Sensitivity Analysis of Door Gap Size and Solar Effect on Multi-zone Indoor Airflow CFD Simulation Using BIM

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Abstract. Indoor airflow analysis using computational fluid dynamics (CFD) helps us study thermal comfort. Using measured data to validate CFD models can ensure the accuracy of simulations, and fine-tuning multi-zone CFD models helps further improve that accuracy. Previous studies have performed sensitivity analysis on isolated rooms to study how physical and turbulence parameters influence airflow patterns and to provide insights on models fine-tuning. However, these results do not reflect the sensitivity of multi-zone models, e.g., an office floor, which consists of zones with different mechanical ventilation and air conditioning (MVAC) layouts and are connected by doors. To investigate how multi-zone models should be tuned for higher accuracy, this study quantifies: (1) the impact that door gap sizes have on velocity variations, and (2) under different weather conditions, how much solar radiation impacts temperature distribution, using a validated CFD model of a typical office floor built with building information modeling (BIM) technology.

1. Introduction

Indoor airflow analysis using computational fluid dynamics (CFD) helps us study thermal comfort and indoor air quality (IAQ) (Nielsen 2015). Validation of CFD models using measured data is usually performed to ensure the accuracy of simulation results. When simulating airflow patterns in a multi-zone case, the model has more complicated geometry than in a single-room scenario. In a multi-zone model, the zones have different mechanical ventilation and air conditioning (MVAC) layouts. This requires applying different boundary conditions to different zones according to the MVAC layouts. Validating a CFD model often requires fine-tuning the accuracy of the model.

Previous studies would isolate rooms when performing sensitivity analysis on them to study how airflow pattern and temperature are influenced by such parameters as door openings (Kalliomaki et al. 2016) and turbulence models (Gilani et al. 2016). These results provide insights on how to fine-tune a CFD model to improve accuracy, but they cannot reflect the sensitivity of a multi-zone model of such places as an office floor, where different zones have different mechanical ventilation and air conditioning (MVAC) layouts. To investigate the sensitivity between different zones and different parameters, a multi-zone model is needed.

How indoor partitioning with doors modifies airflow patterns and pollutant dispersion has been studied in the past. The impacts that differing door sizes and types have on air velocity have been investigated (Kalliomaki et al. 2016, Lee et al. 2016). Closed doors were often assumed to be airtight in these studies. Nevertheless, the findings cannot be applied directly to a multi-zone environment, e.g., an office floor. Different MVAC settings are applied to different zones of an office floor and some of the zones may not have MVAC system installed. As these zones would not have air inlet or outlet, inside each of these zones the airflow is driven by the pressure difference between that zone and its adjacent zones. Therefore, that airflow is significantly affected by the airflows coming from those adjacent zones. Even when doors have been installed between zones and are closed, air can still travel between adjacent zones through the gaps in the doors, and that airflow needs to be taken into consideration. Hence, studying how the size of each door gap affects the velocity of air passing through that gap is necessary for improving the accuracy of multi-zone CFD simulations. When air flows from a tenant area to a corridor through a door gap, a sharp increase in velocity can be expected there. To simulate this sudden increase in velocity, first, the mesh in the door gap has to be made much finer than those in the tenant area and the corridor. This causes large variations in cell size near the door and worsens the aspect ratio of the mesh. Using a very fine mesh to conduct CFD simulations is computationally expensive, but conducting a sensitivity analysis on door gap sizes first can provide insights on how door gaps should be enlarged, in order to simulate the sharp increase in air velocity through door gaps.

The effect that solar radiation has on the temperature distribution in an indoor environment has been studied using transient CFD simulations with radiance models (Saberian and Sajadiye 2019). However, to estimate the solar heat gain for an office floor, any shading effect from the upper floors has to be considered. The CFD simulation must therefore include the whole building, making transient CFD simulations using a radiance model on an office floor computationally expensive. Another approach is to conduct steady-state CFD simulation with solar radiation on any windows that are identified as an internal heat source (Shan and Rim 2018). The solar heat load would then be deduced from the ASHRAE handbook (ASHRAE 2013). However, this approach considers neither the orientation, location, elevation of the testbed office room nor the weather conditions of the location. To properly estimate the solar heat load on the windows, both the geometry and semantic information of the model should be considered.

