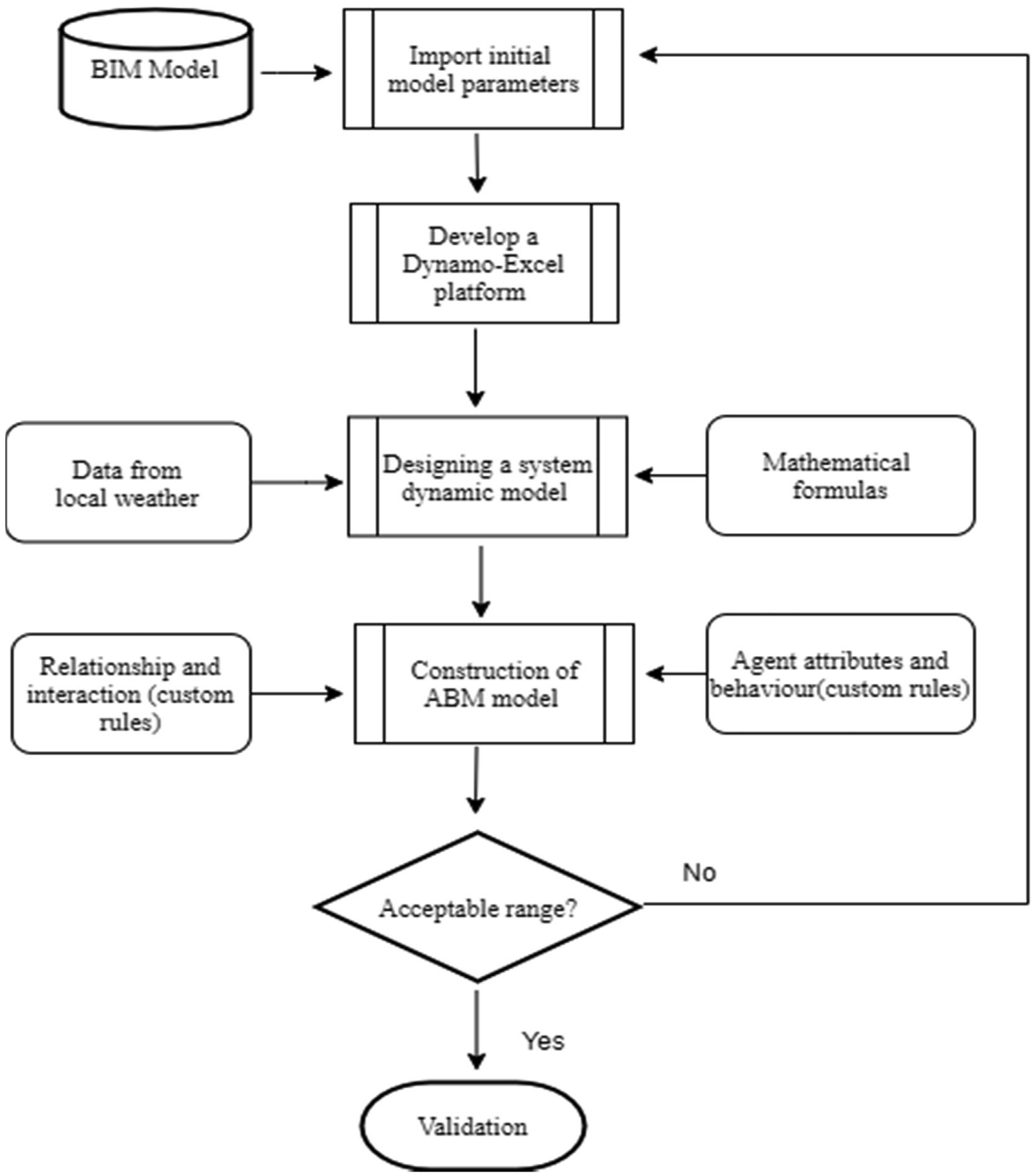

Fig. 2. A flow chart of the research methodology.

