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High-Rise Social Housing in Hot-Humid Climates: Towards an 'Airhouse' Standard for Comfort

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Featured Application: The results of this research can be applied to the ongoing social housing construction program in Malaysia

Abstract: The pressure to provide social housing in a fast and economic way, as well as outdated regulations, constrain the design of these buildings, having serious implications for the comfort of occupants and the environment. This becomes more critical in hot-humid climates, such as Malaysia, with uniformly high temperature and humidity and low wind speeds. In its capital, Kuala Lumpur, an extensive program of construction for high-rise social housing is being carried out, however, shortly after the flats are occupied, or as soon as they can afford it, the residents fit wall mounted air conditioning units. This research started by looking at Malay vernacular architecture and the traditional strategies for ventilation and cooling. After a review of current building regulations and green tools employed in the country, two campaigns of fieldwork were carried out to assess the actual indoor and outdoor thermal and air quality conditions in the buildings, which were found to be inadequate for both the local regulations and international recommendations. The fieldwork also allowed the identification of the critical design issues to address. A ventilation and filtering ceiling system has been identified as one of the possible solutions for the current situation and has been tested through physical and computer models. The system improves comfort by reducing the air temperature, humidity, and amount of airborne particles and gases, as well as constantly providing an adequate airflow rate. It is the first attempt to develop what we have named the 'airhouse' standard for tropical countries.

Keywords: high-rise; social housing; hot-humid climate; comfort; thermal comfort; indoor air quality; dynamic insulation; 'airhouse' standard; Malaysia

1. Introduction

The health and comfort of humans in urban areas are both compromised by high carbon emissions. In the Southeast Asia (SEA) region, these have increased rapidly. Malaysia is one of the five countries that have collectively contributed to 90% of the carbon emissions in the region, which is directly linked to an increase in temperature, projected to be in the country between 1.1 °C and 3.6 °C by 2095 [1]. The carbon emissions from the building sector have doubled from the 1970s, now representing 25% of the total country's emissions. The construction of residential buildings has quintupled during the last four decades [2]. In order to address this problem, the government has recently signed the Paris Agreement, committing to reduce 45% of carbon emissions by 2030, in accordance to the 2005 baseline.

The ongoing People's Housing Programme (PPR) involves the construction of one million high-rise social housing units in Malaysia, but it does not addresses the comfort of the occupants and the wider environmental issues in full [3]. The local hot-humid climate, dense urban environment, layout and orientation of buildings, materials used for the building, and human behaviour contribute to a high indoor air temperature and humidity. Heavyweight construction with concrete panels or brickwork without insulation, which are, at the moment, the common systems of construction in Malaysia for these types of buildings, store heat and release it at night [4]. This gives no option to the occupants but to use individual air conditioning units to achieve thermal comfort, having the implications of high-energy consumption and carbon emissions, as well as unattractive urban facades (Figure 1).

Figure 1. High-rise social housing in Kuala Lumpur.

An additional problem is the outdated regulations. The current building regulations (UBBL) in Malaysia (a British colony until 1957), were implemented in 1984, based on the recommendations given by the United Kingdom's Building Research Station (BRS), currently known as the Building Research Establishment (BRE). The UBBL 1984 does not take Malaysia's hot-humid climate and the current issues concerning carbon emissions in full account [3]. Two main natural ventilation strategies are used for the design of these buildings: Temperature-induced stack ventilation using lightwells, air-wells, or atria, and wind-induced single sided ventilation for external rooms. The building regulations, which have not been revised for 35 years, only have requirements for the sizes of openings (Clause 39) and lightwells (Clause 40) [5]. The regulations establish that the minimum size of openings for natural ventilation purposes in residential buildings should not be less than 10% of the total clear area of the room.

There have been recent developments concerning the use of green rating tools in Malaysia, which have encouraged a number of thermal comfort strategies, helping to improve the sustainable design of buildings [3]. However, they have not been able to acknowledge the current and future climatic conditions of Kuala Lumpur and address the required improvements in terms of occupant's health and comfort, as well as the reduction of carbon emissions.

There are many challenges concerning the provision of conventional natural ventilation in dense urban areas such as Kuala Lumpur, including the problems associated with the urban heat island effect and air pollution (Figure 2). Considering the standard flat layout in these buildings (single-sided), and the high humidity and air pollution, cross-ventilation driven by ambient air movement is not an effective strategy for providing evaporative cooling. Effective ventilation is also hampered by insufficient wind movement: The average wind movement in Kuala Lumpur is 1.1 m/s at 10 m of elevation [6] and 4.4 m/s at 42.8 m of elevation [7]. There are no measurements at higher levels in the city, but we have data from Bangkok, another megacity in the SEA region, where the wind movement was 6.13 m/s at a 65 m elevation [8]. Based on that, we can plot the possible wind movement (Figure 3, dotted-blue line). A high wind velocity (over 1.5 m/s) is only acceptable in very hot and humid conditions when no other relief is available [9]. However, 6.0 m/s of wind speed will cause uncomfortable conditions for the occupants, as well as implications for the operation of the fans and a high rate of polluted air infiltration. Here, this needs to be controlled following the ranges set by

ASHRAE 55 and CIBSE guide A, and the flats and ventilation systems should be designed to acknowledge the different wind movement rates at different heights.

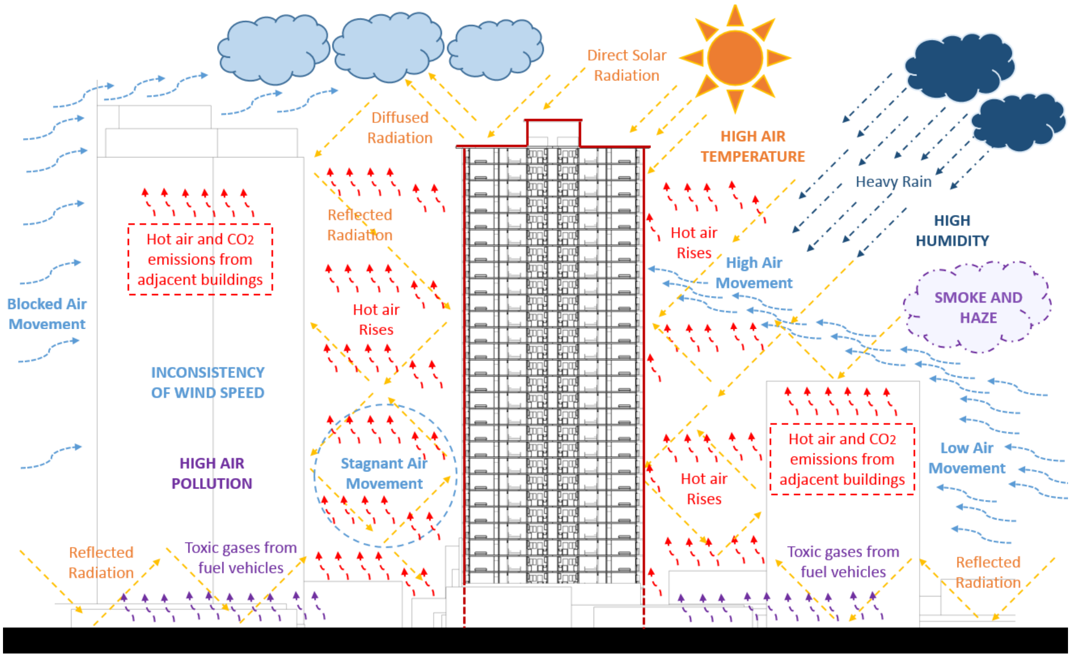
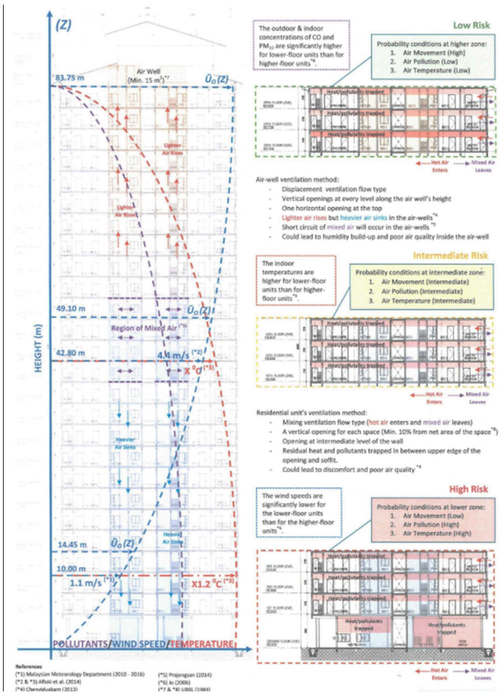


Figure 2. Factors affecting indoor comfort in a typical high-rise building within an urban area in a hot-humid climate.



