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Microclimate Change Outdoor and Indoor Coupled Simulation for Passive Building Adaptation Design

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Abstract

How to deploy passive building design strategy adaptive to climate change scenarios at urban neighbourhood level is currently not well understood. A microclimate change outdoor and indoor coupled simulation assessment framework for passive building adaptation design in an urban neighborhood context is proposed. Based on computational modelling, it was developed to investigate summer overheating and to apply to a passive design strategy in an existing green building case study, taking into account the seasonal conditions in 2012 and 2050 as projected by a current climate change scenario. Through a series of numerical modelling and prognostic visualization, the results from applying the framework show how building indoor thermal performance interacts with specific outdoor microclimates. This study shows the importance of outdoor and indoor coupled assessment at microclimate level to deploy passive design features to changing climate.

Selection and Peer-review under responsibility of the Program Chairs.

Keywords: microclimate change simulation; outdoor and indoor coupled simulation; passive building design; climate change adaptation design; building energy performance; thermal comfort

1. Introduction

It is well-known that urban microclimate is a result of the interaction among the surrounding physical contexts such as urban geometry and skins [1]. Zooming into a single urban neighbourhood, a specific microclimate is formed by its' own physical environment with unique characteristic. In this respect, we are in a city but we are not living in the same microclimates.

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The science of climate change as we understand it today predicts global warming the decades to come [2]. Of the main contributors to accelerate the climate change with greenhouse gas emissions, built environment is responsible for about 25-40% of the total emissions and 40-90% of these emissions are related to operational energy use within building [3,4].

The continuous global warming and climate change affect urban microclimate and it may have some impact on indoor environmental condition and energy performance to maintain indoor thermal comfort [5]. Especially, the performance of buildings is substantially influenced by the exposed microclimate condition during their long life time: it implies that building design needs to consider current and future performance with an aim of adaptation and resilience towards microclimate change [6].

Therefore, the outdoor and indoor coupled assessment at the same time at microclimate level is not new. Flor and Dominguez investigated a clear interaction between microclimate and the surrounding building performance through assessing the modification of climatic variables in an urban context and the influence on the building performance [7]. More recently, Bouyer et al. showed an integration of a building thermal model into the microclimate simulation platform to improve building energy simulation [8].

This paper reports on an initial study of how to deploy passive building design strategy adaptive to climate change scenarios at urban neighbourhood level which is not well understood. To investigate the interaction between them, a microclimate change simulation framework is proposed, showing a series of numerical modelling and prognostic visualization (section 4). It is conducted to show an impact of recent (2012) and future microclimate change (2050) on an existing green building in the University of Sheffield campus as a case study. In addition, a passive building adaptation design strategy in response to the projected microclimate change is conducted. Also, the energy demand to maintain indoor thermal comfort is calculated. Before carrying out the microclimate change modelling tasks, to confirm the methodological appropriateness of the simulation framework and to apply it into passive building adaptation design, a likely performance comparison between simulation result and historical monitored data is presented (section 3).

2. A Microclimate Change Simulation Framework

Figure 1 shows a proposed microclimate change simulation framework from city to building level. First of all, it is to inform climate change weather condition at urban level, considering a present projection of climate change scenario, HadCM3 A2, UK Met Office Hadley Centre general circulation model predictions for a 'medium-high' emissions scenario [9,10,11]. Secondly, the projected urban climate change is simulated at neighbourhood level to generate specific microclimate information. Finally, under the extracted microclimate change condition, building performance is assessed for passive building adaptation design in response to the projected microclimate change scenarios at building level.

The current framework is implemented by using a number of software tools, including CCWorldWeatherGen [12], Envi-met [13] and DesignBuilder [14]. Figure 2 presents a workflow of the proposed framework. A key idea of this workflow is to allow data flow from outdoor microclimate change projections to building indoor environmental performance simulations. The workflow can be applied interactively to test passive building adaptation design strategies under microclimate change scenarios.