This study aims to address the above. It quantifies the impact of door gap size on velocity variations, and solar radiation on temperature distribution under different weather conditions, ultimately investigating how to tune a multi-zone model for higher accuracy. Essentially, this study proposes a workflow to conduct sensitivity analysis on a validated CFD model of a typical office floor using building information modeling (BIM) technology.

2. Methodology

The workflow that this study proposes is illustrated in Figure 1. BIM technology was implemented to modify the parameters for the sensitivity analysis. The illustrative example has a CFD model of a typical office floor, which was validated with field measurements (Kwok et al. in press). Figure 2 shows the BIM model of the office floor. This study used FLUENT to conduct steady-state CFD simulations (ANSYS Inc 2018). The SIMPLE algorithm was adopted for pressure-velocity coupling. A second-order upwind scheme was used for both the convection and viscous terms. An SST k-ω turbulence model was adopted. The transport equations and empirical constants used in FLUENT were the same as the original ones in Menter's paper (Menter 1994).

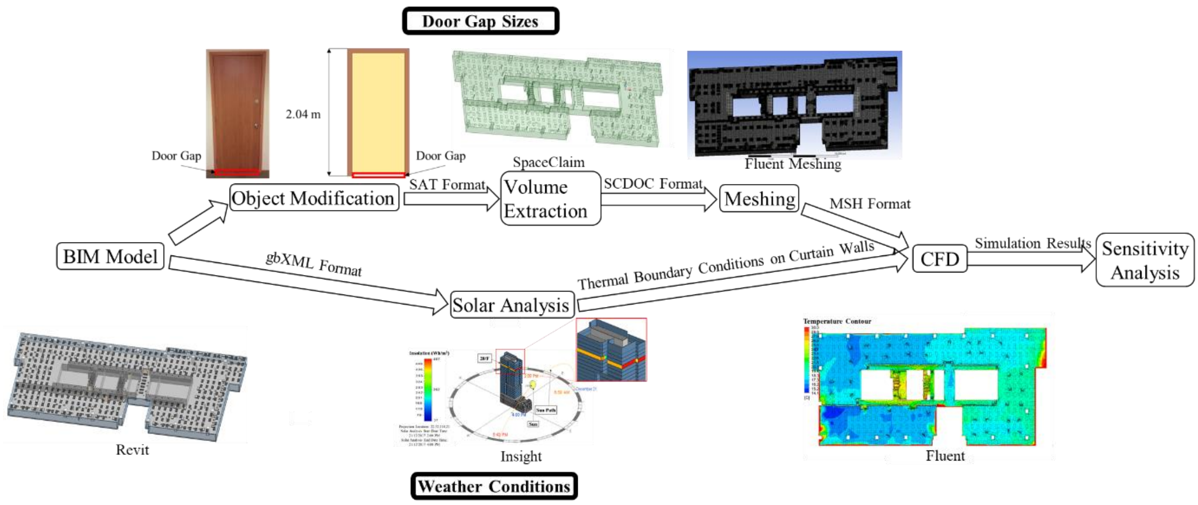

Figure 1: Workflow of Sensitivity Analysis using BIM and CFD

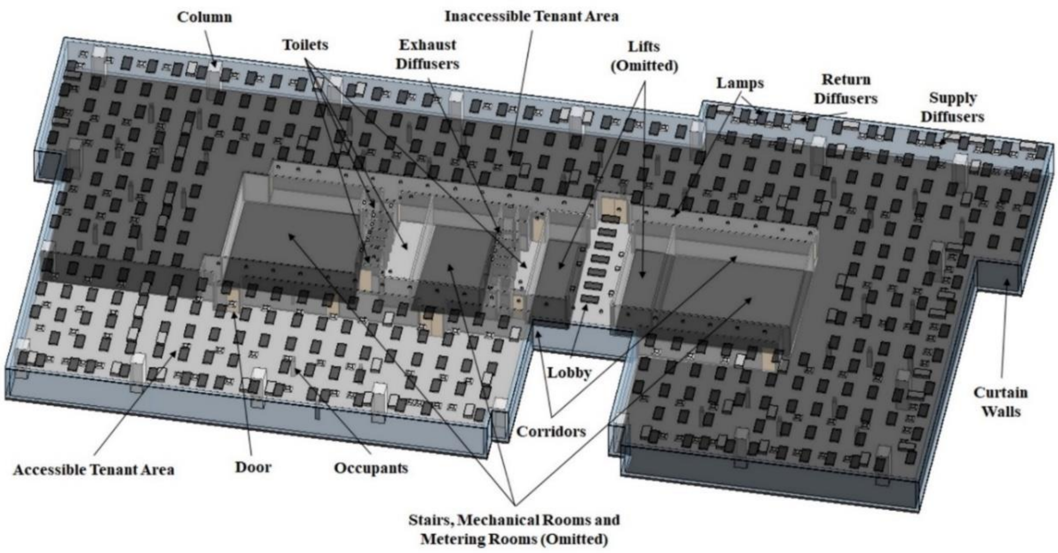

Figure 2: BIM Model of Studied Office Floor

2.1 Airflow Pattern Variation Induced by Different Door Gap Sizes

To study how to better simulate airflows through door gaps in a multi-zone model (where all doors are closed) by fine-tuning the sizes of those door gaps, vertical variations in air velocity caused by changes in door gap size were investigated. By conducting CFD simulations on different door gap sizes, the airflow passing through the door gaps was compared and determined whether a sharp increase in air velocity was present as expected. In the example, the actual size of each door gap was 1% of the height of the door panel; for the CFD simulations, the size of each door gap was varied between 1 and 5% of the height of the door panel. In turn, the size of the cells in the door gap varied with the door gap size: cell size was set to be half of door gap size at all times, in order to ensure that there was enough mesh to capture airflow through the door gap. The number of boundary layers is set to be 5 and the transitional ratio of the boundary layers is set to be 0.272. Using 3D CAD software to adjust the sizes of the door gaps, one by one, in a multi-door scenario, such as in the example (with 14 doors) would be error-prone; BIM technology provided a good alternative as it allowed all door gap sizes to be adjusted simultaneously. The study then used Revit to modified the BIM models (Autodesk Inc