The outdoor & indoor concentrations of CO and PM10 are significantly higher for lower-floor units than for higher-floor units*6.

Probability conditions at higher zone:
1. Air Movement (High)
2. Air Pollution (Low)
3. Air Temperature (Low)

Air-well ventilation method:
- Displacement ventilation flow type
- Vertical openings at every level along the air well's height
- One horizontal opening at the top
- Lighter air rises but heavier air sinks in the air-wells*4
- Short circuit of mixed air will occur in the air-wells*5
- Could lead to humidity build-up and poor air quality inside the air-well

The indoor temperatures are higher for lower-floor units than for higher-floor units*6.

Probability conditions at intermediate zone:
1. Air Movement (Intermediate)
2. Air Pollution (Intermediate)
3. Air Temperature (Intermediate)

Residential unit's ventilation method:
- Mixing ventilation flow type (hot air enters and mixed air leaves)
- A vertical opening for each space (Min. 10% from net area of the space*8)
- Opening at intermediate level of the wall
- Residual heat and pollutants trapped in between upper edge of the opening and soffit.
- Could lead to discomfort and poor air quality*4

The wind speeds are significantly lower for the lower-floor units than for the higher-floor units*6.

Probability conditions at lower zone:
1. Air Movement (Low)
2. Air Pollution (High)
3. Air Temperature (High)

References
(*1) Malaysian Meteorology Department (2010 - 2016)
(*2 & *3) Aflaki et al. (2014)
(*4) Chenvidyakarn (2013)
(*5) Prajongsan (2014)
(*6) Jo (2006)
(*7 & *8) UBBL (1984)

Figure 3. Probabilities of air temperature, wind speed and pollutants concentration in high-rise residential building.

Indoor comfort not only includes the acoustic, thermal, and visual conditions, but also the indoor air quality [10]. For many years, these components have been researched in isolation by various professionals, such as engineers, architects, physiologists, and occupational health and hygiene experts [11]. This research tries to influence the design of new buildings and the retrofitting of existing ones to improve thermal comfort and indoor air quality, learning from traditional vernacular architecture and considering the current climate and environment. It tries to integrate thermal comfort and indoor air quality issues with the ultimate scope of reducing the use of energy and maximizing the use of natural ventilation for the design of new buildings, and the refurbishment of existing ones, in Kuala Lumpur. However, it also aware of the challenges of the low wind speed and air pockets in between existing tall buildings, which complicate the basic requirement for indoor comfort, namely, adequate ventilation [12].

2. Materials and Methods

This research started by exploring the natural ventilation strategies present in vernacular Malaysian architecture, comparing it with modern social housing [4]. Here, we propose the introduction of a new design standard for high-rise social housing, named the 'airhouse' standard. Two traditional houses (TMH) were analysed and compared with PPR first-generation housing units located at levels 1 and 10. Two common areas, the living room and kitchen area, were selected. The air temperature and humidity in both buildings was similar, but the air movement was dramatically different: 1450.3 L/s (1.45 m/s) in the vernacular house and 31.7 L/s (0.03 m/s) in the modern building.

The standard focuses on passive measures, which could be incorporated within the building fabric. The size and location of opening areas are two key factors that can allow air to enter the building and to enhance its movement. The 'airhouse' standard proposes that the percentage of openings in the building façade should be more than 15%, depending on the height of the residential units, increasing or decreasing the area depending on the height of the residential unit. In order to enhance air movement and cross ventilation, a full-height opening configuration with three elements (main window, fixed louvres, and adjustable louvres) is also proposed. Fixed louvres are introduced at the upper level of the internal walls to allow air to circulate throughout the units at all times time. The proposed standard also suggests that the depth of rooms should be decreased to enhance cross ventilation and that overhangs should be provided to protect all windows from solar radiation. This initial research has proven that an appropriate envelope and plan layout configuration could assist in successfully increasing the indoor air movement rate and significantly reduce energy consumption, as well as carbon emissions. Based on all the results defined in the research, the initial design considerations of the 'airhouse' standard were established (Table 1, Figure 4).

Table 1. Design conditions of the 'airhouse' standard (2012) for naturally ventilated buildings.

Recommended Parameters	Airhouse Conditions
Air Temperature	25–27 °C
Relative Humidity (RH)	30–60% RH
Air Movement	0.30–1.5 m/s
Energy Consumption	<5000 kWh/year
Carbon Emissions	<2500 $kgCO_2$/year

Figure 4. The unit plan layouts for the People's Housing Programme (PPR) first-generation units (**left**) and the new proposal for the 'airhouse' standard (**right**) [4].

After a preliminary study of ten high-rise social housing developments across Kuala Lumpur, the research continued by gathering in-situ data to evaluate the actual comfort and health conditions in the existing, recently built, high-rise social housing buildings in Kuala Lumpur in detail. Two cases were considered, namely, the PPR Beringin, first occupied in 2004, consisting of six blocks of 18 and 15 storey height, with 1896 units in total (316 units per block). The design of each block includes two large open atriums in each block to provide natural lighting and ventilation into inward rooms, and a row of residential units abutting to a corridor (Figure 5). The windows are single-glazed glass louvres. Three units in block C were selected, located at level 1, level 10 and level 17, representing lower, intermediate, and upper parts of the block, and different conditions of obstructions (Figure 6).

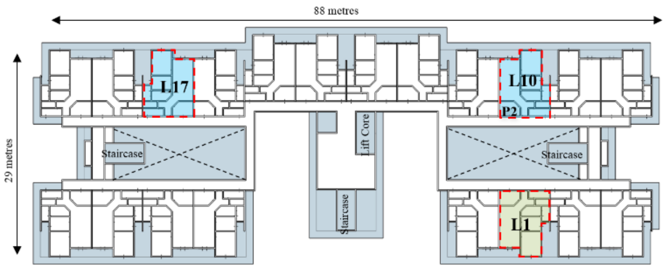


Figure 5. Typical floor plan of the PPR Beringin (First Generation).