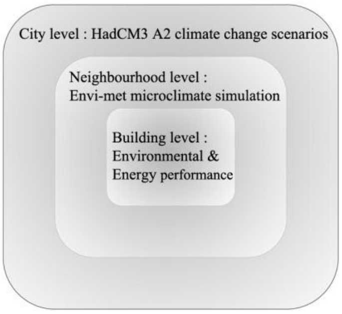

Figure 1. A proposed microclimate change simulation framework from city to building level.

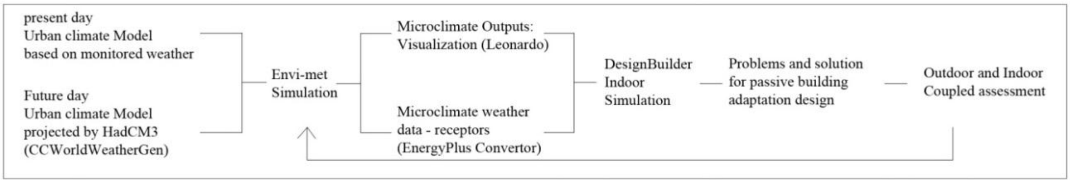

Figure 2. A workflow implementing the microclimate change simulation using CCWorldWeatherGen, Envi-met and DesignBuilder.

3. Applying the Framework to the ICoSS Building: A 2006 Study

To evaluate the above simulation framework and workflow, we carried out a real building case study using the ICoSS building datasets generated by a research team in 2006 [15]. The ICoSS datasets include indoor air temperature, daylight, solar gains and overheating period.

3.1. The ICoSS Building

Designed and built in 2004 as a naturally ventilated office building, the Interdisciplinary Centre of the Social Science (ICoSS) has a south-facing fully glazed façade and atrium where overheated air is released to the ventilation placed on the top floor to drive a passive stack effect vertically and act as a thermal collector (Figure 3) [16]. Moreover, to moderate the overheating problem, automated roller blinds, controlled by a Building Management System (BEMS), are equipped on the south glazed façade.

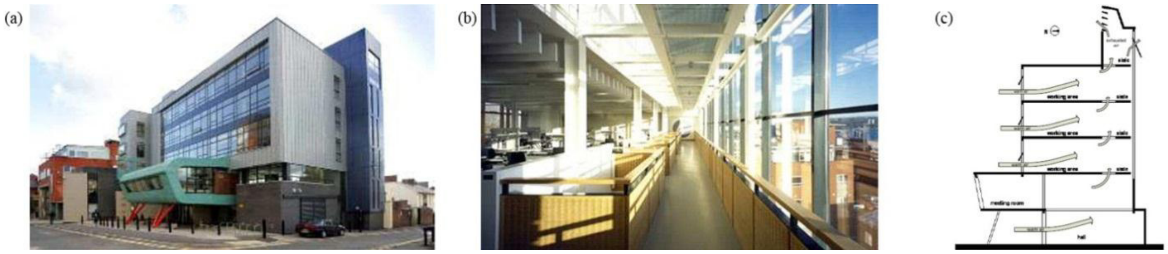

Figure 3. The ICoSS building study: (a) north-facing entrance view, (b) internal south-facing glazed façade, (c) section showing the natural ventilation scheme.

The 2006 post-occupancy evaluation shows that the ICoSS building was overheated despite it is located in a temperate climatic zone (Sheffield, England) and is equipped with a BEM system controlling the roller blinds on the south façade [15]. In the following subsections, we present a comparison of an outdoor-indoor coupled environmental simulation and the monitored building indoor data of 5 May 2006.

3.2. ICoSS Neighbourhood Microclimate Condition

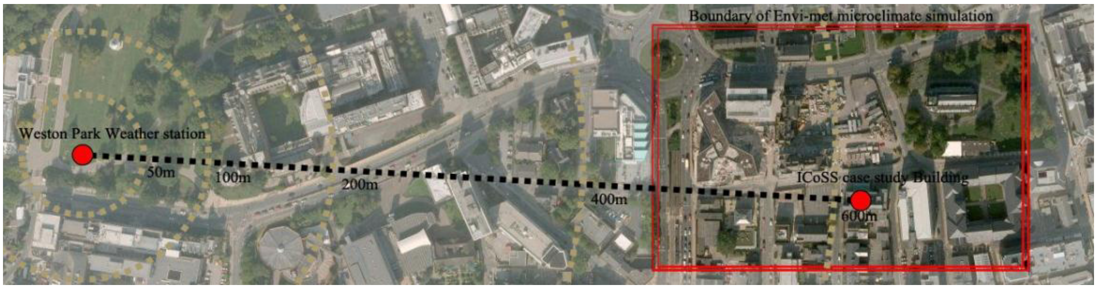

Figure 4. Locations of the Weston Park weather station and the ICoSS building and the boundary of Envi-met microclimate simulation.