In general, indoor data in the office relate to an individual occupant's satisfaction level. The PMV value represents (Fig. 5) that the occupant comfort was not neutral (i.e., PMV = 0) throughout the simulation periods (both summer and winter) whereas it was slightly hot or cool in summer (Fig. 5: Left) and mostly cool during the winter season (Fig. 5: Right). It was also observed that model calculated thermal comfort indices repeatedly fluctuated due to indoor temperature, CO_2 concentration, and occupants' metabolic rate. There is a need to understand the relationship between PMV values, clothing level, indoor temperature, and CO_2 concentrations. In Fig. 5, a wide diversity of thermal conditions among the office occupants is significant. And offices with warmer temperatures during the winter necessarily required a greater number of occupants. For further validation, the actual PMV indices will be obtained for individual comfort level from cold (-3) to hot (+3), and the calculated PMV indices are averaged. This will describe how realistically the PMV indices can capture the actual comfort level under different seasons. Moreover, it also appears that the blunder is higher in the hot climatic region compared with the cold climatic region. It is possible because the occupants' tolerances for thermal conditions of the hot and cold regions are completely dissimilar. Since this model was designed in Hong Kong, which is located in a hot humid climatic region, the occupants who live in this zone may be more responsive to hot environments and have less tolerance of these conditions. Nevertheless, more specifically the indoor temperature and CO_2 concentrations are key factors dominating the occupant comfort level. Fig. 6 and Fig. 7 indicate the 10-day simulation outcomes of temperatures and CO_2 concentration as well. These outcomes reveal the 10-day indoor temperature and indoor CO_2 distribution in the office space which are quite steady.

Typically, a rise in indoor temperature in an office room is dependent on both the occupant number (due to metabolic gains form occupants' bodies) as well as the outdoor temperature intensity. In general, during the daytime, while the outside temperature and solar radiation are high, heat gains from the building envelope (i.e., windows, walls, etc.) raise the interior temperature. The variability of the indoor and outdoor temperature was observed and is shown in Fig. 6. The highest temperatures were found on June 1st, 4th, 5th, and 6th during the daytime with the maximum occupancy. Moreover, during this period, the CO_2 concentration level