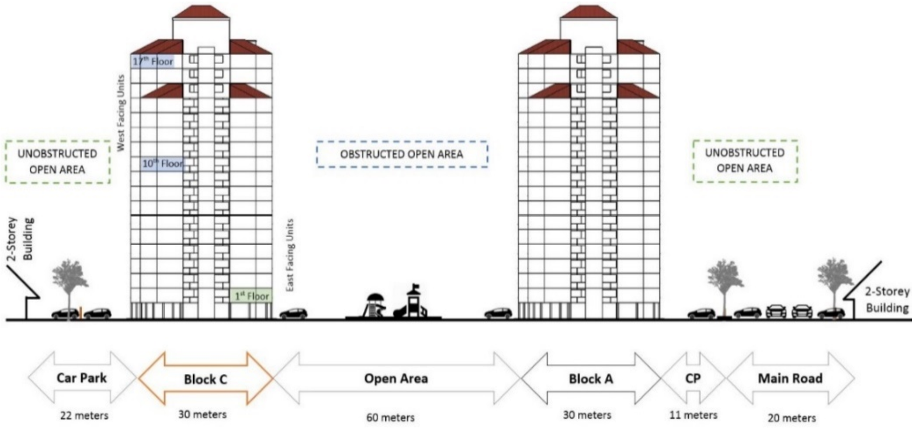


Figure 6. Site section of the PPR Beringin.

The PPR Seri Aman, from the second generation of the PPR, was completed in March 2017 and currently accommodates approximately 1560 units in 4 blocks of 20 and 19 storey height. This second-generation consists of two rows of residential units abutting to a corridor, with an enclosure setting environment compared to the previous design. In contrast to the PPR Beringin, lightwells are the main source of natural lighting and ventilation for the bedrooms, kitchens, and bathrooms facing towards the corridor (Figure 7). The building has single-glazed casement windows. Six house units were selected in block A to represent the block's lower, intermediate, and upper zones. Three of the units are facing unobstructed open areas and another three are facing an obstructed open area (Figure 8).

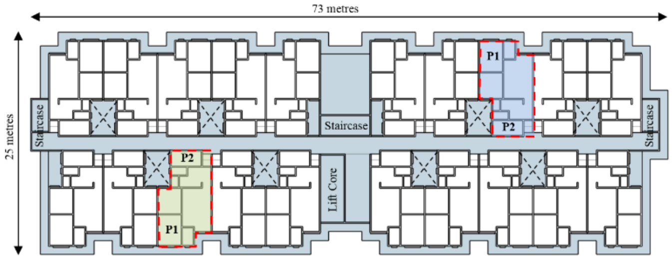


Figure 7. Typical floor plan of the PPR Seri Aman (a second generation building).

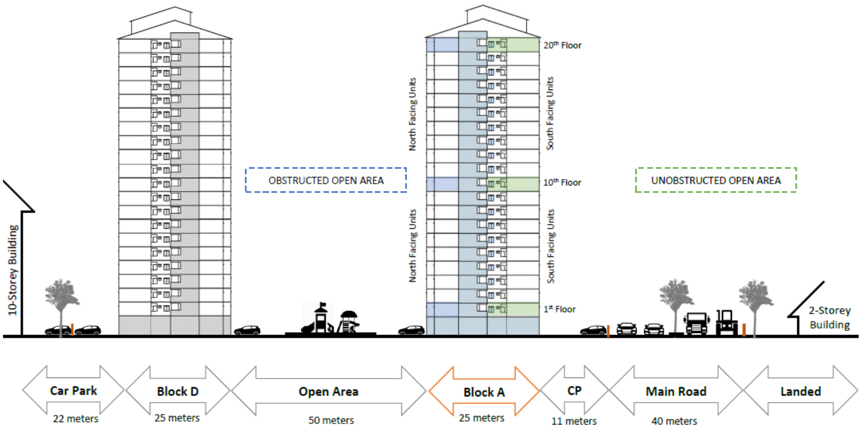


Figure 8. Site section of the PPR Seri Aman.

The existing relevant regulations, standards, and the green rating tools used in Malaysia were studied and compared [3]. In Malaysia, the standard that sets the indoor design conditions for air temperature, relative humidity, and airspeed is MS1525. Unlike the CIBSE and ASHRAE standards, these design conditions are for air-conditioned spaces only. Figure 9 shows the comfort zone (green area) for Kuala Lumpur on a psychrometric chart, according to ASHRAE 55 and CIBSE guide A, in relation to MS1525. This zone is the benchmark for the study and is used for future comparison in this research. In accordance to it, the comfort criteria in Kuala Lumpur are an operative temperature between 24–28 °C, 40–70% relative humidity, and a 0.15–0.50 m/s airspeed [13,14] (Table 2). For air quality, the World Health Organization (WHO) has set annual limits: PM10 < 20 μg/m^3 and PM2.5 < 10 μg/m^3. For a 24 h period, the limit for PM10 is 50 μg/m^3 and PM2.5 is 25 μg/m^3 [15]. CO_2 is one of the parameters measured, and the limits for the gas, according to CIBSE KS17 and the Department of Environment in Malaysia (DOE), are 5000 ppm and 1000 ppm, respectively. The DOE's limit is to indicate the adequacy of ventilation in any particular room. Hence, readings above this limit show an indication of inadequate ventilation [16]. CO, another gas measured in this study, has different limits set by CIBSE, ASHRAE and the DOE, which are 26 ppm, 35 ppm and 30 ppm, respectively.

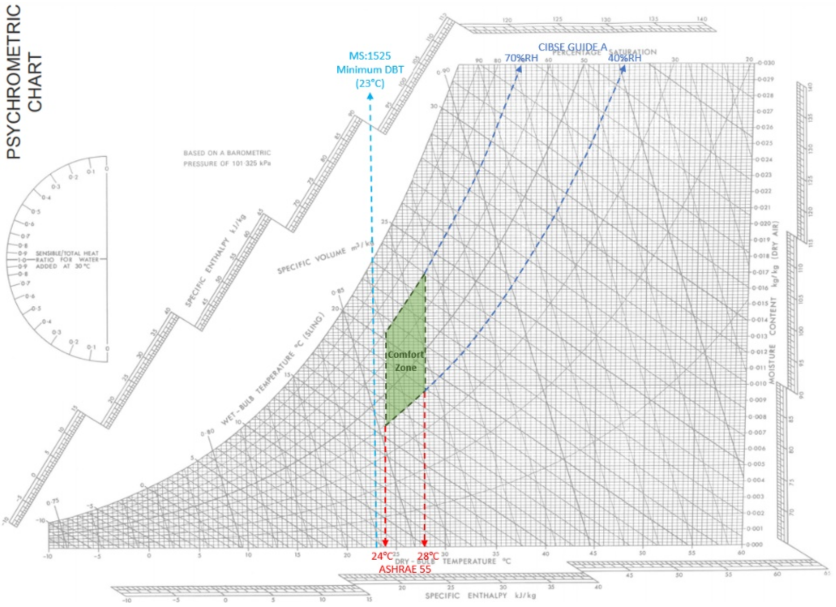


Figure 9. Kuala Lumpur’s comfort zone on the psychrometric chart.

Table 2. Parameters, ranges and limits for fieldwork study.

Parameters	CIBSE Guide A (2015)	ASHRAE 55 (2013)	MS1525 (2014)
Recommended Thermal Comfort Criteria			
Operative Temperature	24.7–28.7 °C	24.0–28.4 °C	24–26 °C
Relative Humidity	40–70% RH	<65% RH	50–70% RH
Air Speed	0.15–0.50 m/s	0.15–0.80 m/s	0.15–0.50 m/s

The methodology used in assessing comfort in the indoor environments follows the ASHRAE Standard 55 ('Thermal Environmental Conditions for Human Occupancy') recommendations [14] (Table 3). The measuring conditions during the cooling period (summer conditions) have been used due to the local hot and humid climatic conditions. There were two campaigns of fieldwork in the two case studies and a computational simulation model. The first fieldwork was carried out between the 11th and 29th of July, 2017, when the southwest monsoon was active. This monsoon runs from May to September every year and provokes relatively dry weather, with an average prevailing wind speed (coming from the southwest) usually below 15 knots (7.7 m/s) [17]. Carrying out the necessary fieldwork during this dry season is highly recommended, due to the high temperatures which usually occur in this period every year. The fieldwork was carried out during the two main seasons (dry and wet) in Malaysia, so they do not represent the whole-year thermal comfort data of Kuala Lumpur. Therefore, simulation modelling using Integrated Environmental Solutions (IES) was used to evaluate the full-year data. This affordable software is suitable for simulating naturally ventilated buildings through its 'Macroflo' and 'Apache' modules for the detailing of the building systems, simulating and calculating the environmental conditions of a 3D model. For air quality, simulation software that could look at the concentration of air pollution substances (i.e., CO, SO_2, benzene and particulate matter) was not available yet. Thus, the fieldwork results (indoor and outdoor conditions) and the full-year data of air quality in Kuala Lumpur (outdoor conditions only) were used for further comparative purposes [18].

