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Effect of Changing Window Type and Ventilation Strategy on Indoor Thermal Environment of Existing Garment Factories in Bangladesh

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This paper presents two workable solutions that can significantly improve the indoor thermal environment within the workspaces in existing ready-made garment (RMG) factories in the tropical climatic context of Bangladesh. The research involved field studies in three multi-storey factory buildings, semi-structured interviews with workers and owners and simulation studies. Field data indicated that the effective window-opening size of existing buildings and limiting the ventilation strategy to occupied hours caused overheating of the indoor environment. Among a list of proposals, the building owners saw value in implementing two solutions (i.e. altering existing window type to one with a higher effective opening area and adopting a night-time ventilation strategy) in their existing buildings as well as proposed new buildings. To quantify the benefits of these two interventions, a validated simulation study on one of the buildings was conducted. The findings confirm that these two solutions can provide reductions of up to 23% in overheated hours during operational time and in so doing, improve workers' thermal comfort and well-being.

Keywords: Effective opening of window, night-time ventilation, indoor thermal environment, workable solutions, ready-made garment factories

Subject classification codes: Effects of Envelope and Materiality on Built Environment (Special Edition)

Introduction

In the tropical climatic context of Bangladesh, most of the workers in ready-made garment (RMG) factories suffer from discomfort in their workspaces and a range of health problems due to the high indoor air temperature and poor air distribution (Authors 2015; Authors 2014; Fatemi 2014). The workspaces include cutting, sewing and finishing sections. Workers' thermal discomfort also hampers productivity (Fatemi 2014), resulting in additional workload to meet production targets without any financial benefit. These workspaces, with a deep floor-plan and low ceiling heights, usually

employ forced cross-ventilation using auxiliary extractor fans located on the external walls. However, the existing active ventilation strategies do not meet the thermal comfort needs of the workers with significant overheating observed in the middle part of the floor plate (Authors 2015) even in the presence a significant difference in 'wind pressure coefficient' between the inlet and outlet openings (CIBSE 2005) due to mechanical ventilation.

Previous theoretical studies and empirical evidence suggest that improving the indoor thermal environment and air quality through the adaptation of available passive technologies can improve health, productivity and wellbeing of the workers in workspace offering financial benefits to both workers and factory owners (Fisk 2000; Hobday and Dancer 2013; Mahbob et al. 2011; Srinavin and Mohamed 2003). In particular, improving the thermal environment of RMG factories helps to reduce production errors up to 1.88% (Fatemi 2014), which may offer added commercial benefit to factory owners and their international buyers. In addition, effective implementation of natural ventilation in the factories can provide a natural environment for the 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 Hydes 2012).

However, there are limitations to the implementation of a wide range of passive and energy efficient approaches in existing RMG buildings. For example, they may not be feasible due to disruption of the ongoing production process or due to structural limitations (Authors 2014). Typically, however, minor or intermediate interventions (Ford, Phan and Francis 2010, 57-59) in the production spaces of RMG factories may

be possible and can improve the thermal performance of existing built environment subject to factory owners' agreement (Authors 2014). A recent parametric study by Chowdhury, Ahmed and Hamada (2015) considered the thermal performance of RMG workspaces with respect to use of different building materials. However, these appear to be an absence of studies based on field evidence from RMG factories that quantifies existing ventilation and thermal conditions in different production workspaces. Understanding current conditions during the different climatic seasons that commonly prevail in tropical climates such as that present 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.

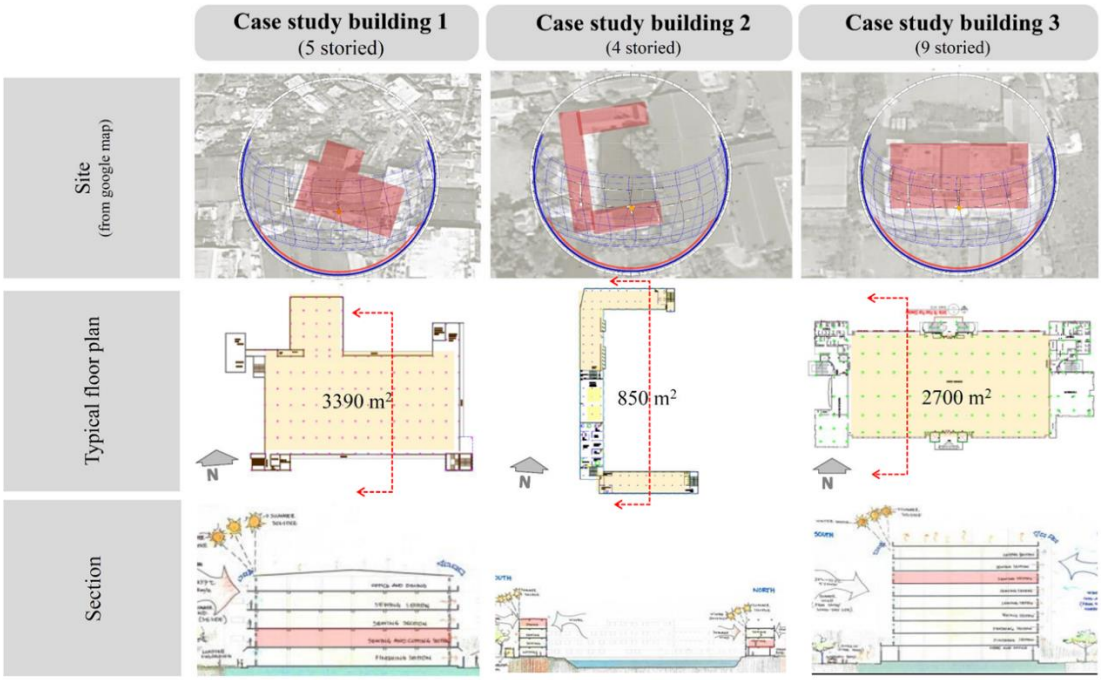
This paper presents field data gathered to quantify indoor thermal environment on the production floors of three multi-storied RMG case study buildings gathered over three climatic seasons, viz, hot-dry, warm-humid and cool-dry seasons (Authors 2014). Based on the holistic field study and a literature review seeking applicable design strategies, a list of possible solutions was developed. Feedback on the proposed design interventions from factory owners, managing directors and workers was used to identify the most acceptable and workable solutions. A validated simulation study was undertaken to explore the likely benefits of the two most popular solutions on the internal thermal environment in RMG factories located in a tropical climate in order to estimate potential improvements to the comfort of their occupants.

Research Methods

Selection of case study buildings

Three multi-story case study buildings (figure 1) were selected in the Dhaka and Chittagong regions of Bangladesh from the existing RMG building stock of over 6000

buildings documented on the official website of Bangladesh Garment Manufacturer (as of 15 October 2014) and Exporters Association and Bangladesh Accord Foundation 2013. These were identified using a number of selection criteria which include multi-story construction, regular rectangular form on a plan, the presence of auxiliary ventilation fans and a workforce of at least 500. Figure 1 illustrates the relevant information of the three case study buildings.



	Case study building 1 (5 storied)	Case study building 2 (4 storied)	Case study building 3 (9 storied)
Floor width (m)	40	10	35
Effective window: Floor area ratio	1:45	1:18	1:55
Average number of workers per floor	880	285	725

Figure 1. Site plan with sun path diagrams, typical floor plans, sections and information on selected case study buildings (source: https://www.google.co.uk/maps/, drawings from factory owners and field study)

Building-1 and Building-3 are located in the Dhaka region and Building-2 is located in Chittagong region 250km to the south-east of Dhaka. The buildings are located within a semi-urban context where adjacent building types are a mixture of industrial and residential blocks (Figure 1). They all share the same construction type,

namely a reinforced concrete beam-column structure with concrete floor plates and 125mm thick external brick walls.

Field data collection

The field studies took place in 2015 during three different climatic seasons in Bangladesh, namely the cool-dry season (December –February), the hot-dry season (March – May) and the warm-humid season (June-November). Using Tinytag data logging sensors (types TGU-4500 and TV-4505), indoor and outdoor Air Temperatures (AT) and Relative Humidity (RH) were monitored continuously. Regular spot measurements were also made to record indoor thermal and ventilation conditions. These included AT, RH, surface temperature, ventilation flow rate, globe temperature (GT), carbon dioxide (CO2), carbon monoxide (CO) and air velocity (AV) including speed and directions combined. These are made using handheld instruments including a FLIR Thermal Imaging Camera (Model no-E60), vane anemometer (Testo 417), heat stress tracker (Kestrel 4600) with portable Vane Mount (Model: KVANE – 0791), CO/CO2 monitoring device (Testo 315-3) and a laser distance measuring instrument (Stanley TLM165). Different production sections, such as cutting sections (CS), sewing sections (SS) and finishing sections (FS) are located on different floors of multi-storied RMG factories. As they have different occupant density and internal heat gains, separate surveys were made of each floor.

These data were used to understand the prevailing condition and as the input to validate simulation models of the building. The models were informed by architectural layouts, the number and electrical consumption and efficiencies of equipment, and the numbers of workers in each production floor. These were collected from the owners of the selected buildings and by observation during site visits. In addition, meteorological data

including AT, RH, AV and solar radiation data were collected from the meteorological department of Dhaka, Bangladesh to supplement the outdoor field data.

Thermal comfort assessment criteria

Thermal comfort of workers was used as a criterion for assessing the thermal performance of the case study RMG factories. These criteria usually reflect a number of indoor environmental parameters including AT, RH, AV, GT, Mean Radiant Temperature (MRT), Standard Effective Temperature (SET) and Operative temperature (OT). There is no specific regulatory guidance relating to indoor thermal comfort for non-air conditioned factories in the Bangladesh National Building Code (BNBC) 2006. Rather it recommends designing mechanically ventilated factory buildings with a minimum of 8-10 air change per hour (ACH). Within the limited number of studies on multi-storied RMG factories, Fatemi (2014) has proposed a thermal comfort target for s 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°Cand RH between 56-72%, if the AV can be maintained between 0.8-1.5 ms^{-1}. This AT and AV ranges are higher than that assumed in Olgyay's comfort zone. If the AV is less than 0.8 ms^{-1}, the comfort temperature needs to be reduced below 28.5°C and increasing the AV perceptibly improves the thermal comfort condition (Fatemi 2014, Humphreys 1970). Chowdhury, Hamada and Ahmed (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 AV of is maintained.

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 AV between 0.2-3.0ms^{-1} is maintained if the indoor AT

and RH varies within the ranges of 26-36°C and 50-80%. Their study observed that the AV may need to exceed $3ms^{-1}$ by increasing the ventilation flow rate, if the AT increases above 34°C. However, to avoid disturbance due to noise level from fans, the AV is to be maximum $3ms^{-1}$. Moreover, these recommendations need to be set against other considerations, for example for industrial buildings in the tropics, the AV is to be below $1.6ms^{-1}$ 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, Hamada and Ahmed (2017) recently 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 AV.