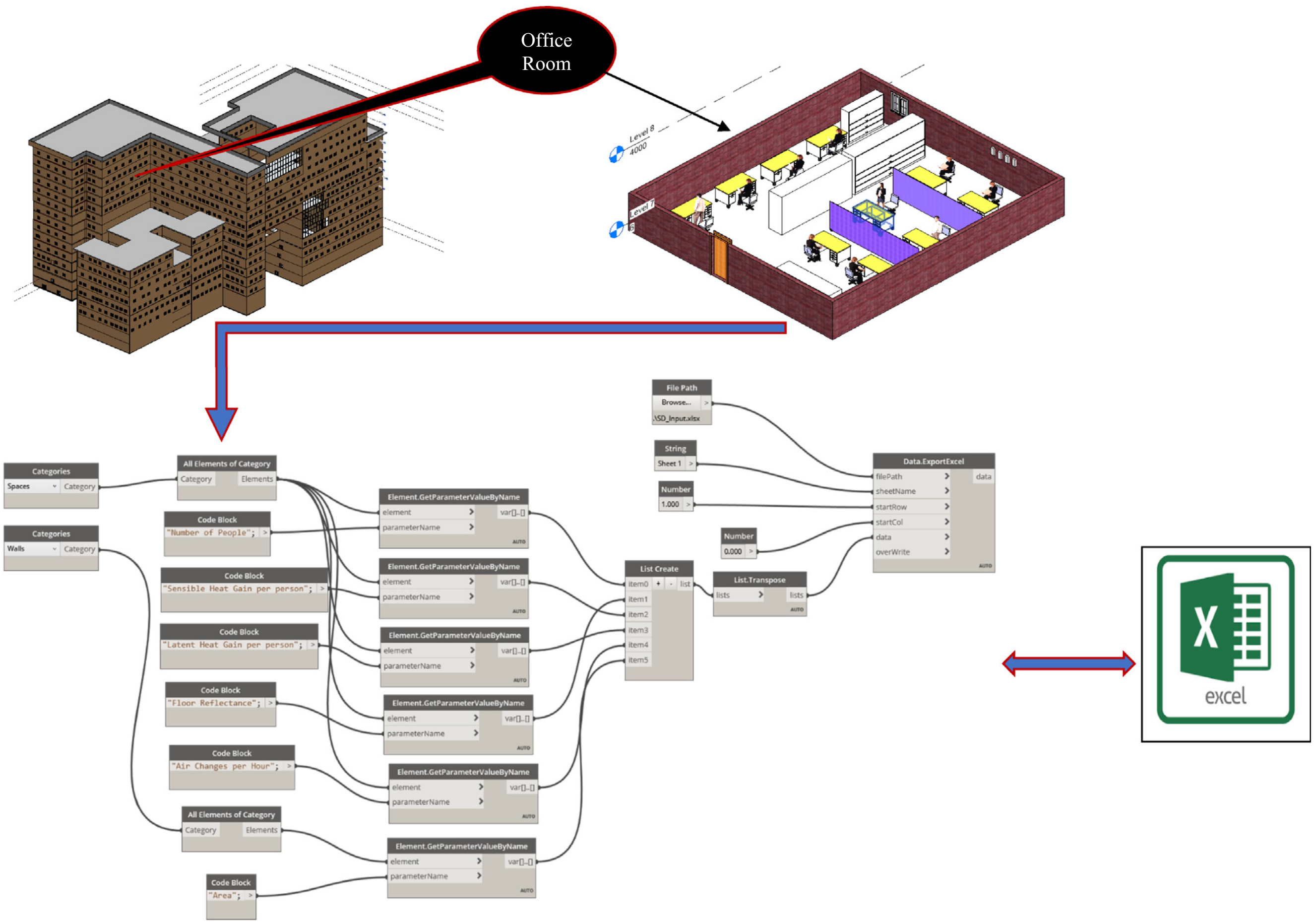

Fig. 3. Data exchange between BIM and Excel through Dynamo API.

and indoor temperature was also higher. Throughout the 10-day simulation period, the indoor temperature (^{0}C) in the office space was measured in the range of 18.31 °C to 20.97 °C where the outdoor temperature was measured in the range of 25.5 °C to 29.87 °C. The high increment of the outdoor temperature of 29.87 °C was recorded on June 1st while the interior temperature was stated to be 20.27 °C due to controlling HVAC and the tight infiltration system.

The consequences of measurements and model computations of indoor carbon dioxide level based on Equation (4) are presented in Fig. 7. For most of the days, the indoor CO_2 levels started at ~275 ppm and rose to a stable value within 10–20 mins. There is no proper correlation visible between the indoor CO_2 levels and number of occupants. But indoor CO_2 levels did not exceed 300 ppm for any of the days, staying below 285 ppm on most of the days. So, it indicated that the office had appropriate ventilation and air quality and were not a cause for occupant concern. Moreover, this value is accepted by the World Health Organization (WHO) as the maximum allowable value for indoor [50] environments. The highest level of outdoor CO_2 concentration observed for 10 days of the simulation period was June 10th (approximately 573.13 ppm). This is also a daytime fact when the office space is mostly occupied. Also, there is a higher fluctuation of natural factors and outdoor CO_2 contamination on consecutive days.

5. Validation and calibration tolerance

Validation and data reliability checking permit the systematic gathering of information about the object of study while taking into consideration the setting of information gathering. For these tasks, it is important that the depth and scope should be taken into consideration. As discussed earlier, the current office building model is a realistic building model located in Hong Kong, and its occupancy-based building performance was calculated using an automated platform of BIM, SD, and ABM approach. In this section, the above-mentioned platform which generated a data evaluation technique has been discussed. The purpose of this task was to verify the data validity/reliability as well as the robustness of the applied framework. Here the data verification study of computational outcomes was performed using the realistic data obtained from the office occupants as well as sensor data. Typically, real data are empirical, often called "true" data, and are considered a powerful validation tool [51]. In order for the results obtained from the automated platform to be reliable, the data from this framework must be within an acceptable limit as well [51]. Here, the validation and reliability checking in this study was mainly performed in two parts:

1. Validation and reliability checking for PMV indices and
2. Validation and reliability checking for environmental data (Temperature, CO_2, etc.)

Here, the data generated using the proposed framework were verified against the occupant survey (for PMV indices) and hourly data (e.g., sensor data for temperature, CO_2) generated from the real office building located in Hong Kong. In this process ASHRAE Guideline 14–2002 [52] and FEMP standards [53] were followed to check the calibration tolerance as well. This involved determining two dimensionless indicators of errors, such as Co-efficient of