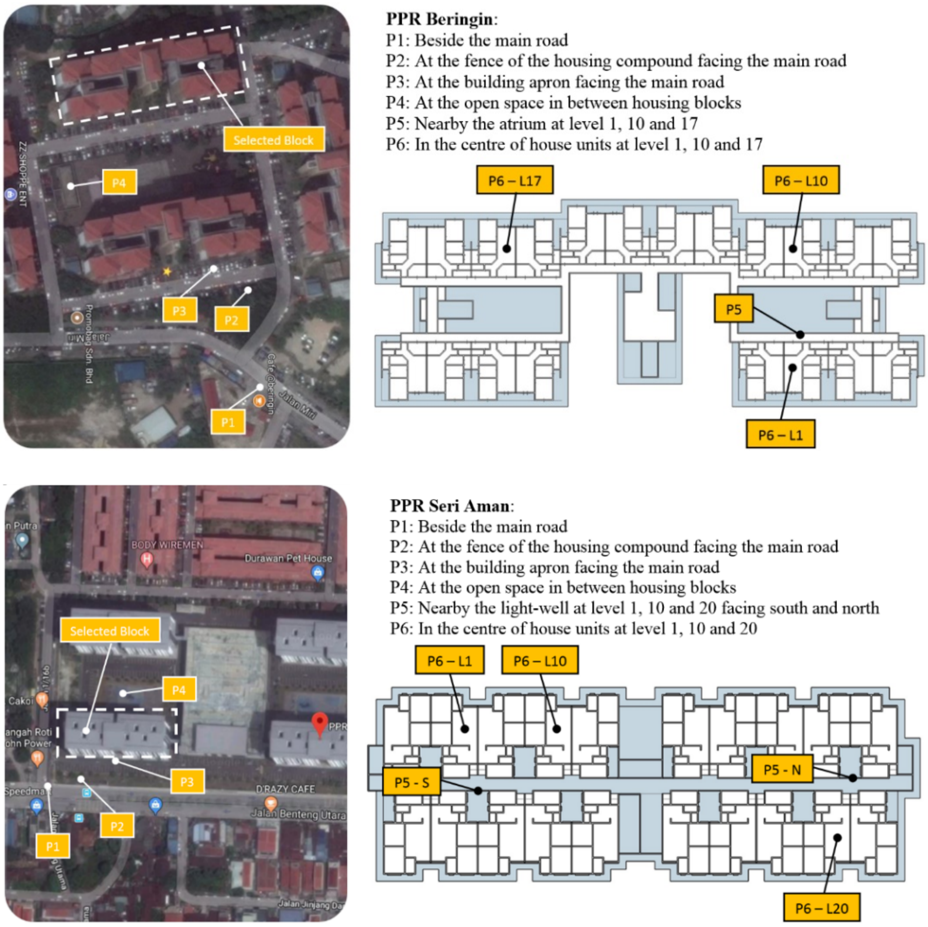
Table 3. Evaluation of thermal environment in accordance with ASHRAE 55 (Thermal Environmental Conditions for Human Occupancy).

Parameters	ASHRAE 55 Recommendations	
Measuring Device Criteria	Meet the requirements in ASHRAE Standard 70 or Standard 113 or ISO 7726	
Measurement Positions		Location of Measurements:
	a.	In occupied zones—where the occupants are known to spend their time, OR
	b.	In unoccupied rooms—an estimate of the most significant future occupant locations within the room, OR
	c.	If occupancy distribution cannot be estimated—in the centre of the room
		Height Above Floor of Measurements:
	a.	Operative temperature—at the 0.6 m level for seated occupants and 1.1 m level for standing occupants
	b.	Airspeed—0.1, 0.6, and 1.1 m levels for sedentary occupants
	c.	Humidity—shall be measured at 0.6 m high from floor level for seated occupants
Measuring Periods	a.	Temperature—minimum 3 min to 15 min to average cyclic fluctuations
	b.	Airspeed—for determining the average airspeed at any location shall be three (3) minutes
Measuring Conditions	a.	Test during the cooling period (summer conditions)

For air quality, the methods for monitoring indoor air quality (IAQ) follow those set by the WHO, where the two main types of samples are gases and particles [19]. The minimum duration of air quality sampling is 48 h, and, therefore, this study has taken the measurement for 54 h, specifically, three days in the weekend and weekdays. The sampling period was only for 18 h a day, specifically, from 6 a.m. to midnight. From midnight to 6 a.m. it was not possible to take measurements due to safety factors and the privacy of occupants.

Four types of equipment were used to measure the thermal comfort parameters (air temperature, operative temperature, relative humidity, and airspeed) and two types of equipment were used for the IAQ parameters (PM10, PM2.5, CO_2 and CO). The data were logged manually, but the accuracy of the data recorded is reliable [20]. The instruments used for thermal comfort evaluation in the first fieldwork were Tiny Tag Ultra 2, Kimo AMI 310, and Aercus Instruments WS1093. The TinyTag Ultra 2 can monitor the temperature and humidity with ranges between −25 to 85 °C and 0 to 95% RH, respectively. For internal and incoming airspeeds, the Kimo AMI 310 and Aercus WS1093 measure airspeeds at ranges of 0 to 44 m/s. Two types of direct-reading instruments for IAQ evaluation were used: The Fluke 975 Airmeter, to measure the CO_2 and CO, and the HoldPeak SD-5800D, to monitor PM10 and PM2.5. The Fluke 975 Airmeter can monitor the CO_2 and CO gases in a a range between 0 to 5000 ppm and 0 to 500 ppm, respectively. For the PM10 and PM2.5 monitoring tool, the concentration ranges for both substances are similar, namely, between 0 to 999.9 µg/m3.

Two campaigns of fieldwork were carried out to measure the actual thermal and air quality conditions in the two selected social housing settings in Kuala Lumpur, in accordance to the methods and parameters described above. For the unoccupied spaces, the location of the instrument was at the centre of the room or space. In the cases of the PPR units, bedrooms are the best data gathering locations for occupied and unoccupied units, since the majority of the occupants work during the day and spend most of their remaining time resting and sleeping (Figure 10). Four outdoor locations were determined which are beside the main road (P1), at the fence of the housing compound or buffer zone (P2), at the sample block's apron (P3) and at the open space in between the blocks (P4). For indoor and semi-indoor locations, two points were selected which are near the atrium areas (P5) and in the centre of the house units (P6).



PPR Beringin:
P1: Beside the main road
P2: At the fence of the housing compound facing the main road
P3: At the building apron facing the main road
P4: At the open space in between housing blocks
P5: Nearby the atrium at level 1, 10 and 17
P6: In the centre of house units at level 1, 10 and 17

PPR Seri Aman:
P1: Beside the main road
P2: At the fence of the housing compound facing the main road
P3: At the building apron facing the main road
P4: At the open space in between housing blocks
P5: Nearby the light-well at level 1, 10 and 20 facing south and north
P6: In the centre of house units at level 1, 10 and 20

Figure 10. Locations of the outdoor, semi-outdoor, and indoor measurement points in the PPR Beringin and PPR Seri Aman.