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. However existing ventilation strategies cannot ensure uniform airflow within the workspaces of the case study buildings explored in this paper (Authors 2014, Authors 2015). 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 current investigation. Based on the above studies, this paper will assess the thermal comfort condition of workspaces and will follow the criteria shown below:

- 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 AV

is assumed to be below 0.2ms^{-1}. 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 ms^{-1}. In both cases, acceptable RH is below 65%.

- Additionally, preferable AV range will be considered as 0.8-1.5 ms^{-1} to evaluate only the air circulation profile within a workspace. SS will be considered as the most overheated workspace. AT and RH values in an existing SS, measured from field study during a typical day in warm-humid season, will be considered as constant to focus on air velocities and directions.

Further details are provided in 'Results from dynamic thermal simulations and Discussions' section.

Review of design strategies for RMG factories

Given the importance of air speed in determining thermal comfort in a tropical climate, it is useful to review the literature to identify strategies that have been employed to enhance its benefits. Ford, Phan and Francis (2010) also suggested night-time ventilation (NTV) and refurbishment of windows as a complementary strategy and intermediate interventions. These two approaches are discussed here and will be explored further in this paper in the context of the three case study RMG factories.

Changing Window type and effective opening size

Previous studies have demonstrated that window configuration contributes to the enhancement of the thermal performance of the space they serve. The studies carried out by Artmann, Manz and Heiselberg (2008) showed that appropriate selection of window type can contribute to reducing overheating degree hours by controlling the air speed and direction. In another study, Amos-Abanyie, Akuffo, and Kutin-Sanwu (2013) revealed that combining application of effective window size, NTV and thermal mass

can reduce the peak indoor temperature and improve thermal comfort in a warm-humid context. The required percentage of the effective window opening may vary depending on the outdoor weather conditions and heat gain from occupants (Lomas 2007).

Window configuration, such as top hung, bottom hung, side hung, pivoted or sash window etc., also plays a significant role in moderating the indoor thermal environment. In particular, windows with operable panels and louvres can effectively enhance or hinder the flow pattern of ventilation air, allowing it to reach the middle of occupied zones (Heiselberg, Svidt and Nielsen 2001; Kang and Lee 2008). This approach needs to strike balances between providing thermal comfort and simultaneously avoiding draughts caused by direct air flow on the occupants (CIBSE 2005). For garment factories, the AV limit should lie between 0.8-1.5 ms^{-1} (Fatemi 2014) for workers' thermal comfort and window design plays a vital role in controlling both the AV and air direction in RMG factories.

In the context of Bangladesh, traditional houses employed operable side-hung windows offering effective opening areas up to 85%. However, side hung windows are not effective in controlling air flow in response to the changing ventilation requirements observed during different climatic seasons (Heiselberg, Svidt and Nielsen 2001). As a general principle, however, increasing 'window to wall area ratios' can improve ventilation flow rates significantly and in warm-humid climatic context, can also impact on improving indoor thermal comfort and reducing energy consumption (Liping and Hien 2007; Cui, Stabat and Marchio 2013).

According to International Labour Organisation Action Manual (1998), thermal comfort in RMG factories where air is supplied from the sides depends on the uniformity of indoor air speed and reduction of AT in the production spaces. In this study, therefore, flexible configuration of windows with the higher effective opening

area was considered as one of the key design strategies for improving the thermal condition in RMG factories.

Night-time ventilation

Previous studies have shown that ventilation strategies that combine daytime ventilation (DTV) and NTV generally help to reduce internal peak temperature and cooling load (Santamouris and Asimakopoulos 2013; La Roche and Milne 2004; Givoni 1994). In a warm climate, night-time outdoor AT can be low 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 (Designing Buildings Ltd 2015). Harnessing the reduced night-time AT depends on the presence of thermal mass, the size of the temperature swing and the volume flow rate of night ventilation (Shaviv, Yezioro and Capeluto 2001). Even in the hot-humid climatic context of Malaysia, the research of Kubota, Chyee and Ahmad (2009) found that ventilation strategies in residential buildings that include NTV can deliver up to 2.5°C reductions in day-time peak AT and reduce night-time AT by up to 2°C.

Rijal et al. (2007) found that controlling the opening frequency of windows can help to slow down the temperature response to internal and external heat gains, in buildings that combine thermal mass and NTV offering the potential to reduce the running period of existing fans used to drive the ventilation flow. Therefore these studies suggest that adopting full day ventilation that incorporates NTV and thermal is an appropriate candidate as a design strategy for application in the RMG factories over all climatic seasons.

Semi-structured interview with factory owners

In order to understand the practicality of introducing design changes into the existing

RMG factories, interviews were arranged and undertaken with building owners and managing directors of the three case study buildings. These were designed to collect feedback on a list of design proposals that might help improve their factories' existing thermal comfort conditions. Ten semi-structured questions, as shown in the attached supplementary section, were posed to the participants during the interviews seeking feedback on issues around improvements to the working environment, the practicality of interventions to their existing buildings and views on the implementation of any new RMG building project. A standard ethical approval was followed in this study to keep the privacy of the participants.

Focus group discussions with workers

Workers' feedback on how to improve their existing workspace conditions and their existing adaptive comfort strategies was collected through a total of six focus group discussions. Each group consisted of 8-9 participants and two groups drawn for in each case study building. For each building one group comprised workers whose work-desks were located near the windows and the other group comprised workers whose work-desk were in the middle of the floor (i.e. remote from windows) (Authors 2015). Their feedback was compared with the owners' responses to identify design solutions that were acceptable to all stakeholders.

Simulation study and validation process

This section provides a brief description of the simulation study. Further details of this method including validation process can be found before the section entitled 'Results from the Simulation Study and Discussion'.

Building selection for simulation study

Case study building-3 was adopted as the subject of a simulation study. It is a purpose built RMG factory building with a deep plan that is regular in shape with its long axes north-south oriented. As such it is representative of many of the multi-storey RMG building stock of Bangladesh (Naz 2008; Fatemi 2014, Authors 2014) in addition to being located within the Dhaka region where 74.7% of 'Bangladesh Accord' enlisted garment factories may be found (Authors 2014, Bangladesh Accord Foundation 2013). 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. As all of its production areas are located above ground level, the wind shielding offered by adjacent buildings can be ignored (Ramponi, Gaetani 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.

Brief details on modelling, validation and simulation scenarios

A licenced simulation software package named 'Integrated Environmental Solutions-Virtual Environment (IES-VE) version-2015' 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 (Loonen et al. 2016).

The 3D modelling of the building with its surrounding contexts was completed within IES-VE, based on the official architectural drawings and field data. These were also used to specify construction materials and occupancy patterns. The analyses were

completed using IES-VE's Dynamic Thermal Simulation tool 'Apache' and its Computational Fluid Dynamics' (CFD) simulation tool 'Microflo'.

For the thermal simulations, meteorological data from a Dhaka weather station were converted into Energy Plus weather file (i.e. epw format) and compared with the external data taken at the case study building during the same period. These 'validated' input data were then used in the simulations and compared with data recorded inside the building.

Following recommended procedures set at by Nguyen, Reiter and Rigo (2014), four 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 cutting, sewing and ironing sections changing different climatic seasons. A more detail study of ventilation wad made possible through the use of CFD (Chen 2009) with a focus on improvement of air movement within the sewing section of the building.

Results from the field study and discussion

This section presents two key observations about the operation of the case study RMG factories, namely:

- The absence of ventilation during night time hours
- Window design and its impact on ventilation and hence thermal performance of the selected production spaces.

Thermal performance of the workspaces

Indoor and outdoor ATs for the SS of the three case study buildings are compared in Figure 2. The data show that the production spaces overheated reaching ATs of up to 32°C during all climatic seasons. These sections are subject to high internal heat gains

as compared with the CS. During the cool-dry and hot-dry seasons, peak outdoor AT occurs between 11:00 – 16:00tackling the presence strong solar radiation. During the reminder of a day, the outdoor AT was cooler dropping by up to 10°C at night.

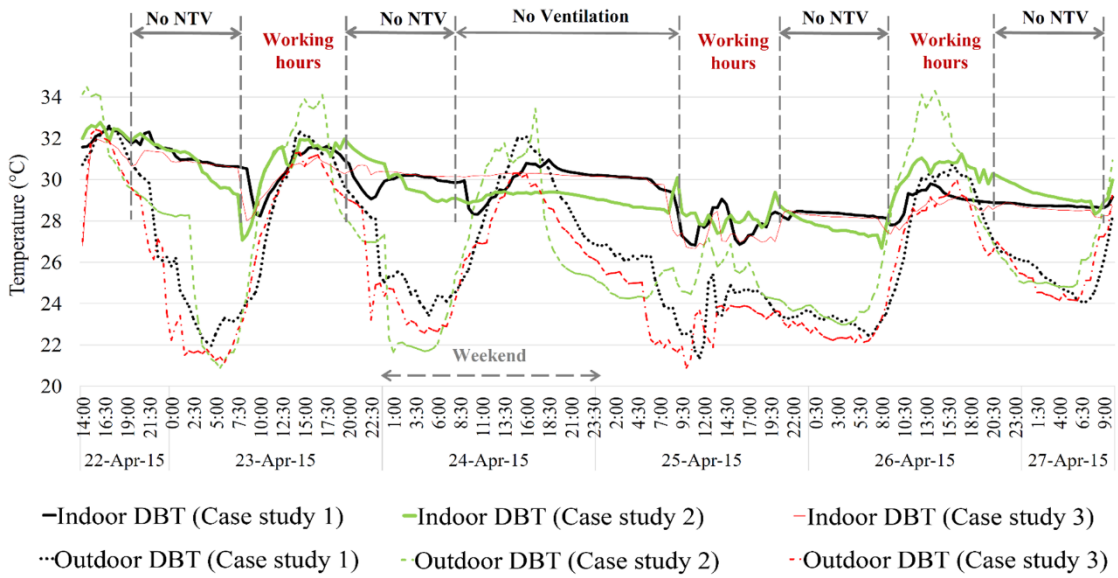


Figure 2. Data logger record from SS in case study buildings during hot-dry season

Figure 3. (a) Extract fans at ventilation outlets (b) Sliding windows at ventilation inlets with hardboard to protect workers from direct air flow

Figure 3 illustrates a combination of sliding windows acting as ventilation inlets and extract fans on the opposite side of the floor plate acting as ventilation 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 undesirable air flow pattern for those sitting close by, as witnessed by user interventions such as the use of hardboard to reduce draughts. It was also found that at night, when extended air temperatures are sufficiently low to provide passive cooling of the building fabric, the windows were closed and the fans switched off. This evidence triggered a need for further investigation of the thermal performance of these spaces during occupied and unoccupied hours.