To extract ICoSS neighbourhood microclimate condition, Envi-met simulation is implemented. All input data are based on the existing urban context and historical weather data collected from the Weston Park, the closest weather station from ICoSS building (Figure 4). Also, the boundary scale is limited in 150m x 100m to generate the specific microclimate information.

Figure 5 presents Envi-met simulated ICoSS neighbourhood microclimate visualizations at the hottest hour (15:00) of 5th of May 2006. As shown in figure 5-a, most of high temperature areas are placed on western area and the wind direction is the west. It results in substantial impact on the rest of area with increasing air temperature.

Moreover, the wind speed around ICoSS building is dramatically reduced, which may have impact on indoor thermal condition in the naturally ventilated ICoSS building (Figure 5-b).

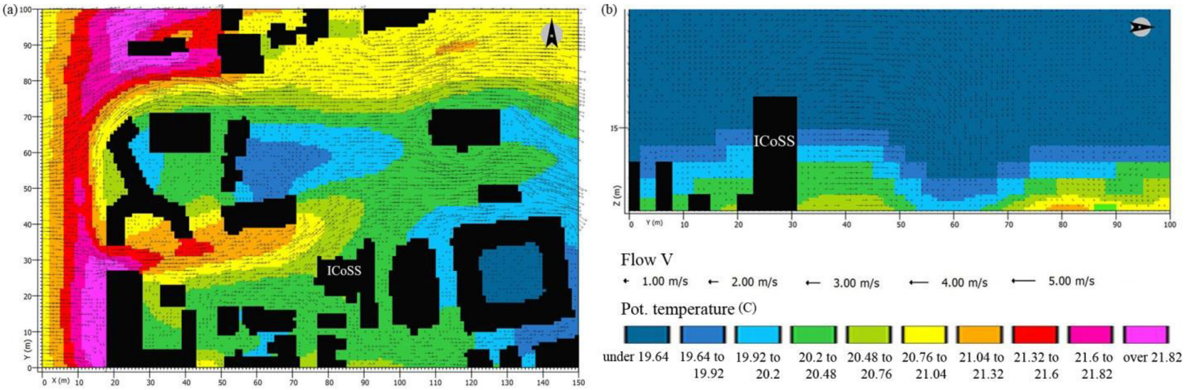

Figure 5. Envi-met simulated ICoSS neighbourhood microclimate visualization at 3pm 5 May 2006, showing potential air temperature, wind speed and wind direction: (a) x-y plan at 1.2m height from ground, (b) y-z section at x=83.

3.3. ICoSS indoor thermal performance

Under the ICoSS neighbourhood microclimate condition, building thermal performance is simulated. One of considerable strengths of Envi-met simulation is to be able to extract a specific microclimate data file around a target building for indoor performance simulation based on “EnergyPlus” calculation platform. It is generated by climatic information collected from virtual weather stations, called “receptors”, around ICoSS building.

Due to the limited operational information of past ICoSS building (2006) for indoor performance simulation, we used current occupancy data and scheduling. Table 1 shows key assumption for indoor performance simulation.

Table 1. Key assumption for DesignBuilder indoor thermal performance simulation.

Operational use	Occupancy density	Office equipment	Glazing area opens	Window opening	HVAC
value	0.11 (people/m^2)	15 (w/m^2)	5 (%)	Always on	none

Table 2 shows a comparison of indoor thermal performance between simulated results and actually monitored data of working area, 2nd, 3rd and 4th floor. To confirm the methodological appropriateness, a correlation analysis was applied.

Table 2. Comparison of indoor thermal performance between (A) simulated results and (B) monitored data in 5th May 2006 (ºC).