Following the fieldwork, an environmental simulation using IES Virtual Environment (IESVE) software was carried out to assess the comfort conditions of the PPR second-generation block for a full year in detail, as the PPR first-generation has now been terminated by the Malaysian government. The main objective of this simulation was to establish the average operative temperature (OT) and relative humidity (RH) in the building over a full year. The three levels defined in the fieldwork (1, 10, and 20) were also used in the simulation model to represent the lower, intermediate, and upper levels of the PPR block. At each level, two housing units were also selected, one facing the north (unobstructed open area) and the other the south (obstructed open area). The results gathered from the fieldwork and computer model were then compared, informing the selection of the most suitable system to test.

The system was selected by considering its capabilities in addressing the four major issues of thermal comfort and indoor air quality without neglecting the criteria of low cost, low energy efficiency, and low carbon emissions. A series of experiments were carried out using a reduced-scale physical model to test the performance of the new proposed system. These experiments completely evaluated the system by taking into account the main parameters of thermal comfort and indoor air quality in urban contexts, such as the temperature, humidity, airspeed (and airflow rate) and particulate matter. The results in these experiments were compared to discover the effectiveness and readiness of the system in addressing the thermal and air quality issues using different materials and additional elements added. Computational simulations took place after that to determine the system's energy consumption and carbon emissions. The final stage involved the analysis and evaluation of the results.

3. Results

3.1. Fieldwork Results

The first fieldwork study assessed thermal comfort and found that the operative temperature (above 29 °C) and relative humidity (above 70%) in the case studies have firmly surpassed the limits set by the established standards (Table 4). Among the factors that cause this to happen were the presence of human activities and closed-environment setups (using curtains, blinds, etc.) that also significantly reduced the airflow rate in the house samples [21]. Without using fans, the average internal airspeeds were recorded to be very low, even almost no air movement at all. Considering that the standard flat layout is single-sided, with cross-ventilation driven by ambient air movement, this is not a particularly effective technique for providing evaporative cooling. Here, different façade-facing obstructions produce different indoor thermal and air quality conditions (Figure 11).

Table 4. Fieldwork study 1 findings.

Case Studies	Mean Operative Temperature (OT, °C)	Mean RH (%)	Mean Indoor Airspeed (m/s)
PPR First-Generation	29.0	73.7	0.0
PPR Second-Generation	29.3	70.1	0.1
IES Baseline Simulation	29.1	66.4	-
ASHRAE 55 Ranges	24.0–28.4	<65.0	0.15–0.80
CIBSE Guide A	24.7–28.7	40–70	0.15–0.50

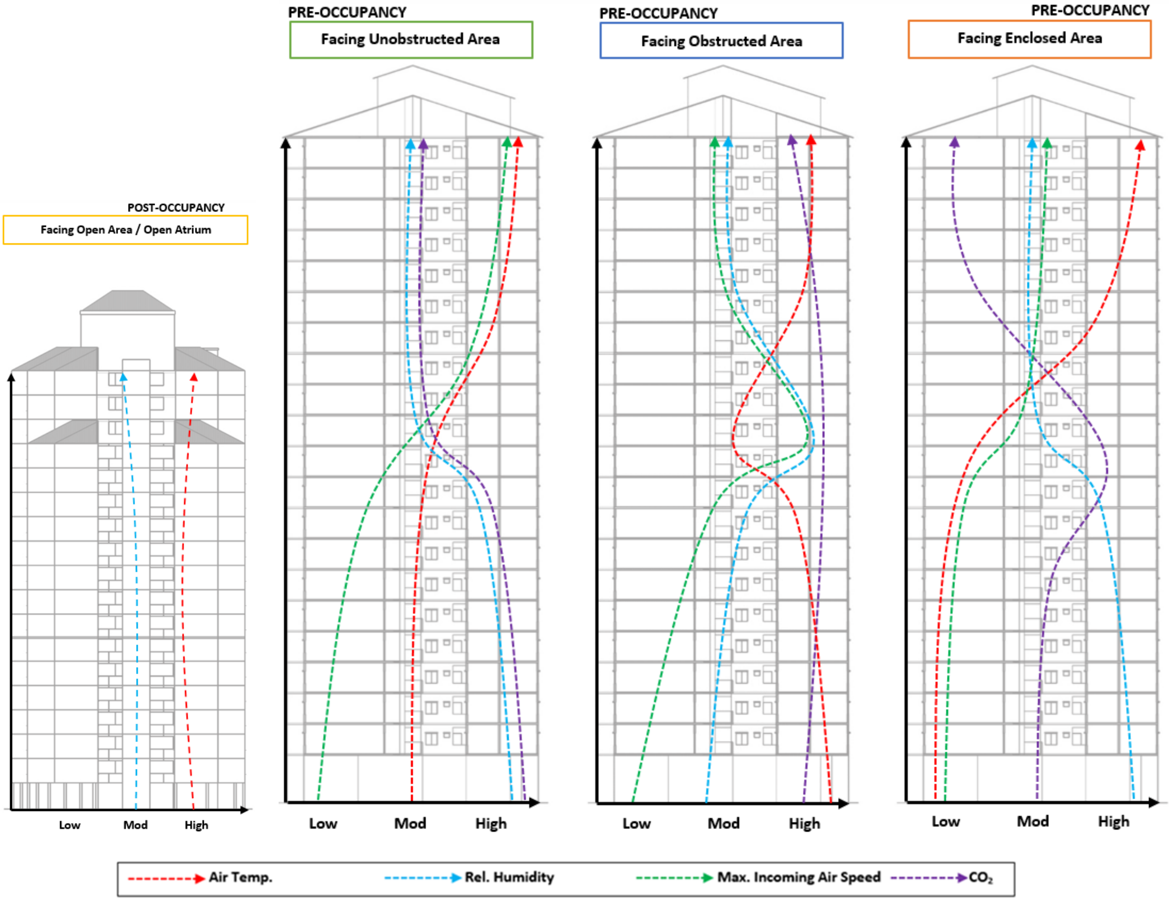


Figure 11. The identified four different environmental conditions zones in the PPR Seri Aman and PPR Beringin.

The second fieldwork study evaluated indoor air quality and found that the average PM10 and PM2.5 concentrations in indoor spaces in the PPR second-generation housing were high (53.5 µg/m3 and 44.2 µg/m3, respectively), surpassing the WHO 24-h limits (Table 5). This is due to the compact plan layout in the building, as it includes lightwells. This layout decreases the air movement in comparison with the PPR first-generation housing, which has a more open layout with two large atriums, substantially reducing the PM10 concentrations. The CO_2 concentrations were still below the limit of 1000 ppm set by the Department of Occupational Safety and Health in Malaysia (DOSH) [16]. This suggests that the CO_2 concentrations in indoor spaces in both PPR housing generations were at moderate levels (circa 500 ppm), indicating signs of inadequate ventilation in these buildings.

Table 5. Findings of the second fieldwork study.

Case Studies	Mean PM10 (µg/m3)	Mean PM2.5 (µg/m3)	Mean CO_2 (ppm)
	Indoor (Outdoor)	Indoor (Outdoor)	Indoor (Outdoor)
PPR 1st Generation	25.6 (31.5)	29.2 (36.3)	590 (498.4)
PPR 2nd Generation	53.5 (49.9)	44.2 (42.3)	600 (529.9)
WHO Limits (24 h)	50.0	25.0	1000 *

* Department of Occupational Safety and Health (DOSH) Malaysia [16].