Table 1. Surface temperature ranges in FS of the case study buildings (source: onsite recorded thermal images in August 2015)

Period	**Case study 1**	**Case study 2**	**Case study 3**
Occupied hours	38.5ºC – 108ºC	32ºC – 54ºC	35.1ºC – 85.7ºC
Unoccupied hours	38.1ºC – 111ºC	35.6ºC – 50.7ºC	34.7ºC – 92.7ºC

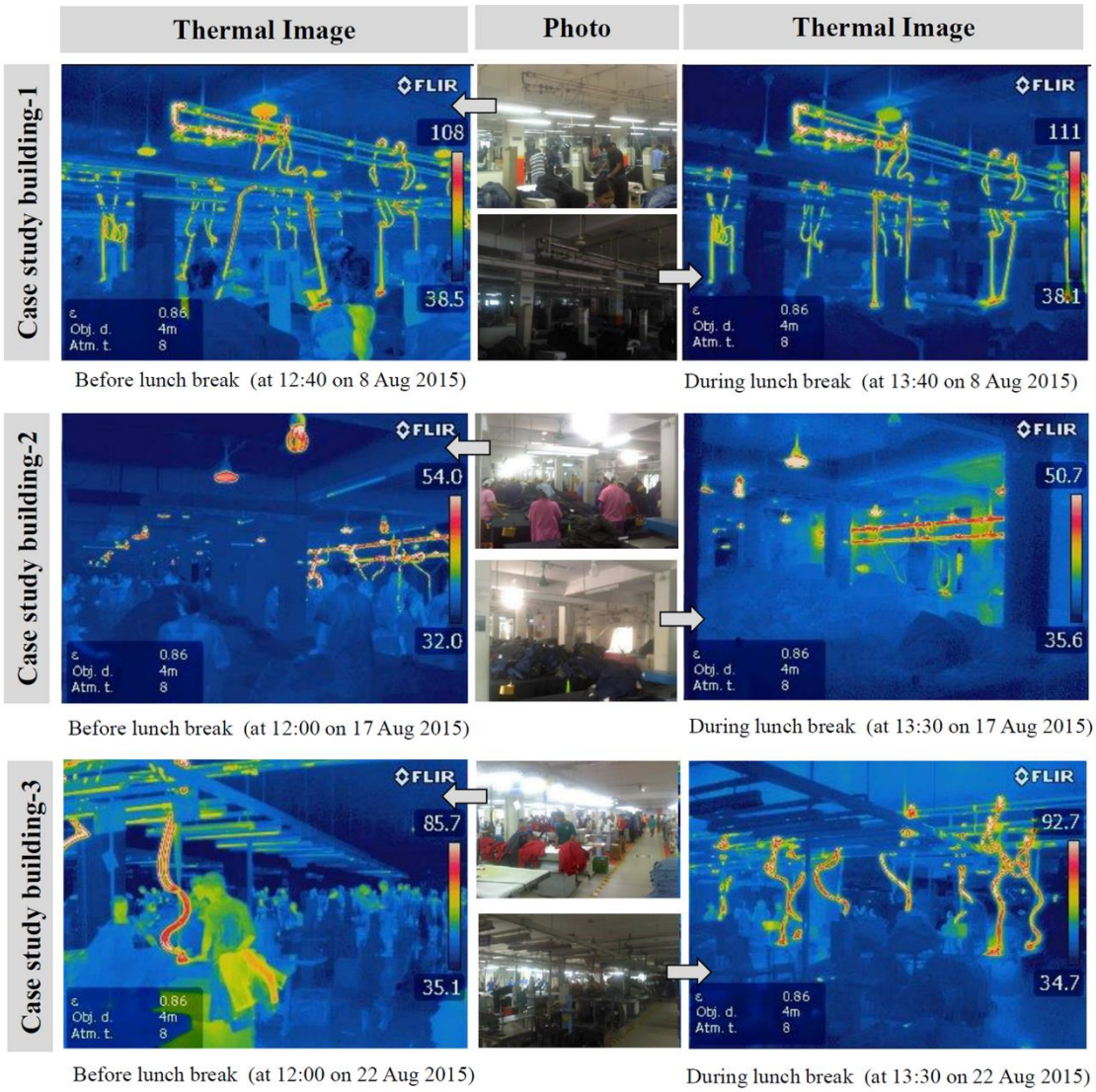


Figure 4. Surface temperature profile the FS of the three case study buildings before and during lunch break

Temperature profile during unoccupied hours

Thermal images such as those shown in figure 4 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, night time and weekends. For instance, the recorded surface temperatures of the workstations and machinery in the FS of case study building-3 recorded a maximum of 92.7°C during the unoccupied hours and only 85.7°C during occupied hours. Heat transfer between the

room internal surfaces and the room air through convection and radiations has the potentials to limit some of these temperature rises. This effect will depend on the extent of the exposed building fabric and the heat transfer coefficient of the surfaces which for these buildings are likely to be 5.9 – 10 W/m^{2}K (Artmann, Manz and Heiselberg 2008). Ventilation is potentially a more effective way to remove this unwanted heat and there are potentials to utilise it more, as currently, the extract fans do not operate during the unoccupied hours in these RMG factory workspaces. Figures 2 and 4 indicate the potential of ventilation for an extended period to reduce the overheating.

High internal heat gain from the equipment (Authors 2015) also indicates that increasing equipment efficiency may be a strategy to complement the extended operation of ventilation as a mean of tackling overheating.

Effect of size and operation of inlet-window

This section describes field data that illustrate the effect of window configuration on the AT profile within existing workspaces. According to the workers' feedback (Authors 2015), 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. Their normal response is to either shut the sliding window or fix a hardboard to restrict the direct breeze (figure 3). It consequently incurs the overheating problem. 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).

To explore the impact of changing effective area of the inlet windows on the indoor AT profiles, an onsite field experiment was conducted in the SS of each case study building. 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. Measurements were conducted simultaneously on two floors using data loggers and anemometers placed 1m and 10m away from the ventilation inlets. Factory owners 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 5 shows the results from the experiment on case study building-1 and illustrates that changing the effective opening area from 45% to 0% increased internal AT by approximately 1ºC 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 of a malfunction manifestation of the temperature sensor response The conditions monitored deeper inside the space showed similar, however, more heavily damped response to change in window opening area.

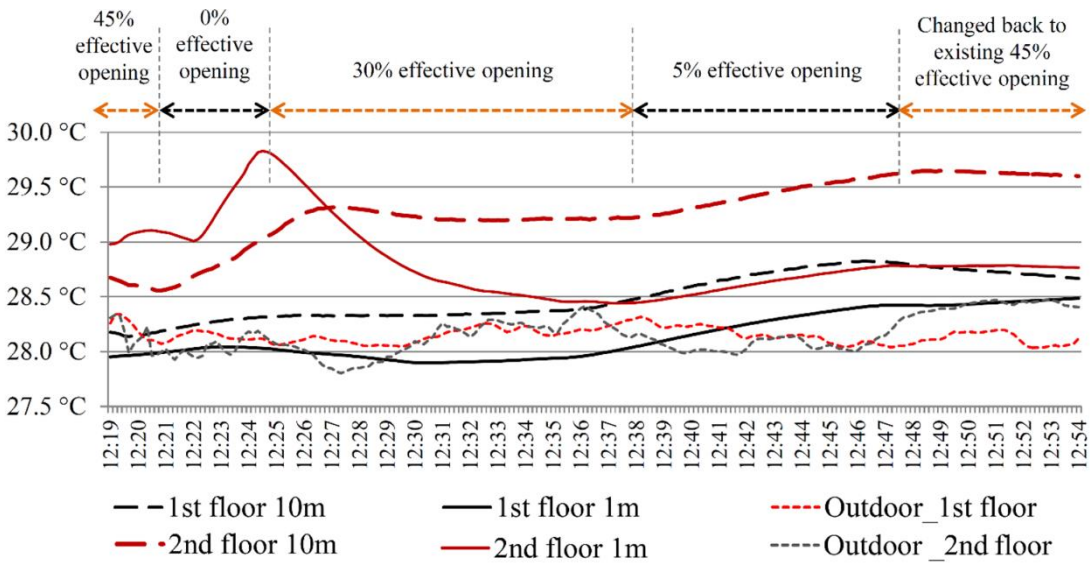


Figure 5. Effect of the inlet window opening area on indoor air temperature for case study building 1

Table 2. Effect of changing inlet area on surface temperature for case study building 1

Case study	Time (thermal imaging)	Effective inlet size	Range of surface temperature (°C)		Deviation from the first state with 45% open (°C)	
			Min.	Max.	Min.	Max.
Case study building-1	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

Indoor surface temperatures determined from thermal images indicated an increase of between 0.7 and 3ºC when the windows were closed (Table 2) and that surface temperature dropped in response to reopening the windows.

In addition to measuring the thermal response of the SSs in case study building 3, which showed similar changes in temperature in response to changes in ventilation inlet area, the workers were conversed 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 workspace caused by changes to the ventilation inlet windows. Although only AT and surface temperature profiles were recorded in case study buildings, it can be safely assumed that changes in the AV also occurred and when opening areas were reduced, then combined with the increase in AT and surface temperature force up the Standard Effective Temperature (SET). This being reflected in the additional thermal discomfort expressed by the workers. An additional figure is attached in the supplementary section of this paper to present the findings from this experiment.

Table 3. Proposed interventions for existing buildings

Sl no.	Existing scenario	Proposed interventions
01*	Ventilation operated during working hours only	Implementation of continuous day time ventilation complemented by an NTV / thermal mass strategy
02*	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
03	Reliance on mechanical ventilation	Introduce a ventilation stack into the centre of the building to induce buoyancy driven flow
04	125mm thick brick masonry external wall and concrete floor plates	Changing wall, ceiling and roof design to increase thermal mass
05	Production sections present a barrier to air flow	Segmented production area to enhance more effective air flow to reduce overheating

*Strategies within the scope of this paper

Discussion of strategies selected for the simulation study

This section reviews potential interventions to the design and operation of RMG factories intended to improve the indoor thermal environment when subject to the climatic conditions prevailing in Bangladesh.

The workers from all case study buildings suffer from thermal discomfort, particularly inside the SS and FS, as described in previous papers (Authors 2015). Focus group discussions confirmed a preference for work-stations located next to the windows where AV is high, as opposed to work-stations in the middle of the floor plate where perceived AV was negligible. They recommended providing more flexibility in operating the windows, even in the rainy seasons, and more personal control over the operation of the extract fans.

Interviews with the owners and managing directors confirmed that they received complaints from workers experiencing thermal discomfort in the SS and FS areas. In

response to this, the number of ceiling fans was increased in the first two case study buildings, however, this intervention did not help reduce discomfort. As a result, they 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. Since the internal functional layout and the building façades are fixed, they face limitations to making major layout and structural changes in their existing buildings. Moreover, they were only prepared to implement changes that could be completed during vacations without hampering the ongoing production lines in their RMG factories. They unanimously agreed that it is feasible to implement the introduction of an NTV strategy, changes to the configuration of all windows and segmentation of work zones to enhance the uniformity of air flow if it would be demonstrated these improve workers' thermal comfort. They were of the view that the remaining strategies and retrofit features would only be adopted in any future RMG buildings subject to further evidence of the environmental benefits. Table 4 summarises the feedback obtained from the interviews.

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, which is presented in the next section.