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
2nd floor (A)	22.6	23.5	24.0	25.2	26.1	26.7	27.0	27.1	26.9	26.3	25.5
2nd floor (B)	21.6	22.1	22.3	23.0	24.0	24.2	24.5	24.6	24.7	25.0	24.9
3rd floor (A)	22.6	23.2	23.5	24.6	25.5	26.1	26.4	26.6	26.5	26.0	25.2
3rd floor (B)	21.2	21.4	21.8	22.8	23.5	23.9	24.3	24.6	24.8	25.1	25.1
4th floor (A)	23.3	23.6	23.6	24.7	25.7	26.3	26.7	26.9	26.8	26.3	25.5
4th floor (B)	21.5	21.5	21.6	22.9	24.8	26.0	26.7	27.1	27.4	26.7	25.6

Table 3 presents that indoor simulated hourly air temperature is correlated with monitored temperature in each floor. It shows strong relationship of both temperatures’ distribution on the linear regression: correlation value (r) = 0.911, 0.911 and 0.985 in 2nd, 3rd and 4th floor respectively in spite of a few number of measurement (n) = 11. In addition, the coefficients of determination (r^2) are 0.829, 0.829 and 0.971 respectively. Especially, in case of 4th floor, the coefficient of determination value is 0.971, which represents about 97% of the variations in simulated air temperature are matched with the historical monitored data under the standard deviation (STD), 1.38. Given the result of our 2006 ICoSS study, the simulation workflow seems reasonably calibrated to be applied to further studies involving future climate change projections.

Table 3. Correlation relationship between (A) indoor simulated and (B) monitored temperature in 5th May 2006: Mean (average temp), STD (standard deviation), r (correlation value), r^2 (coefficient of determination value) and N (number of variation).

	2nd floor (A)	2nd floor (B)	3rd floor (A)	3rd floor (B)	4th floor (A)	4th floor (B)
Mean (°C)	25.54	23.72	25.11	23.50	25.40	24.71
STD	1.55	1.24	1.43	1.48	1.38	2.39
r	0.911	0.911	0.911	0.911	0.985	0.985
r^2	0.829	0.829	0.829	0.829	0.971	0.971
N	11	11	11	11	11	11

4. ICoSS Passive Building Adaptation Design: A 2012 and 2050

On the basis of the methodological framework as evaluated in our ICoSS 2006 study, we conducted a passive building adaptation design exercise in response to microclimate change projections. As the building design needs to consider current and future performance at the same time, we applied the simulation framework into 2012 and 2050 for passive building adaptation design. In the following subsections, we present the sequential process with outdoor and indoor coupled microclimate change simulations for the passive building adaptation design in two steps, taking into account the seasonal conditions: (4-1) summer condition and (4-2) winter condition.