As in all PPR housing, the bedrooms in these buildings were initially designed to be naturally ventilated. During the fieldwork study, it was clear that this was not the case now. All the bedrooms were supposed to have single-sided ventilation, but the occupants have installed curtains and blinds, and thus, changed the performance of the spaces. Ceiling fans, in most cases, were periodically switched on to provide air movement in these rooms. Bedrooms facing the atrium at level 10 in PPR first generation housing were using the air conditioning system for several hours at night. These changes and uses are among regular additions, modifications, and adaptations made by the residents after occupation.

3.2. Computer Modelling and Comparison

The simulation modelling using IES Virtual Environment (IESVE) software confirmed that the actual climatic conditions in Kuala Lumpur are not able to create the right comfort by natural means in indoor and outdoor spaces as required by the established standards. In a year, approximately 70% of the time, the operative temperature in indoor spaces in the PPR second generation housing is above 28 °C, and 85% of the time the relative humidity is above 65% RH. The simulation has also confirmed that the RH in inward-facing rooms and lightwells is high, especially at levels 1 and 20. There is a weaker stack effect in place inside the light-wells. The average operative temperature and relative humidity in PPR second generation housing is in accordance to the simulation, namely, 29.1 °C and 66.4% RH, respectively (Table 6). The temperature is similar to the results from the fieldwork and still surpasses the ASHRAE and CIBSE requirements. The RH is slightly lower, but still in the higher range of the requirements.

Table 6. Fieldwork studies and IES 1 results for the PPR second generation housing.

PPR Second-Generation	Mean OT (°C)	Mean RH (%RH)
Ranges	24.0–28.4 [1]	40.0–70.0 [2]
Fieldwork Studies (1 and 2)	29.3	70.1
IES Simulation 1 (Full-year)	29.1	66.4

Note: i. [1] ASHRAE 55, [2] CIBSE Guide A.

The fieldwork studies and simulation identified the four issues that need to be addressed in achieving indoor comfort in high-rise social housing buildings in Kuala Lumpur: (1) Reducing the air temperature, (2) reducing humidity, (3) filtering airborne particles, and (4) providing adequate and constant air movement.

3.3. Physical Model Experiments

The idea of permeable buildings is common in traditional vernacular Malay houses, which have been used for hundreds of years, achieving thermal comfort in the tropical environment [4]. However, these are mainly individual dwellings made out of timber, with all the building elements exposed to the exterior, which is a very different configuration than in the case of high-rise housing. Inspired by the strategies present in vernacular architecture, a predominantly natural/hybrid ventilation system located in the ceiling compartment was considered, which allows a deeper penetration of air within the flats. The use of dynamic insulation (DI) was identified to have potential in solving the four issues mentioned above, as it allows a constant air stream to be delivered through an insulation matrix above an air-permeable ceiling. DI makes use of a fan to suck the fresh air into the room through the porous insulation, which also filters particles, heat, and moisture [22]. Having hybrid ventilation and a filter membrane in its system, the four indoor comfort issues highlighted could possibly be solved using this strategy

DI also has the additional advantage of providing a large volumetric filter membrane that can filter air pollution [22] and at the same time filter heat and moisture [23,24]. Two tests, using a physical model, have been carried out to evaluate the new proposed DI system, called the ‘dynamic hybrid air-permeable ceiling’ (DHAPC) (Figure 12).

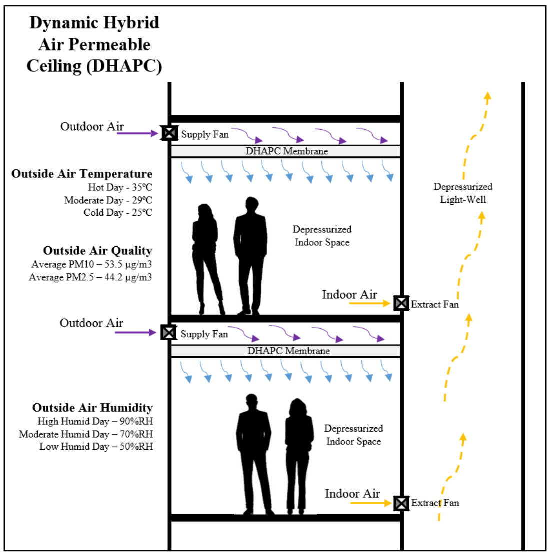


Figure 12. Dynamic hybrid air-permeable ceiling (DHAPC) schematic design in a high-rise building (not to scale).

The ceiling was identified as the most suitable element to integrate the system in the already-built high-rise buildings due to the availability of surface and enough floor to ceiling height to integrate the system. The basic concept of the system is the supply of hot and polluted air into the room through the ceiling compartment of the housing units. The air is sucked into the ceiling compartment by a supply fan, filtered by a membrane, and dispersed equally throughout the depressurized indoor spaces before the air is taken out to the depressurized lightwell using an extraction fan (Figure 12). From the fieldwork, we have found that the naturally ventilated lightwells create a short circuit of airflow, which contributes to high moisture at lower levels [21]. The large ceiling surface contributes to a better air distribution and a reduction of clogging problems of the filter membrane. DI has so far been implemented mainly in advanced applications using directional airflow, for example in healthcare and electronic facilities, known as ‘cleanrooms’ [25]. We have considered its potential application in high-rise social housing buildings in Kuala Lumpur.

A reduced-scale model of the actual master bedroom in PPR second generation housing was built on a 1:5 scale. The model had three compartments, reproducing the different environments and elements, namely, the outdoor chamber, the DHAPC, and the indoor space (Figure 13). The outdoor chamber compartment tried to reproduce the average outdoor thermal and air quality in Kuala Lumpur during daytime and night-time in the dry season. The condition ranges used were based on the first and second fieldwork studies done by the authors, as described above. The overall form of the test model was a straight duct, equipped with a high-efficiency particulate air (HEPA) filter in the DHAPC compartment, as recommended by ASHRAE 52.2 and EN779. Instruments to measure indoor comfort were placed in the outdoor compartment and indoor space compartment during the test.

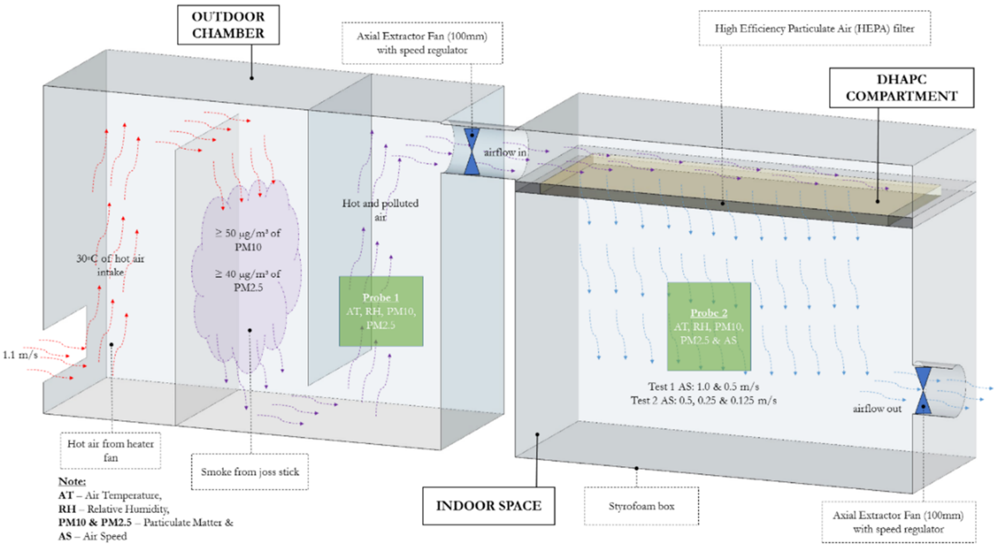


Figure 13. Theoretical dynamic insulation (DI) model concept.