Table 4. Summary of factory owner feedback on proposed strategies

proposed strategies	Case study building-1	Case study building-2	Case study building-3
Run full day ventilation complemented by NTV	Yes	Yes	Yes
Change window type	Yes	Yes	Yes
Add ventilation stacks	No Possible in new buildings	No (structural limitation)	No Possible in new buildings
Re-arrange functional layout and segment zones	The layout is kind of fixed Segmentation is possible	The layout is fixed. Segmentation is possible	The layout is fixed. Segmentation is possible.
Change construction materials	No Possible in new buildings	No	No Possible in new buildings

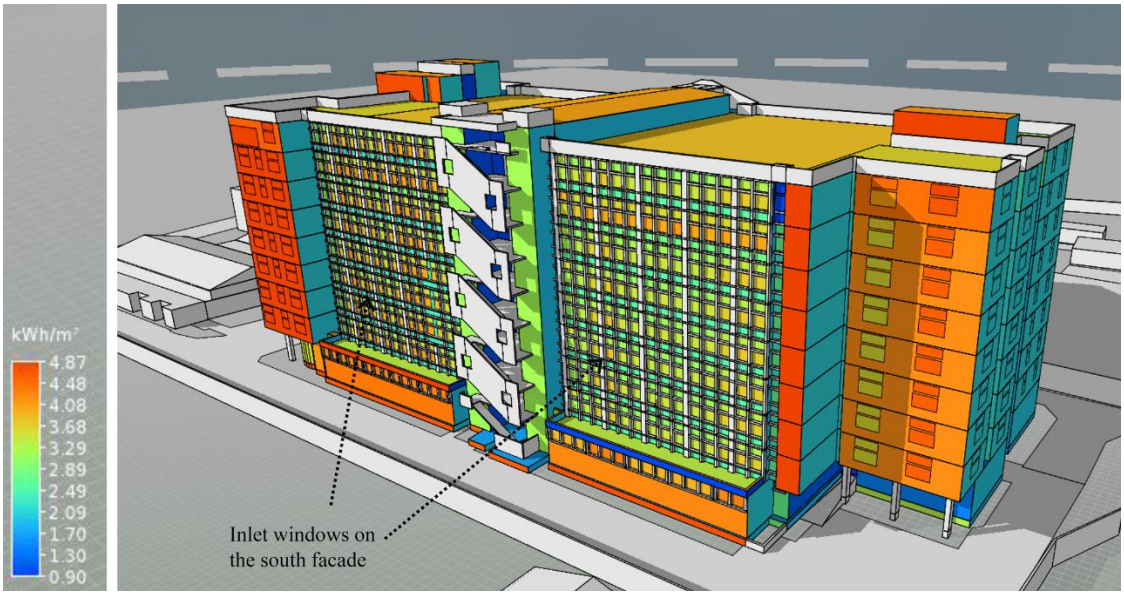


Figure 6. 3D Model showing the surface solar radiations of the case study building -3 in IES-VE (source: author)

Results from 'dynamic thermal simulations' and discussion

To quantify the benefits of changing window configuration and adding NTV strategy, a validated IES-VE simulation model of the case study building-3 with the immediate site context was prepared, the geometry of which is shown in Figure 6. Table 5 summarises the input parameters applied to the model before running the in dynamic thermal simulations 'ApacheSim'.

Table 5. Fixed and variable parameters used the IES-VE model of 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).	
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	Comfort range of 24-28 ºC AT and moderated comfort range of 28.5-33ºC AT. Where, RH is <65% and air velocity to be maintained within 0.8-1.5 ms^{-1}	
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 each 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 concrete with light-weight plaster (U-value:2.557 $W/m^2.K$	
Ventilation (MacroFlo): variable parameters		
	Scenario A and B (Table 7)	Scenario C and D (Table 7)
Opening type	Opening Category: Sliding windows on external walls with 45% openable area.	Pivoted (louvre type) windows on external walls with 75% openable area.
Door	Sliding door (50% effective opening)	Sliding door: (50% effective opening)
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.	
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

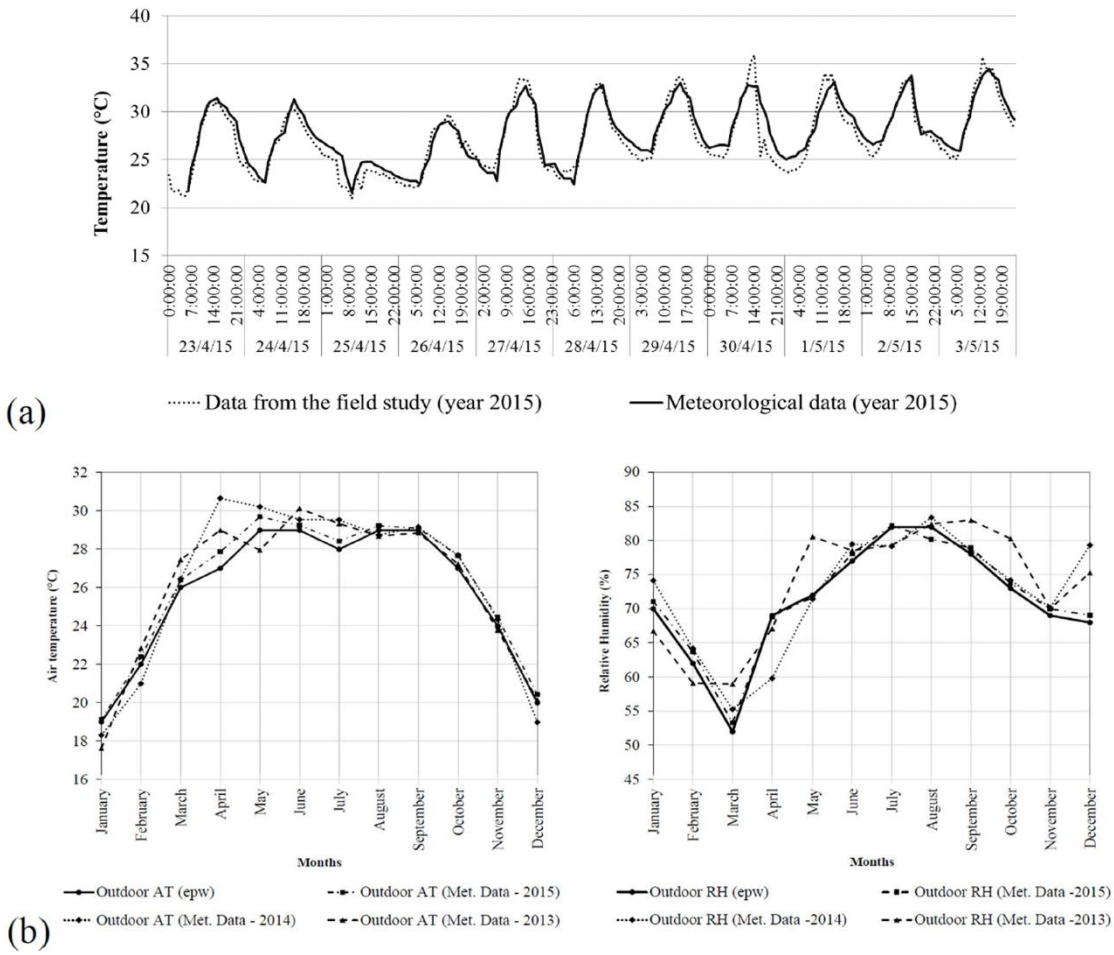


Figure 7. Comparison between (a) measured outdoor AT and meteorological data for Dhaka in the hottest month (b) Simulated weather data and annual meteorological data for Dhaka

Further detail on validation and simulation scenarios

As the first step of the validation process, Figure 7(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. The meteorological data was therefore converted into a '.epw' formatted weather data in order to provide simulated results for comparison with the indoor field data. Figure 7(b)

illustrates deviations between monthly average weather data and meteorological data for the years 2015, 2014 and 2013.

As the second step of the validation process, the model of the existing building should be validated using major input variables from field data (Strachan et al. 2016). The results from the model of case study building 3 were compared with measured indoor AT and RH data. Table 6 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 0.7ºC higher and 2.5% lower than the measured mean values respectively. Figure 8 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 according to the comfort criteria used to estimate conditions for the occupants (ASHRAE 2013).