4.1. 2012 and 2050: Summer Condition

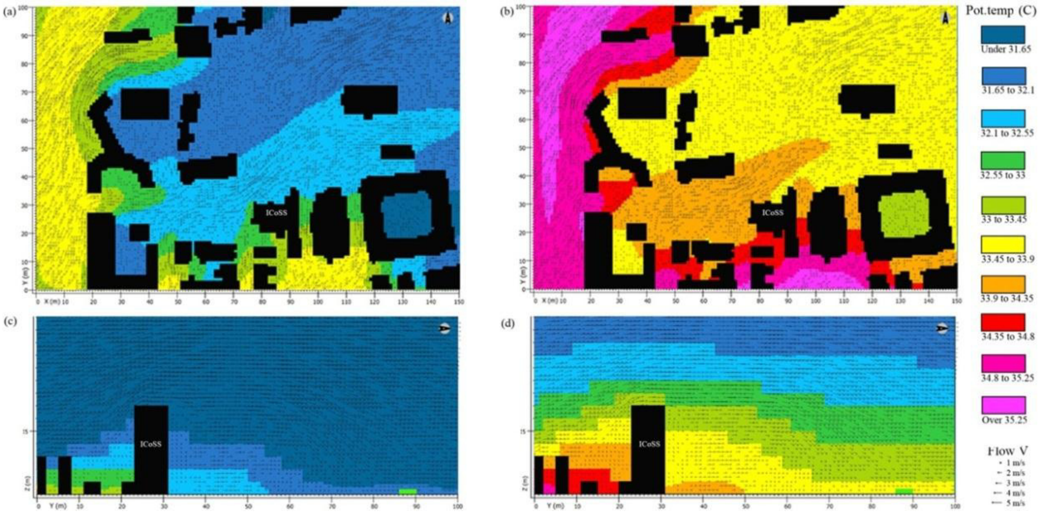

Figure 6. Envi-met simulated visualization of ICoSS microclimate condition of 2012 and 2050: (a) Visualization of the ICoSS neighbourhood, 15:00pm 24 July 2012, showing potential air temperature, wind direction and wind speed at 1.2m height; (b) 2050, (c) section of ICoSS neighbourhood condition at x=83m for 2012; (d) 2050.

Figure 6 shows Envi-met simulated ICoSS microclimate condition at the hottest hour (15:00) in the hottest day of the year (24 July) in 2012 and 2050. Here, the visual comparison between 2012 and 2050 implies that the overall change in potential air temperature around the ICoSS building is significantly dramatic due to the climate change scenario projected by CCWorldWeatherGen. Notably, this simulation does not take into account any change of urban context. It represents that the ICoSS neighbourhood context does not cope with the climate change situation.

In detail, Table 4 shows how climate change substantially impacts on ICoSS neighbourhood microclimate condition numerically, comparing the hourly air temperature between 2012 and 2050 (see row B and D). Moreover, it shows the high density of urbanized area has higher temperature than remote green space, Weston Park weather station (see row A and B). It may have some impact on the indoor thermal performance of ICoSS building.

Table 4. ICoSS microclimate houly air temperature (^{o}C), 24 July as the hottest day of the year: (A) Remote weather station (Weston Park weather station), (B) Envi-met microclimate 2012, (^{o}C) Remote CCWorldWeatherGen 2050 scenario, (D) Envi-met microclimate 2050.

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
(A)	22.1	23.1	24.2	25.4	24.6	25.0	27.3	27.2	27.0	26.9	26.7
(B)	24.7	25.9	26.9	28.4	30.0	31.4	32.1	32.1	31.7	31.0	29.7
(C)	23.8	24.8	25.9	27.1	26.3	26.7	29.0	28.9	28.7	28.6	28.4
(D)	26.3	27.5	28.6	30.0	31.7	33.1	33.7	33.8	33.5	32.8	31.7

Under the 2012 and 2050 microclimate change conditions, the indoor thermal performances are simulated. Figure 7 shows simulated DesignBuilder CFD visualization of 2012 and 2050 ICoSS indoor thermal conditions (15:00 24 July). The overall visual comparison shows how the changed outdoor microclimate impacts on the indoor thermal performance substantially. Given that all other internal input data, such as operational office equipment, lighting and occupancy activity and density are the same, the main source for increased indoor thermal level may result from an external environmental aspect.