Two tests of the DHAPC system were carried out using this model, reproducing different types of ventilation, namely, fully passive ventilation, hybrid ventilation, and fully mechanical ventilation. Using three different synthetic insulation materials, test 1 achieved better reduction rates for all four parameters (air temperature, humidity, PM10, and PM2.5) when passive ventilation was applied. However, this ventilation approach solely depends on wind buoyancy pressure, which is unreliable and inconsistent in Kuala Lumpur [3]. The hybrid ventilation protocols with low airspeed have fulfilled three out of the four parameter's requirements set by ASHRAE Standard 55 and the WHO's air quality guidelines. Thus, they were considered suitable options to be studied in test 2.

In test 2, recycled insulation materials and activated carbon (AC) cartridges were added and tested in the system. Using these elements, the air temperature and humidity reduction rates were circa 14%, and for PM2.5 and PM10, the reduction rates were circa 90%. It can be deduced that the lower airspeed of 0.125 m/s could produce better results than in the case of higher airspeeds. The use of this material reduced air temperature and relative humidity, especially when applying hybrid ventilation with recycled glass material, where the reduction rates were approximately 18% and 16%, respectively. AC cartridges, in this test, added approximately 10 to 30% reduction rates for PM10 and PM2.5.

3.4. Computer Model Simulations

Given the above outcomes obtained in the tests, the DHAPC system appears to be a good option for further exploration. However, due to the geographical location of the test site, which was in a temperate climate, the reduction rates for heat and humidity seemed lower (circa 14%) [26,27] than expected (circa 20%). We believed that the reduction rates could be more significant if the tests were conducted in the actual hot and humid climate conditions.

The 'dynamic hybrid chilled beam ceiling' (DHCBC) system was integrated with the main DHAPC system (Figure 14) based on three factors: (1) Smaller space requirements, (2) thermal comfort and air quality performance, and (3) energy saving potential [28,29].

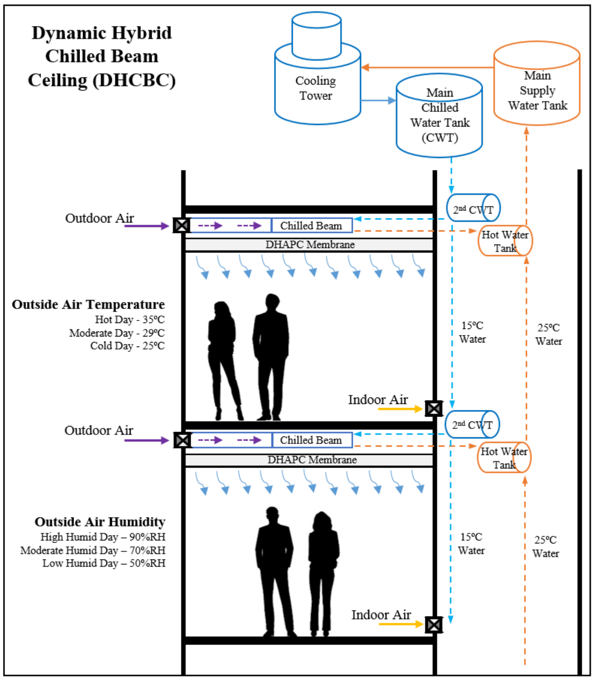


Figure 14. Dynamic hybrid chilled beam ceiling (DHCBC) schematic design in a high-rise building (not to scale).

To further assess the DHCBC system, two computational models were created and analysed. The most accurate model was carried out during the second simulation exercise (Figure 15), which included three housing units located at levels 1, 10, and 20. Four rooms in each unit were included in the simulation, namely, the master bedroom (MB), bedroom 2 (BR2), bedroom 3 (BR3), and the living room-dining area (LR-DN). One lightwell, directly connected to the BR2 and BR3 was also simulated, equipped with an exhaust fan at the top, called the active lightwell (ALW) (Figure 15).

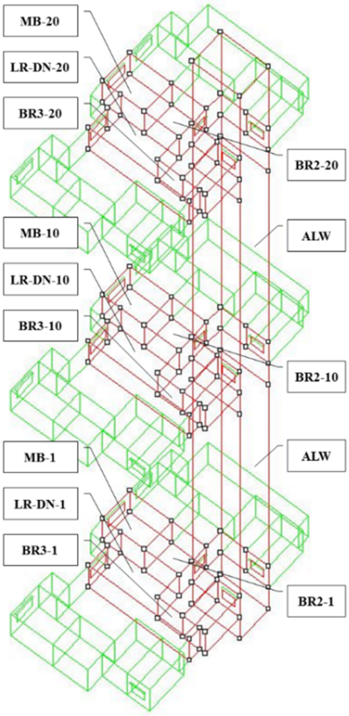


Figure 15. The second simulation model in Integrated Environmental Solutions (IES).

The DHCBC system is able to reduce energy consumption by reducing cooling delivered to the space without the use of parasitic reheating. In addition, cooling is delivered with a chilled-water coil with pumps rather than through air with fans, resulting in additional energy savings. The system introduces coil pipes and aluminium plates into the ceiling void to reduce the average operative temperature to be below 28 °C while suppressing humidity to be below 65%. Considering that the maximum outdoor air temperature in Kuala Lumpur is 35 °C, chilled water at 15 °C is required and circulated in the coil pipes to reduce the air to meet the cooling requirement for the air supply temperature of 25 °C. The optimum combination appears to be 20 °C of supply air temperature at a 30 L/s airflow rate. This combination can significantly reduce the average results of the operative temperature and humidity to be within the lower threshold of the proposed comfort zone. When both systems (DHAPC and DHCBC) are combined together, they produce maximum reduction rates for the operative temperature and humidity of up to 20% and an average power consumption of 1.86 kW (680 kWh/year). Considering that the annual energy consumption for cooling (air conditioning and ceiling fans) in Malaysian housing is 1973.6 kWh/year (29% of total consumption) [28,30], this could represent an overall saving of circa 66% of power consumption for cooling purposes.

4. Discussion

The two fieldwork campaigns have successfully identified the actual indoor comfort deficiencies in high-rise social housing in Kuala Lumpur. Obviously, by allowing outside air circulation, hot and polluted air enters into indoor spaces. In addition, the location of the studied buildings introduce obstructions, hindering air movement. The fieldwork studies have allowed the identification of the four issues that need to be addressed to achieve indoor comfort in high-rise social housing buildings in Kuala Lumpur: (1) The reduction of air temperature, (2) the reduction of humidity, (3) the filtering of airborne particles, and (4) to providing adequate and constant air movement.

Building regulations in Malaysia, especially for high-rise residential buildings, only emphasize natural ventilation strategies. They are only concerned about the proportion of windows (Clauses 39) and size of lightwells (Clauses 40) and do not explicitly consider the health and comfort of the building occupants. The results of the fieldwork clearly indicate that the current building regulations are not adequate to achieve indoor comfort by natural means in these buildings. They should be revised to take into consideration the critical conditions as well as allow for passive and low-energy strategies to constantly provide air movement, reduce the airborne particulate matter, operative temperature, and humidity levels in indoor spaces.

The proposed integrated DHPAC and DHCBC system fitted in ceilings is an initial exploration about possible systems which could help to improve indoor thermal comfort and air pollution in these buildings, also reducing carbon emissions. The two systems could run separately, according to the occupant's needs. The DHAPC, which requires energy for the fans, is the main system and can reduce approximately 16% of heat and moisture and 90% of airborne particles, with a constant airflow rate. The DHCBC is a supporting system to provide approximately an additional 10% reduction in temperature and humidity, so the recommendation would be to use it during the hottest times of the day only.