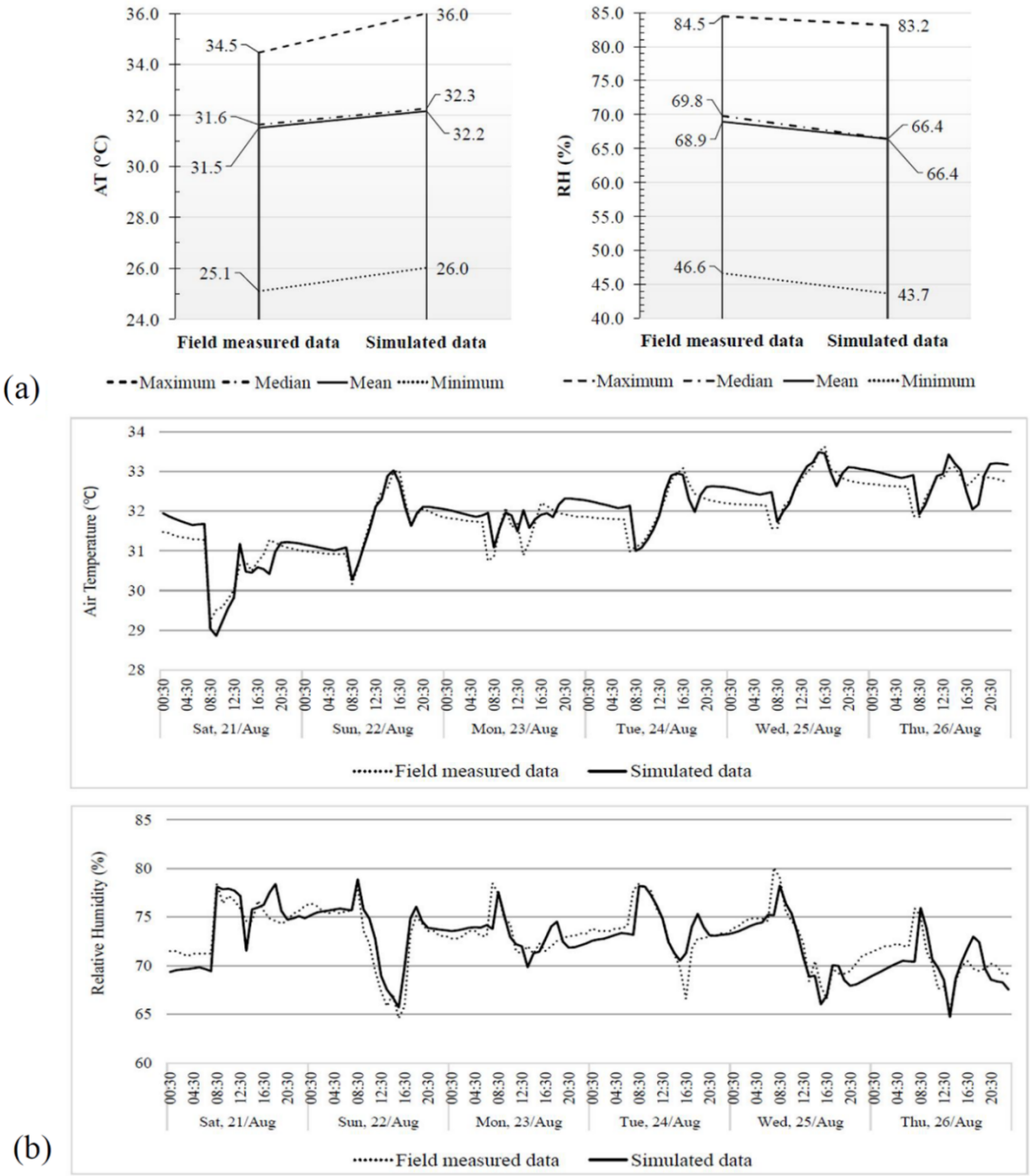


Figure 8. Comparison of a sample of measured and simulated data

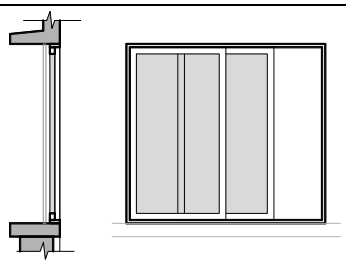
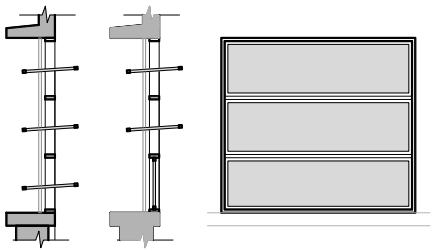
Table 6. Comparison of field-measured and simulated data during the warm season

	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 among data set, Data Count: total number of hourly data considered

Dynamic simulations were run on the 1st floor (FS), 5th floor (SS) and 8th floor (CS). Table 7 shows the four simulation scenarios that were considered. Scenario-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-B and scenario-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-C (which assumed DTV only) and scenario-D (where both DTV and NTV were assumed).

Table 7. Four selected simulation scenarios for thermal analysis

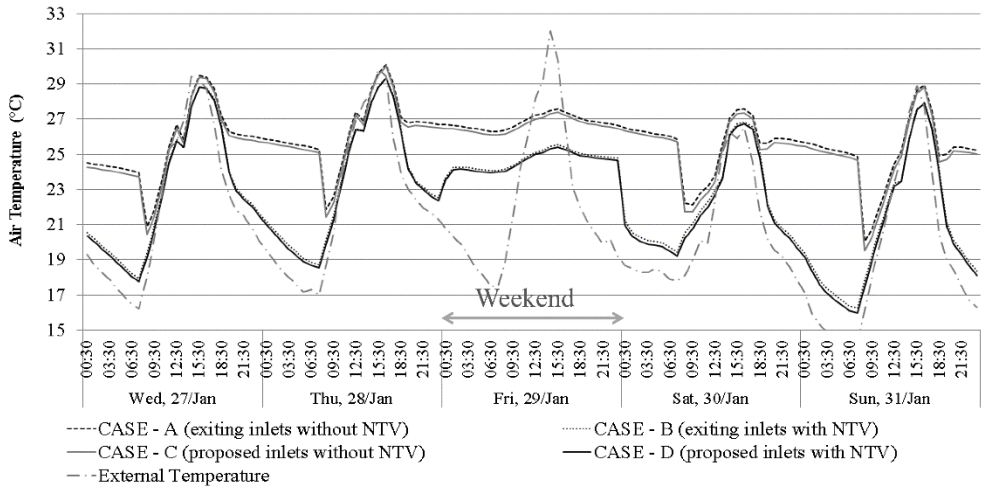
Simulation Scenarios	Type of inlet windows and their effective open area for air circulation		Ventilation Strategy
Scenario - A (base scenario)	Existing sliding windows with 45% effective open area		DTV
Scenario - B			Continuous ventilation (DTV+NTV)
Scenario - C	Pivoted windows with up to 75% effective open area*		DTV
Scenario - D			Continuous ventilation (DTV+NTV)

*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.

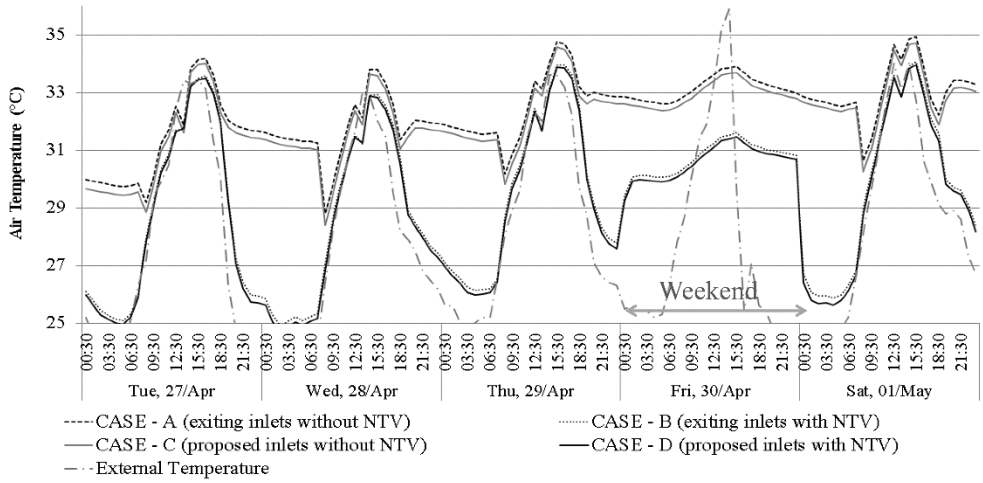
Results and discussion

Figure 9 shows the indoor AT profiles in the SS under the four simulation scenarios. The results for scenario A and scenario B indicate that for changing the window design

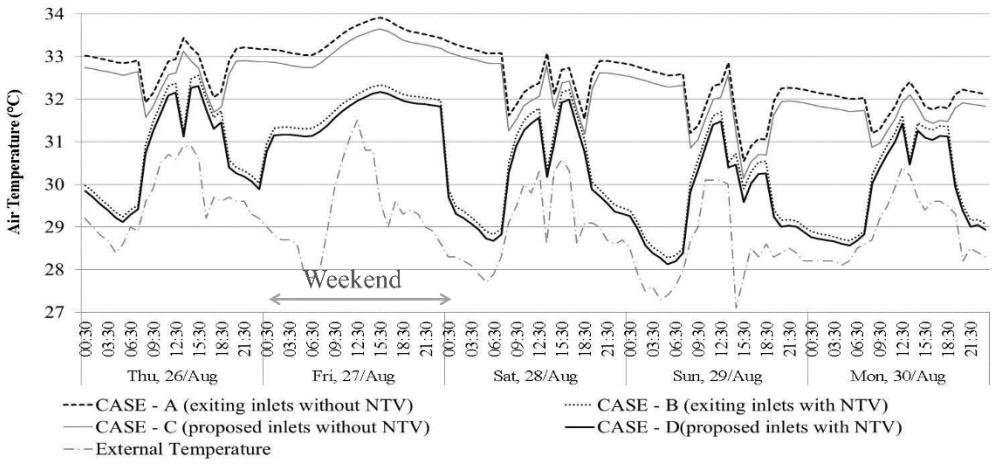
can offer a modest reduction in indoor AT of around 0.3ºC if the existing DTV only is maintained. Comparison of scenario-B and scenario D indicates the active NTV strategy can reduce peak indoor AT by 0.8°C, 0.9°C and 1.3°C during the cool-dry, hot-dry and warm humid seasons respectively compared with the base scenario.



(a)



(b)



(c)

Figure 9. 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 10 indicates that the active NTV strategy of scenarios B and 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 indicates that modifying the configuration of the windows to provide 75% effective opening area can reduce overheating by up to 15% of working hours in the FS, 12% in the SS and 2% in the CS. The introduction of active NTV can reduce overheated working hours by up to 23% in the FS, 17% in the SS and 3% in the CS. It is clear from figure 11 that the majority of the overheated working hours fall within the warm-humid and hot-dry season and that the ventilation during the cool-dry season is negligible.

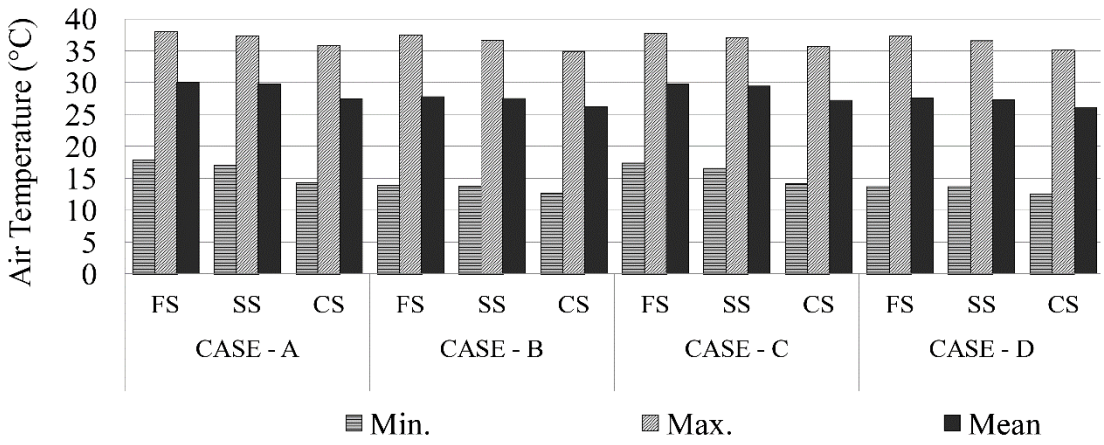


Figure 10. Comparison of maximum, minimum and mean annual indoor air temperature

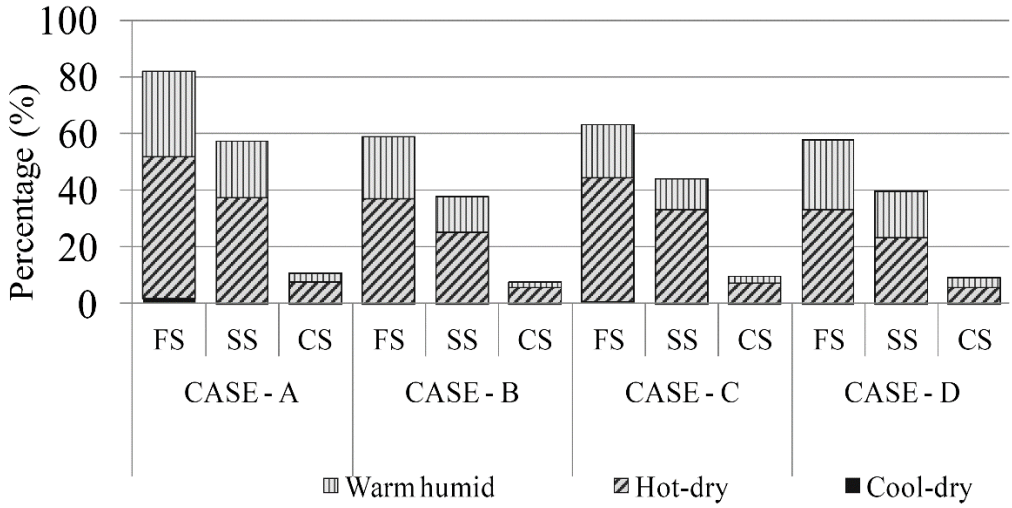


Figure 11. Percentage of working hours exceeding the maximum comfortable air temperature