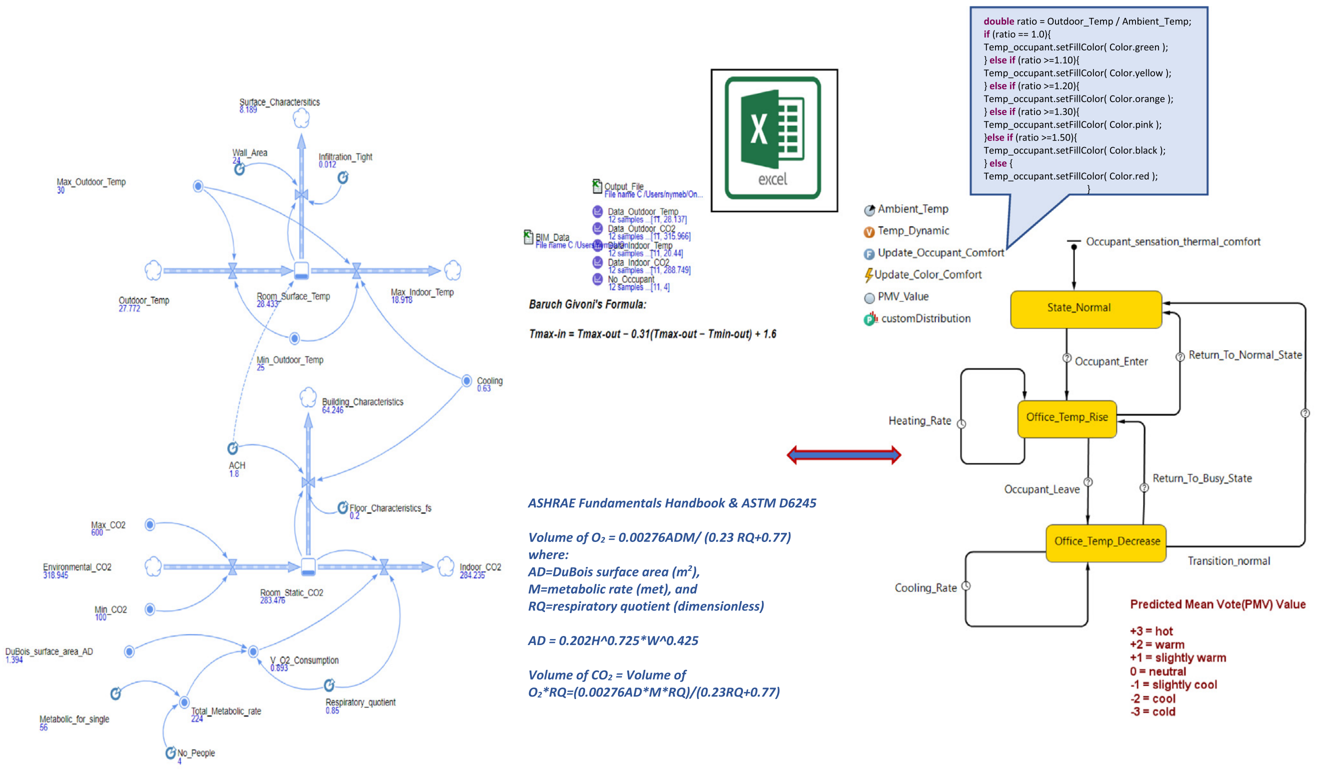

Fig. 4. Data exchange between SD (Left) and ABM (Right).

Variation of Root Mean Square Error CV(RMSE) and Mean Bias Error (MBE). Typically, the acceptable calibration tolerance of MBE and CV(RMSE) are ± 10% and 30% respectively while utilizing system-level calibration with hourly monitored data. The MBE and the co-efficient of variation CV(RMSE) were calculated and verified to be consistent with the ASHRAE and FEMP guideline. Eqs. (5) and (6) represent the formulas employed for RMSE and MBE, where n is the number of observations, Tavg.m. is the average monitored data for n observations, Ts is the simulated data for n observations, and Tm is the monitored data for n observations.

