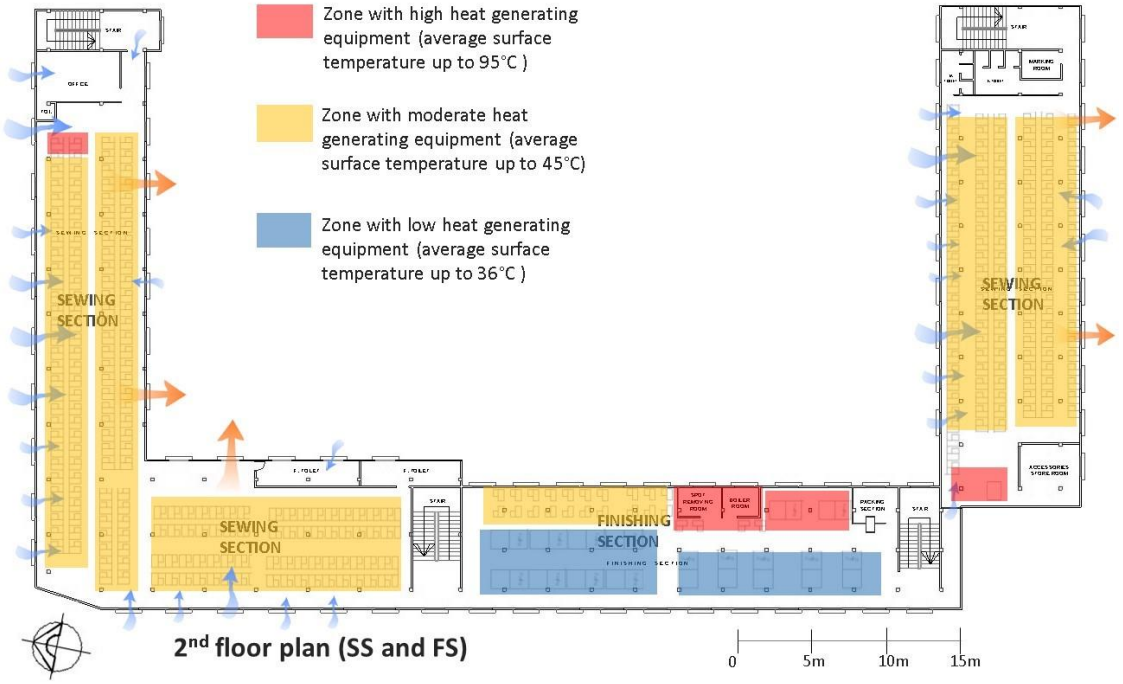
<u>Appendix H-1.</u> Zones highlighting the different heat generating equipment in production spaces (*RMG factory 1*):



(Source: author-generated during field study, year 2015)

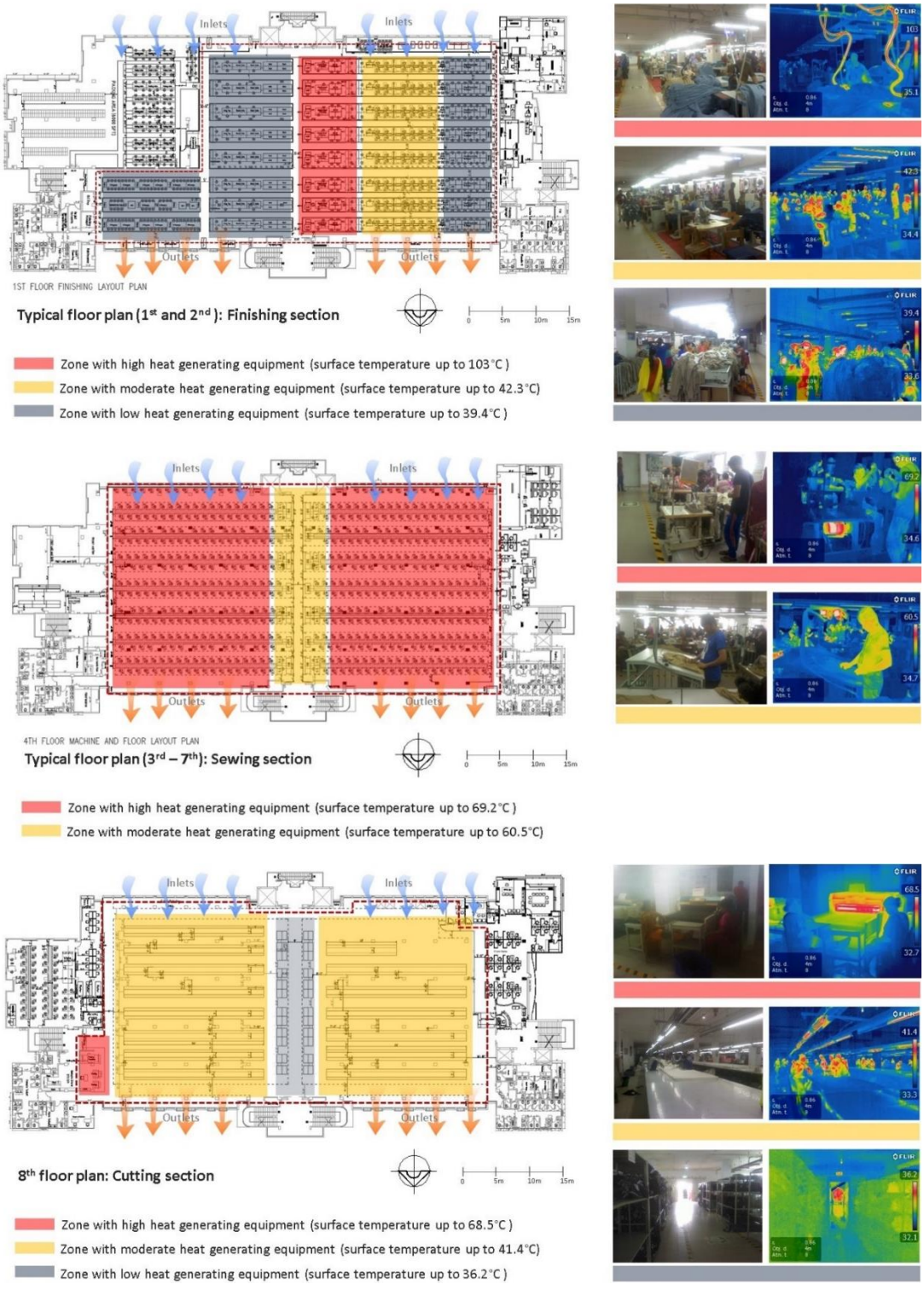
<u>Appendix H-2.</u> Zones highlighting the different heat generating equipment in production spaces (*RMG factory 2*):





(Source: author-generated during field study, year 2015)

<u>Appendix H-3.</u> Zones highlighting the different heat generating equipment in production spaces (*RMG factory 3*):



(Source: author-generated during field study, year 2015)