Table 08. Comparison of annual AT, SET, MRT and RH for comfort evaluation

Workspace	Scenario	AT			SET*			MRT			RH	
		Working hours (%)		Mean AT (°C)	Working hours (%)		Mean SET (°C)	Working hours (%)		Mean MRT (°C)	Working hours (%)	Mean RH (%)
		>24°C to ≤28.5°C	>28.5°C to ≤33°C		>24°C to ≤28.5°C	>28.5°C to ≤33°C		>24°C to ≤28.5°C	>28.5°C to ≤33°C		<65%	
CS (8th floor)	A	32.8	43.5	30.1	13.1	23.8	33.0	22.8	56.9	28.4	42.8	66.8
	B	36.2	39.4	26.2	13.5	24.7	32.2	27.7	52.3	27.2	38.2	72.0
	C	33.9	41.7	27.2	13.3	24	32.8	24.4	55.5	28.1	41	67.8
	D	36.5	38.3	26.1	13.5	25	32.1	28.4	51.4	27.0	37.3	72.5
SS (4th floor)	A	19.4	48.5	29.8	9.4	22	34.2	17.8	43.4	30.2	67.6	58.6
	B	23.3	49.4	27.5	12.3	23.3	32.8	18.2	47.1	28.0	59.1	66.9
	C	20.7	49.4	29.5	10.1	22.5	34.0	21.9	56.2	29.9	63.5	59.7
	D	24.7	48.5	27.3	12.5	23.5	32.7	21.2	55.4	27.9	56.1	67.6
FS (1st floor)	A	18.1	43	30.1	8.2	20.9	34.3	16.9	37.8	30.4	74.6	57.9
	B	19.7	47.4	27.8	11	22.4	33.0	19.3	50.9	28.3	67.2	65.9
	C	18.7	46.1	29.8	9	21.6	34.2	17.2	40.6	30.1	70.5	58.9
	D	20.9	47.9	27.6	11.2	23.1	32.9	19.8	52.4	28.1	63.5	66.7

*According to ASHRAE-55 (2013), RH is 50%, average AV is below 0.1 ms^{-1} and MRT is equal to average AT with standard 'clo' and 'met' value.

Table 8 presents the annual mean values of AT, SET, MRT and RH in all production spaces for the scenarios A, B, C and D along with the percentages of

working hours within the targeted ranges. 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 working hours by up to 55.4% within the moderated comfort range. 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.

Results from CFD simulation and Discussion

Further detail on the CFD validation process

To visualise the effect of changing the window design on indoor temperature and air distribution in the SS, scenario-A and scenario-C 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. The components such as work-desks, workers, fluorescent lights etc. inside the workspaces were simplified and presented as boxes of approximately the same size. Each of the extractor fans was capable of delivering 12m^3/s air flow rates and was located in the CFD model as found in the field study.

Table 9. Comparison between field-measured* AV and simulated AV

Grid points**	**AV, ms^{-1}** ***(source: Field measurement)***	**AV, ms^{-1}** ***(source: CFD simulation in IES-VE)***	**Deviation (ms^{-1})**	**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 12)

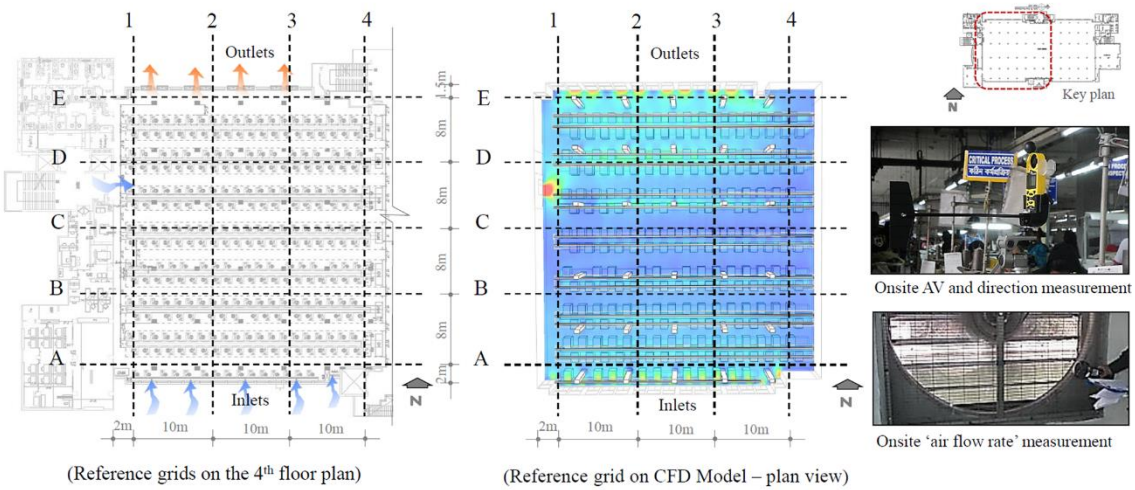


Figure 12. Reference grids to validate field-measured and simulated air velocity

The validation process was done following the previously established methods (Almhafdy et al. 2015; Kang and Lee 2008; Karniadakis 2002). For example, the simulated air volume flow rate through individual openings, as well as the total volume of the SS section for the existing scenario (scenario A) was cross-checked with the field data. Figure 12 shows the reference grids points of the field measurements and Table 9 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 (Almhafdy et al. 2015; Kang and Lee 2008).

Results and discussion

Figure 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 13). To quantify the improvement of ventilation inside the workspace, simulated data are presented in Table 10. These reveal that the middle zone, near the reference grids B and C, achieved higher velocities of around $0.2ms^{-1}$ higher than the existing scenario A.

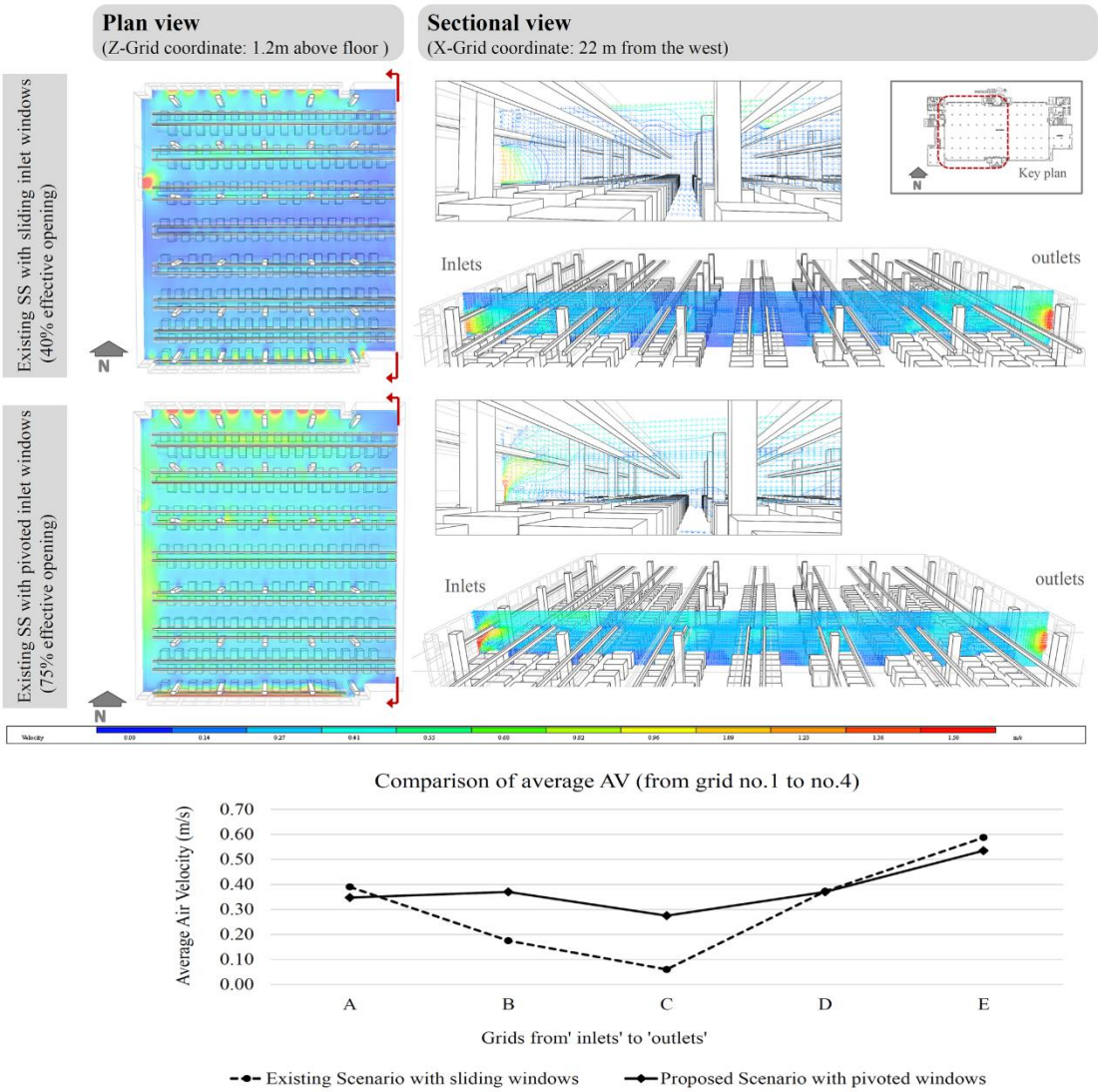


Figure 13. Comparison of air flow distribution and average air velocity between existing and proposed scenario

Table 10. Comparison indoor air velocity (AV) profile between existing and proposed scenarios

	AV, ms^{-1} (Existing Scenario A with sliding windows: 45% effective opening)					**AV, ms^{-1}** (Proposed Scenario 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) showed 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 (193m3/s or 68.2 ACH) is not enough to ensure the desired AV range of 0.8-1.5ms-1. 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.

Conclusion

This paper aimed to investigate indoor environments of workspaces in RMG factories in Bangladesh and to present the scope of improving these issues through detailed studies of the two readily implementable solutions, i.e. changing window design and adopting NTV. The key findings of this study based on field data collection and building energy simulation are:

- Due to constrained active ventilation and opening of windows being restricted to working hours, the indoor air and surface temperature of workspaces remained overheated during unoccupied hours during all three climatic seasons.