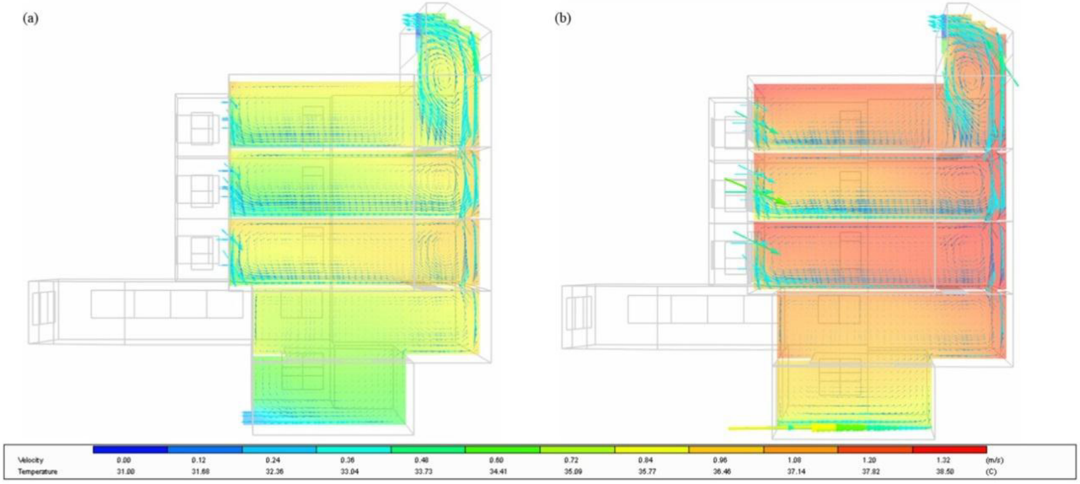

Figure 7. ICoSS microclimate outdoor and indoor coupled CFD simulation for 15:00pm 24 July 2012(a) and 2050(b)

Table 5 shows solar gain analysis to investigate internal heat gain source. Through the internal heat gain analysis, up to 60% of internal heat gain occurs at solar gain from the south-facing windows, that is the increased thermal level is caused by solar gain from south-facing fully glazed façade (see row 2012B and 2050B). The main purpose of current outdoor and indoor coupled simulation is to investigate and evaluate main reason for the overheating problem in working environment. Also, it is to find a solution to mitigate the overheating problem with passive design strategies. We applied two different shading devices of south-facing glazed façade: interior roller screen currently equipped and external louvre shading: vertical spacing (0.5m), number of blades (7), blade depth to window (0.8m), blade angle to window (10^{o}) on 3.5m height of window.

Table 5. Internal solar gain analysis: (2012A) Solar gain (KW) 2012, (2012B) % of solar gain over total internal heat gain 2012, (2050A) Solar gain (KW) 2050, (2050B) % of solar gain over total internal heat gain 2050.

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00
2012A	13.9	20.8	30.7	44.9	63.8	55.4	46.7	35.5	22.7	12.3	8.4
2012B	25.3	32.6	42.2	52.2	61.9	59.1	55.1	48.4	37.5	25.1	18.6
2050A	13.9	20.7	31.6	48.1	63.8	55.6	47.3	35.9	22.7	12.3	8.5
2050B	25.6	33.3	43.7	54.9	62.6	59.5	55.7	48.8	37.6	25.1	18.7

Table 6 shows the estimated hourly indoor temperature under each shading device and the predicted energy requirement in case of requirement of mechanical chiller to maintain thermal comfort level calculated by DesignBuilder thermal comfort assessment based on ASHRAE 55-2004 [17]: air temperature 24C, relative humidity 50% and mean radiant temperature 31C approximately.

The dramatic changes occur at external louvre case in both 2012 and 2050 cases rather than internal roller screen; the air temperature is reduced by about 1.2^{o}C to 1.4^{o}C in 2012 and 2050 from both no shading cases respectively (see row 2012C and 2050C). However, the naturally ventilated system of ICoSS cannot cover the future and even recent summer condition and it represents mechanical chiller is required. Table 6 also shows the required energy to maintain thermal comfort. The predicted energy requirement of external louvre case is significantly reduced from 53.63% to 49.28% and from 55.72% to 51.30% in 2012 and 2050 respectively. However, this result only considered summer condition. To confirm the applicability of external louvre as a passive building adaptation design, the coupled simulation is extended to winter condition.

Table 6. Comparison of average hourly indoor temperature (^{o}C) of working area and predicted energy demand under three different shading systems (total chiller KW and % of chiller energy demand over total operational office energy consumption (%)): (2012A) no shading 2012, (2012B) internal roller screen 2012, (2012C) external louvre 2012, (2050A) no shading 2050, (2050B) internal roller screen 2050, (2050C) external louvre 2050.