$$RMSE(\%) = \left(\frac{100}{Tavg.m}\right)X\left[\frac{1}{n}X\sum(Ts - Tm)^2\right]^{0.5} \quad (5)$$

$$MBE(\%) = \left(\frac{100}{Tm}\right)X\frac{1}{n}\sum(Ts - Tm) \quad (6)$$

5.1. PMV indices

Ten office occupants were enlisted for this validation study. These office occupants worked in a large office space situated in the Hong Kong Polytechnic University. The occupants comprised five males and five females of various nationalities. All the office occupants were within the age range of 23 to 32. The occupants were distributed an information sheet clarifying the study's aims and objectives. Meanwhile, the occupants' consent was obtained using the typical consent form. Afterwards, the occupants were asked to assess their thermal sensation based on ASHRAE seven-point scale from cold (-3) to hot (+3) as presented in Fig. 4 (ABM component). This was to collect the computed thermal sensation of the office occupants (-3 to + 3) known as Real Mean Vote (RMV). The occupants were requested to freely mark anywhere on the scale at every 20-minute interval. These are the values that Fangers' PMV equation tries to forecast. Finally, in order to investigate the model's validity, the model-generated PMV indices were compared to the real PMV data obtained from the office occupants. Fig. 8 indicates the model-calculated PMV indices and occupant-reported RMV indices for 20-minute intervals.

Generally, the prediction success of the earlier PMV model never exceeded 30% [54]. When the PMV fails to predict the occupant thermal sensation perfectly, it usually undervalues it, especially the occupant stochastic nature and air speed inside the space. In this study, the model-predicted PMV findings concur with the other previous studies from different regions as well [54–57]. Also, this study revealed that there is an acceptable calibration tolerance level of MBE and CV(RMSE) for both simulated and experimental comfort indices. The current values of MBE and CV(RMSE) are 0.35% and 2.70% respectively while the acceptable tolerance of MBE and CV(RMSE) are ± 10% and 30% respectively.

5.2. Model- and Sensor-Estimated temperature data

Indoor and outdoor environmental data collected using a customized sensor platform are shown in Fig. 9. The time interval for environmental data collection was approximately 1–2 h and these data were stored on a Micro-SD card. One of the key benefits of the customized sensor is its flexibility, and allows more sensors to be added whenever required.

Temperature computed from the model versus the actual temperature obtained from the sensors is plotted in Fig. 10. The model-predicted maximum and minimum indoor temperatures were 20.97 °C and 18.31 °C respectively whereas the sensor-recorded maximum and minimum indoor temperatures were 22.2 °C and 21.5 °C. The average difference between the maximum and minimum indoor temperatures was roughly 1.13 °C and 3.18 °C. This indicates that the model-predicted indoor temperatures were slightly lower than the actual temperature. Some other occupant comfort studies [58–60] also revealed several reasons for this discrepancy between the model- and sensor-predicted temperatures. The difference between the predicted and actual temperatures was

Fig. 5. The dynamic thermal comfort level for three occupants: Summer season (Left) and Winter season (Right).

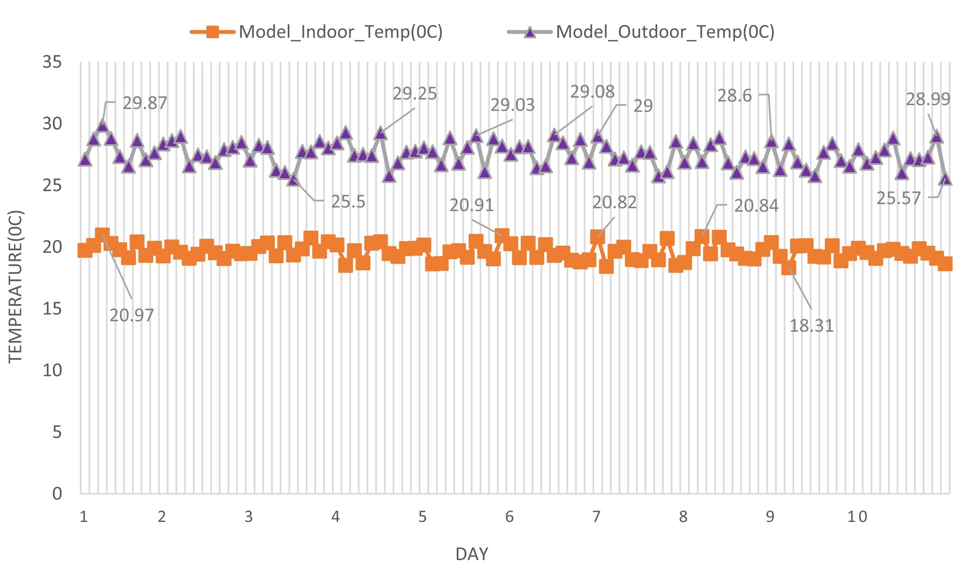

Fig. 6. Indoor and outdoor temperature (^{0}C) variation in office space.