- Sliding windows restricted air to enter the workspaces and restricted the ability of ventilation to reduce indoor AT.
- Interviews and focus group discussions with factory owners and workers indicated that the full day ventilation with an NTV strategy and changing the window configurations are the immediately implementable modifications that could improve workers' thermal experience in existing RMG factories.
- Both strategies were unable to improve the existing RH range to fulfil the comfort criteria. However, they ensured that 74.8%, 73.2% and 68.8% of working hours in CS, SS and FS are respectively kept within the comfortable AT range.
- Changing the existing sliding windows to pivoting windows can reduce overheating by up to 15% of working hours in FS, 12% in SS and 2% in CS.
- Adopting full day ventilation can reduce overheated working hours by up to 23% in FS, 17% in SS and 3% in CS during all climatic seasons.
- Changing from sliding windows to pivoting windows improved air flows in work-stations located in the central regions of production spaces, remote from ventilation inlets and outlets.

The limitations of this study are, firstly, the results based on short periods of simulation especially in the case of the CFD analysis. They do not, therefore, 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, this study also has a limited scope as it considered a partial comfort range based on previous studies to evaluate the thermal performance.

However, the key findings of this research could potentially be incorporated into the national building code of Bangladesh. Architects and engineers could adopt these

viable ventilation strategies to refurbish the existing workspaces or to design new multi-storied RMG factories.

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References:

Almhafdy, A., N. Ibrahim, S. S. Ahmad, and J. Yahya. 2015. "Thermal Performance Analysis of Courtyards in a Hot Humid Climate Using Computational Fluid Dynamics CFD Method." Procedia - Social and Behavioral Sciences no. 170: 474-483. doi: 10.1016/j.sbspro.2015.01.012.

Amos-Abanyie, S., F. O. Akuffo, and V. Kutin-Sanwu. 2013. “Effects of Thermal Mass, Window Size, and Night-Time Ventilation on Peak Indoor Air Temperature in the Warm-Humid Climate of Ghana.” *The Scientific World Journal*, Volume 2013: 1-9. doi: 10.1155/2013/621095.

Artmann, N., H. Manz, and P. Heiselberg, 2008. “Parameter study on performance of building cooling by night-time ventilation.” *Renewable Energy* 33: 2589-2598. doi: 10.1016/j.renene.2008.02.025

ASHRAE. 2013. “ANSI/ASHRAE Standard 55-2013”, *Thermal environmental conditions for human occupancy*. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Bangladesh Accord Foundation. 2013. “Factory record status”. *ACCORD on Fire and Building Safety in Bangladesh*, Accessed 13 March 2014. http://bangladeshaccord.org/factories/list-factories/

BNBC. 2006. “Bangladesh National Building Codes” Bangladesh Gazette, Housing and Building Research Institute and Bangladesh Standards and Testing Institutes. Dhaka: City Art press Ltd.

Chen, Q. 2009. “Ventilation performance prediction for buildings: A method overview and recent applications.” *Building and Environment* 44(4): 848-858. doi: 10.1016/j.buildenv.2008.05.025.

Chowdhury, S., Y. Hamada, and K.S. Ahmed. 2017. "Prediction and comparison of monthly indoor heat stress (WBGT and PHS) for RMG production spaces in

Dhaka, Bangladesh." Sustainable Cities and Society no. 29:41-57. doi: 10.1016/j.scs.2016.11.012.

Chowdhury, S., K. S. Ahmed and Y. Hamada. 2015. “Thermal performance of building envelope of ready-made garments (RMG) factories in Dhaka, Bangladesh.” *Energy and Buildings*, vol.107: 144-154. doi: 10.1016/j.enbuild.2015.08.0140378-7788/

CIBSE. 2005. *Natural ventilation in non-domestic buildings: CIBSE Applications Manual AM10*: Norwich: The Chartered Institution of Building Services Engineers (CIBSE) Publications.

Cui, S., P. Stabat, and D. Marchio. 2013. “Influence of Natural Ventilation on Solar Gains and Natural Lighting by Opening Windows”. *Proceedings of 13th Conference of International Building Performance Simulation Association (IBPSA), Chambéry, France on August 26-28, 2013*, edited by Etienne Wurtz, 8-15. Red Hook: Curran Associates. http://www.ibpsa.org/proceedings/BS2013/p_1515.pdf

Designing Buildings Ltd. 2015. “Night-time purging” [Online]. Available: http://www.designingbuildings.co.uk/wiki/Night-time_purging [Accessed 24/10/2016].

Fatemi, N. 2014. *Thermal comfort in production spaces of ready-made garments Factories the context of Dhaka, Bangladesh*, Germany: LAP Lambert Academic Publishing.

Fisk, W. J. 2000. “Health and Productivity Gains From Better Indoor Environments and Their Relationship with Building Energy Efficiency.” *Annual Review of Energy and the Environment*, vol. 25: 537–566. doi: 10.1146/annurev.energy.25.1.537

Ford, B., R. S. Phan and E. Francis, eds. 2010. *The Architecture & Engineering of Downdraught Cooling: A Design Sourcebook*. UK: PHDC Press.

Givoni, B. 1994. “Building design principles for hot humid regions.” *Renewable Energy*, 5 (5): 908-916. doi: 10.1016/0960-1481(94)90111-2.

Heiselberg, P., K. Svidt and P. V. Nielsen. 2001. “Characteristics of airflow from open windows.” *Building and Environment*, no. 36: 859–869. doi: 10.1016/S0360-1323(01)00012-9.

Hobday, R. A. and S. J. Dancer. 2013. “Roles of sunlight and natural ventilation for controlling infection: historical and current perspectives”. *Journal of Hospital Infection* 84 (4): 271-282. doi: 10.1016/j.jhin.2013.04.011

Humphreys, M. A. 1970. “A simple theoretical derivation of thermal comfort conditions.” *Journal of the Institute of Heating and Ventilating Engineers.* 38: 95–98.

ILO. 1998. *Improving Working Conditions and Productivity in the Garment Industry, An action manual.* Geneva: International Labour Organisation. http://www.ilo.org/wcmsp5/groups/public/---ed_protect/---protrav/---safework/documents/instructionalmaterial/wcms_228220.pdf

Kang, J. H. and S. J. Lee (2008). Improvement of natural ventilation in a large factory building using a louver ventilator. *Building and Environment*. 43(12), 2132-2141. doi: 10.1016/j.buildenv.2007.12.013

Karniadakis, G.E. 2002. "Quantifying Uncertainty in CFD". *Journal of Fluids Engineering.* no. 124 (1):2. doi: 10.1115/1.1447925.

Khedari, J., N. Yamtraipat, N. Pratintong and J. Hirunlabh. 2000. “Thailand ventilation comfort chart”. *Energy and Buildings*, 32, 245–249. doi: 10.1016/S0378-7788(00)00050-5

Kubota, T., D., T. H Chyee and S. Ahmad. 2009. “The effects of night ventilation technique on indoor thermal environment for residential buildings in hot-humid climate of Malaysia.” *Energy and Buildings* 41 (8): 829-839. doi: 10.1016/j.enbuild.2009.03.008.

La Roche, P. and M. Milne. 2004. “Effects of window size and thermal mass on building comfort using an intelligent ventilation controller.” *Solar Energy* 77: 421-434. doi: 10.1016/j.solener.2003.09.004.

Liping, W. and W. N. Hien. 2007. “The impacts of ventilation strategies and facade on indoor thermal environment for naturally ventilated residential buildings in Singapore”. *Building and Environment* 42(12): 4006-4015. doi: 10.1016/j.buildenv.2006.06.027.

Loonen, R. C. G. M., F. Favoino, J. L. M. Hensen and M. Overend. 2016. “Review of current status, requirements and opportunities for building performance simulation of adaptive facades.” *Journal of Building Performance Simulation*: 1-19. doi: 10.1080/19401493.2016.1152303.

Lomas, K. J. 2007. “Architectural design of an advanced naturally ventilated building form.” *Energy and Buildings* 39 (2): 166-181. doi: 10.1016/j.enbuild.2006.05.004.

Mahbob, N. S., S. N. Kamaruzzaman, N. Salleh and R. Sulaiman 2011. "A Correlation Studies of Indoor Environmental Quality (IEQ) Towards Productive Workplace." *Proceedings of the 2nd International Conference on Environmental Science and Technology*. Singapore: IACSIT Press. vol.6: p.434-438. url: http://www.ipcbee.com/vol6/no2/96-F30033.pdf

Matthews, J. and F. Nicol, 1995. "Thermal Comfort of Factory Workers in Northern India". In F. Nicol, M. Humphreys, O. Sykes & S. Roaf (Eds.), *Standards for thermal comfort: indoor air temperature standards for the 21st century*. London: E & FN Spon.

Naz, F. 2008. "Energy Efficient garment factories in Bangladesh." Paper presented at the 25th Conference on Passive and Low Energy Architecture (PLEA), Dublin, October 22-24 2008, Dublin, Ireland. http://plea-arch.org/ARCHIVE/2008/content/papers/oral/PLEA_FinalPaper_ref_586.pdf

Nguyen, A.T., S. Reiter and P. Rigo. 2014. "A review on simulation-based optimisation methods applied to building performance analysis." *Applied Energy*, no.113: 1043–1058. doi: 10.1016/j.apenergy.2013.08.061.

Rajapaksha, U. and R. Hydes. 2012. "Barriers to and opportunities for advanced passive cooling in sub-tropical climates." *Architectural Science Review* 55 (1): 49–60. doi: 10.1080/00038628.2011.641730.

Ramponi, R., I. Gaetani and A. Angelotti. 2014. "Influence of the urban environment on the effectiveness of natural night-ventilation of an office building." *Energy and Buildings*, no. 78: 25–34. doi: 10.1016/j.enbuild.2014.04.001.

Rijal, H. B., P. Tuohy, M. A. Humphreys, J. F. Nicol, A. Samuel and J. Clarke. 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 (7): 823-836. doi: 10.1016/j.enbuild.2007.02.003.

Santamouris, M. and D. N. Asimakopoulos. eds. 2013. *Passive Cooling of Buildings*. 13th ed. Abingdon: Earthscan, Routledge.

Shaviv, E., A. Yezioro and I. G. Capeluto. 2001. "Thermal mass and night ventilation as passive cooling design strategy." *Renewable Energy*, 24: 445-452. doi: 10.1016/S0960-1481(01)00027-1.