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	Chiller total KW (%)
2012A	28.7	30.4	31.4	32.8	34.5	35.8	36.4	36.7	36.5	35.9	35.0	595.98 (53.63)
2012B	28.4	30.1	31.5	33.1	35.2	36.1	36.7	36.6	35.9	35.1	34.3	598.17 (53.38)
2012C	28.1	29.7	30.6	31.7	32.9	34.0	34.8	35.1	35.0	34.7	33.9	479.77 (49.28)
2050A	30.5	32.1	33.3	34.7	36.2	37.6	38.2	38.5	38.3	37.7	37.0	648.50 (55.72)
2050B	30.1	31.7	33.3	35.0	37.0	38.0	38.5	38.4	37.8	37.0	36.3	662.72 (55.92)
2050C	29.6	31.1	32.2	33.3	34.5	35.6	36.4	36.7	36.7	36.4	35.8	520.09 (51.30)

4.2. 2012 and 2050: Winter Condition

Table 7. Comparison of average hourly indoor temperature (^{o}C)/ hourly solar gain(KW) of working area (2nd, 3rd and 4th floor) and predicted discomfort hour under the proposed two different shading systems (no shading and external louvre system): (2012A) no shading 2012, (2012B) external louvre 2012, (2050A) no shading 2050, (2050B) external louvre 2050.

	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	Discomfort hour
2012A	18.8 / 0.8	19.8 / 4.7	21.6 / 8.4	22.5 / 12.4	23.3 / 17.4	24.3 / 14.6	24.0 / 9.8	24.3 / 5.9	23.6 / 2.1	22.7 / 0	22.2 / 0	0
2012B	15.0 / 0.5	15.9 / 2.0	16.8 / 2.5	17.4 / 2.6	17.6 / 2.9	17.8 / 2.4	18.0 / 1.9	18.1 / 1.5	17.7 / 0.7	17.2 / 0	16.9 / 0	0
2050A	20.9 / 0.8	21.9 / 4.7	22.9 / 8.4	23.7 / 12.4	24.9 / 17.3	25.4 / 14.5	25.2 / 9.7	25.0 / 5.8	24.8 / 2.0	24.5 / 0	24.1 / 0	0
2050B	17.4 / 0.5	18.3 / 2.0	19.2 / 2.5	19.8 / 2.6	19.2 / 2.8	20.0 / 2.3	20.1 / 1.9	20.2 / 1.5	20.0 / 0.7	19.4 / 0	19.1 / 0	0

Table 7 shows a predicted average air temperature of working area and solar gain to assess the performance of the external louvre on indoor environment without applying HVAC. Also, it presents the estimated discomfort hour for 11 Feb 2012 and 2050 as the coldest day of the year. Due to the high level of air tightness and heat insulation property of the ICoSS building, U-value of wall (1.8 W/m^{2}K) and window (1.5 W/m^{2}K) and operational internal heat gain from office equipment, the energy for heating is not required in winter condition both 2012 and 2050. In addition, the indoor air temperature in 2050 is more highly increased than 2012 because of the impact of the projected climate change scenario on the ICoSS neighbourhood microclimate. However, the selected shading device interferes with the inflow of internal solar heat gain, resulting in reduced indoor air temperature, although the indoor thermal comfort level is suitable for working environment.

5. Conclusion and Further Research

A microclimate change outdoor and indoor coupled simulation assessment framework for passive building adaptation design was proposed and applied to the ICoSS building study in its urban neighborhood context. Based on computational modelling, it was developed to investigate summer overheating and to apply to a passive design strategy in an existing green building case study, taking into account the seasonal conditions in 2012 and 2050 as projected by current climate change modelling. Through a series of numerical modelling and prognostic visualization, the results from applying the framework showed how building indoor thermal performance interacts with specific outdoor microclimates. Firstly, while the air temperature of outdoor microclimate in 2050 was predicted to increase about 1.7^{o}C from 2012, the indoor thermal condition was predicted to increase about 1.8^{o}C. Secondly, a selected passive building adaptive device under the proposed framework contributed to reduce the indoor air temperature in both 2012 and 2050 cases, about 1.2^{o}C, 1.4^{o}C respectively. Thirdly, it is predicted to improve energy efficiency by about 4.35% and 4.42% in 2012 and 2050 respectively. Finally, this study showed how outdoor-indoor coupled assessment can be applied with microclimate change scenarios to inform existing building adaptation design.

We intend to carry out further simulation studies into climate change impacts on urban neighbourhoods in other geographical areas. To improve calibration of the simulation framework and dataflow, further validation studies are required by comparing simulation results with outdoor and indoor field measurements.

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