It is important, however, to note the limitations of the research. First of all, the research has been carried out using a limited amount of data and specific systems have been tested. Although the fieldwork was carried out in Kuala Lumpur, the physical model experiments were carried out in the UK, and, thereafter, their outcomes affected by different climate conditions. Every effort has been made in reproducing the real conditions, but we have to consider the substantial difference in local ambient humidity, where in the UK, RH is between 30% and 50%, whereas in Kuala Lumpur it is between 70% and 90%. Higher reduction rates for humidity could have been achieved if the experiment was carried out in Malaysia.

Occupant behaviour is also a critical issue. While the system is in operation, the spaces should be airtight to achieve the best results, so windows have to be kept closed. There is clear thermal discomfort at the moment in these buildings and three common additional elements (awnings, fans, and air conditioning systems) are commonly installed by the occupants to overcome the problem. It was observed that at the side facing the corridor, occupants tend to install curtains and blinds and shut their windows at all times due to privacy reasons. Even if the windows that face open areas were left opened (with the opening areas reduced by the curtains and blinds), the airflow rate was still inadequate to remove heat, moisture, and particles away from the internal spaces. The PM10 and PM2.5 concentrations in indoor spaces in the high-rise social housing were recorded to be high (53.5 μg/m3 and 44.2 μg/m3, respectively), surpassing the WHO 24-h limits.

As explained above, the first 'airhouse' standard proposal was based on natural ventilation, promoting air movement using passive elements such as opening ratios according to altitude, the hierarchy of opening design and effective plan layout to achieve thermal comfort [4]. The new research explores the use of an integrated strategy of using dynamic insulation with a hybrid ventilation with a radiant cooling ceiling, which could also improve the indoor air quality and active lightwells. In general, all the new results are lower than the previous ones (Table 7). For the thermal comfort conditions, the new recommendation for air temperature is set between 23 to 24 °C, where the previous value was 25 to 27 °C. For humidity, a 5% improvement is suggested, from a maximum of 60% RH to 55% RH, and for air movement, it has been reduced from 0.3 to 1.5 m/s, to a minimum of 0.125 m/s. Concerning indoor air quality, the values for PM10 and PM2.5 should be no more than 1.2 μg/m^3 and 1.0 μg/m^3, respectively. For energy consumption and carbon emissions, the recommendations have been substantially reduced, namely, from less than 5000 kWh/year and 2500 kgCO_2/year, respectively, to less than 700 kWh/year and 200 kgCO_2/year.

Table 7. Comparison of the initial 'airhouse' standard (2012) and the new standard (2019).

Recommendations	Initial 'Airhouse' (2012)	New 'Airhouse' (2019)
Air Temperature	25–27 °C	23–24 °C
Humidity	30–60% RH	<55% RH
Air Movement	0.30–1.5 m/s	>0.125 m/s
PM_{10} Level	-	<1.2 μg/m^3
$PM_{2.5}$ Level	-	<1.0 μg/m^3
Energy Consumption	<5000 kWh/year	<700 kWh/year
Carbon Emissions	<2500 kgCO_2/year	<200 kgCO_2/year
Ventilation Approach	Natural	Hybrid
Tandem Strategy	Hierarchy of Openings	Active Lightwell

The series of physical experiments and computational simulations demonstrate that DHAPC is capable of filtering heat, moisture, particulate matter, and toxicant gases, while DHCBC can further reduce air temperature and humidity. As a result, cool and clean air could be supplied into indoor spaces with a constant and adequate airflow rate. This result will improve indoor comfort and air quality and solve the problems of indoor discomfort and indoor air pollution. However, even though this research has combined both physical and computer modelling, the validation of the system should be done using prototypes in actual hot-humid climatic contexts.

The system could be fitted not only in new buildings but also in existing ones. It requires a minimum depth of 600 mm at the ceiling space, which is presently available. Although the UBBL (Clause 44, 1a) sets 2500 mm as the minimum height of living rooms and bedrooms [5], they have commonly been built higher, usually between 3000 and 3500 mm, in order to allow ceiling fans to be installed, as they are considered as a basic requirement in buildings in Malaysia. However, all the buildability issues and implications of the system need to be taken in account and carefully consideration has to be given to fire control and maintenance aspects. It should also be noted that the energy savings obtained were simply estimated by calculating the electricity consumption of a chilled water loop system with supply and extract fans employed in a number of rooms only. A very detailed analysis of the electricity consumption and its potential savings is a very significant task, given the large number of variables involved. In this regard, this task was considered beyond the scope of the present study.

Fans would need to be provided for supplying cool, clean, and constant air into indoor spaces and to assist the removal of the air efficiently inside the lightwell, consuming energy and producing emissions. Fans also require extensive maintenance, in particular, the DHAPC system's fans, ducts, and filter membranes, which, considering the pollution levels in Kuala Lumpur, would need to be cleaned at least every six months in the case of the fans and every year for the ducts to ensure hygienic levels. Consideration has to also be given to the cleaning and disposal of the filter membrane and the contaminants deposited in it.

Overall, this is an additional system to be added to the building, and it can be added in any building, however, the priority should always be the adequate location, design, and construction of the buildings, so that the air movement is enhanced, maximizing the specific conditions found in high-rises. Computer models can assist the design in a very effective way to improve the air movement inside the lightwells, as this is an issue that we have identified to be problematic. However, computer modelling software needs to be refined and calibrated in accordance to fieldwork to achieve maximum accuracy. As we have seen, the temperature in the computer simulation (29.1 °C) was slightly lower than in the actual building. What seems to be more critical is the RH (66.4%), which is almost 4% less than in the actual building. This difference can make a substantial impact in the comfort of the residents.

The integration of dynamic insulation with a chilled beam ceiling system has potential to reduce air temperature, humidity, and airborne particles, as well as to provide a constant airflow rate in a typical social housing unit in tandem with active lightwells. More research needs to be carried out in order to implement this or similar systems and considering all the critical issues mentioned above.

5. Conclusions: Towards the 'Airhouse' Standard

Current building regulations and existing design practices have failed to achieve the required environmental conditions for health and comfort in high-rise social housing buildings in Kuala Lumpur and they need to be revised. At present, building's occupants have to increase the amount of mechanical ventilation to achieve cooling shortly after they occupy the building. This research has assessed the existing situation in situ and investigated a possible energy-efficient system that can reduce air temperature and humidity, as well as provide an adequate airflow rate. It is only the first attempt of looking for solutions to produce more sustainable and healthier buildings.

To achieve indoor comfort conditions (thermal and air quality) in high-rise social housing in Kuala Lumpur, the actual conditions in the buildings, including the users' behaviour, should be further studied. Various systems could be designed to improve the current conditions, but they can be costly and high maintenance. Software for integrated building design and simulation tools should be used to consider the various options available.

As we have mentioned above, Malaysia has committed to reduce 45% of its carbon emissions by 2030. The mechanical and electrical cooling equipment in buildings, largely retrofitted by the occupants, are the greatest contributors to the emissions. A more appropriate and sustainable ventilation design that achieves adequate thermal and air quality conditions in these residential buildings, in particular for high-rises, that can be monitored and adjusted by the occupants, is critical to reduce carbon emissions and to mitigate climate change, ultimately refining a more specific 'airhouse' standard.

New design strategies and systems are required to deal with these issues of indoor discomfort in urban areas, at both building and urban levels. The first priority should be the reduction of pollution at the urban level so that buildings can be naturally ventilated as much as possible. This can only be made possible by addressing the challenges of dense urbanization and industrialization that cause global warming, which is even more critical in Malaysia because the scarcity of urban land areas [31].

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