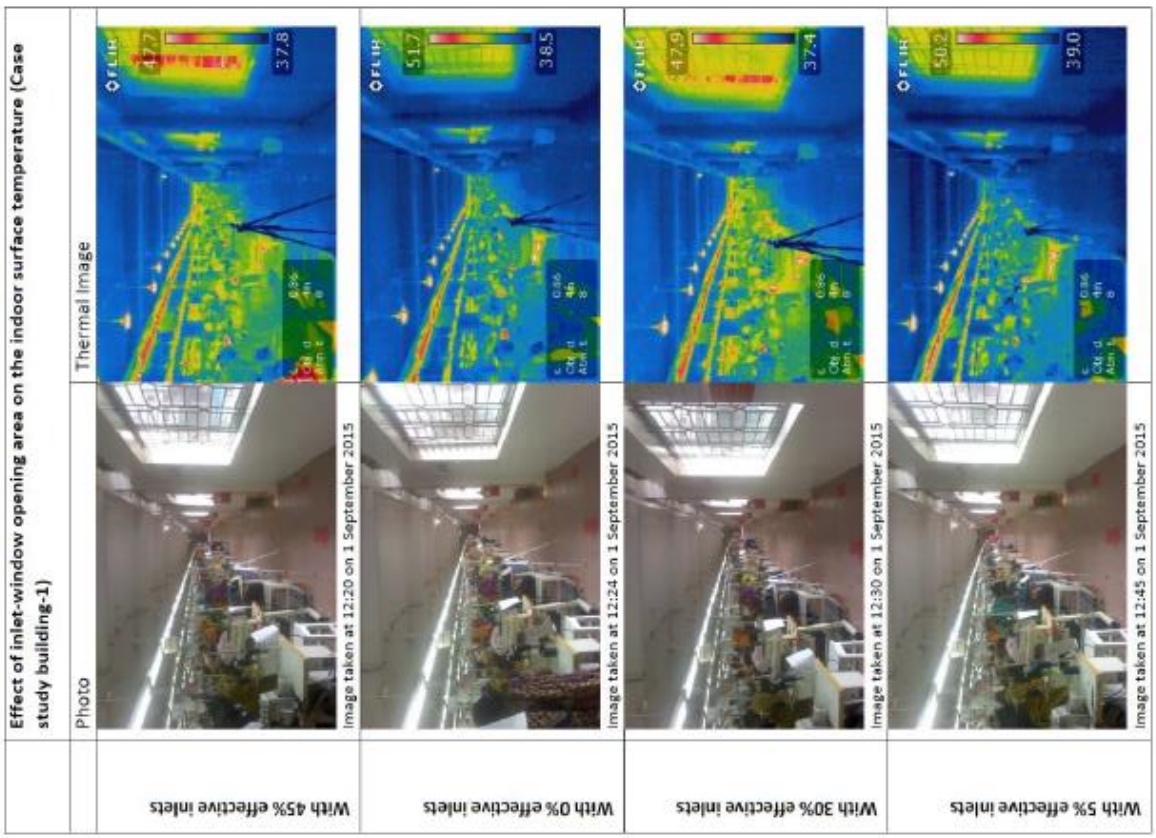
Srinavin, K., & S. Mohamed. 2003. "Thermal environment and construction workers' productivity: some evidence from Thailand". *Building and Environment*, 38, 339–345. doi: 10.1016/S0360-1323(02)00067-7

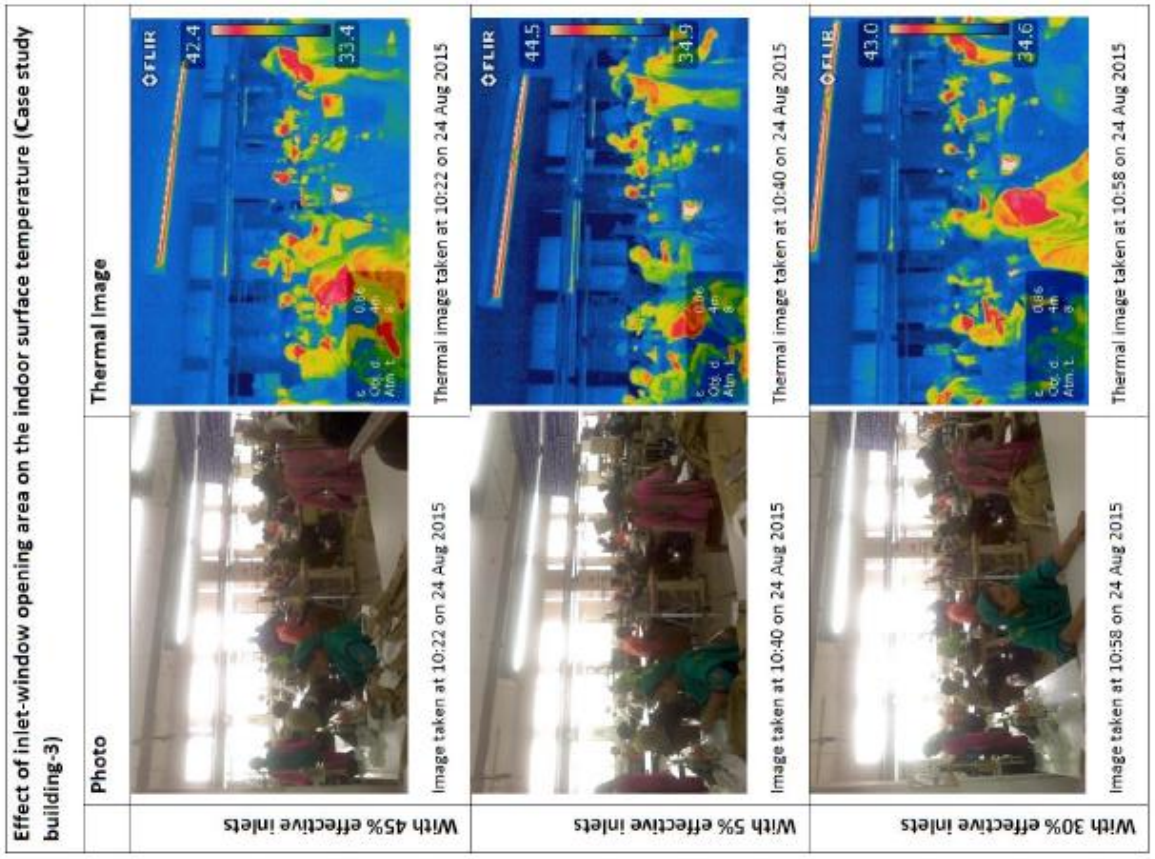
Strachan, P., K. Svehla, I. Heusler and M. Kersken. 2016. “Whole model empirical validation on a full-scale building.” *Journal of Building Performance Simulation* 9 (4): 331-350. doi: 10.1080/19401493.2015.1064480.

Wijewardane, S. and M. T. R. Jayasinghe. 2008. “Thermal comfort temperature range for factory workers in warm humid tropical climate.” *Renewable Energy*, no. 33: 2057-2063. doi: 10.1016/j.renene.2007.11.009

Wong, N. H., E. Tan, O. Gabriela and S. K. Jusuf. 2016. “Indoor Thermal Comfort Assessment of Industrial Buildings in Singapore”. *Procedia Engineering*, 169, 158-165. doi: 10.1016/j.proeng.2016.10.019

Supplemental file 1:





Supplemental file 2:

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?

Supplemental file 3:

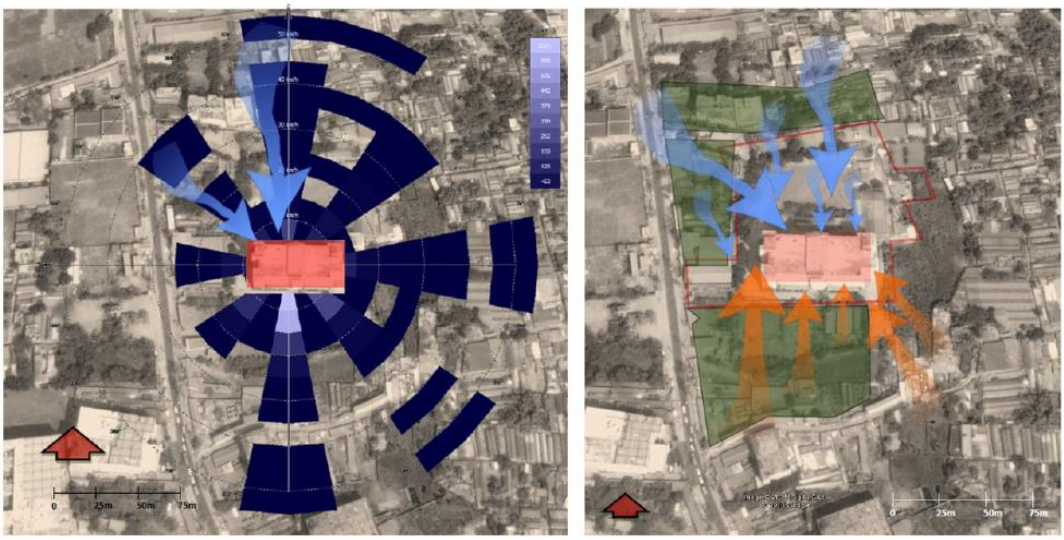


Figure: Average wind regime around the case study building-3

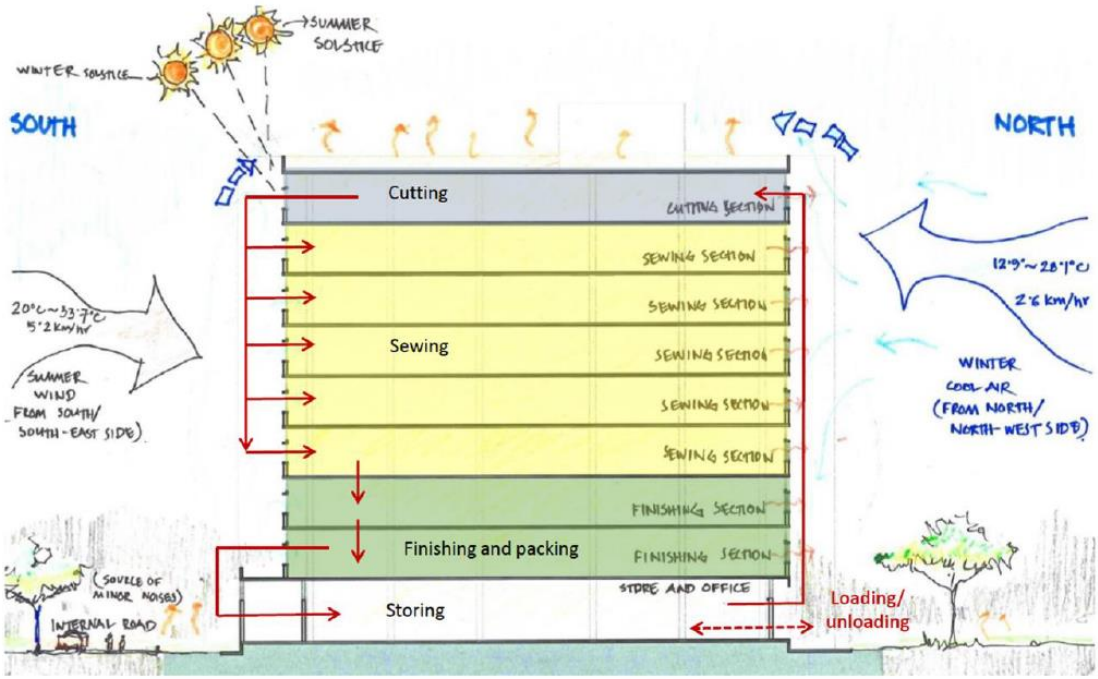


Figure: Location of the production spaces and activity flow in case study building-3