2018). Doors were modeled as objects belonging to the same family, allowing the doors to have different sizes but identical material properties. Figure 3 shows one of the doors and its BIM model. The BIM models were then exported in SAT format to become part of the geometry of the model for CFD simulation.

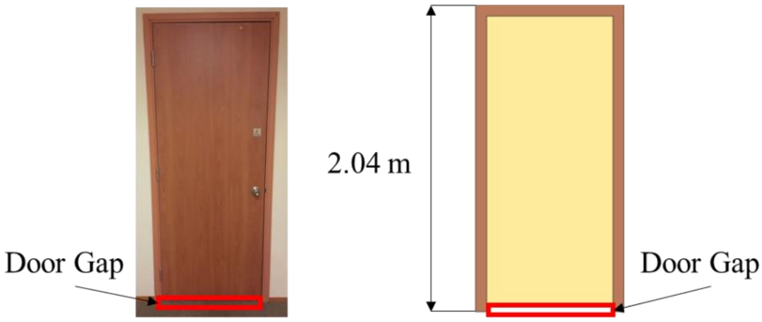

Figure 3: Actual Door (left) and BIM Model of the Door (right)

2.2 Temperature Variation Induced by Solar Radiation under Different Weather Conditions

The sensitivity analysis on how, under different weather conditions, solar radiation would impact temperature distribution on the office floor was conducted next. To simulate how much solar heat was gained and how it was distributed on the curtain walls, a solar analysis was conducted using Autodesk Insight (Autodesk Inc 2015). Autodesk Insight supports BIM-based solar analysis; its daylighting engine has been validated with measured data, and simulation results have been verified using Radiance, a popular daylighting engine. As there would be more floors above the one being studied, some of the solar radiation would be blocked or prevented from reaching its curtain walls; in other words, the solar analysis must be conducted on the entire building and not just on a particular floor. A BIM model of the whole building was used to conduct solar analysis on the exact location and orientation. The BIM model provided building geometry, orientation, location, material information, and weather data from nearby weather stations for the solar analysis. The generated 2-hour averaged insolence values on the curtain walls are inputted as heat flux boundary conditions of the curtain walls for the CFD simulations. To examine how different weather conditions affect solar radiation, the solar analysis was conducted at different times of the day (i.e. morning, noon and afternoon) and during different seasons of the year. Figures 4 and 5 show results of the solar analysis at different times of the day, and on different days of the year respectively.

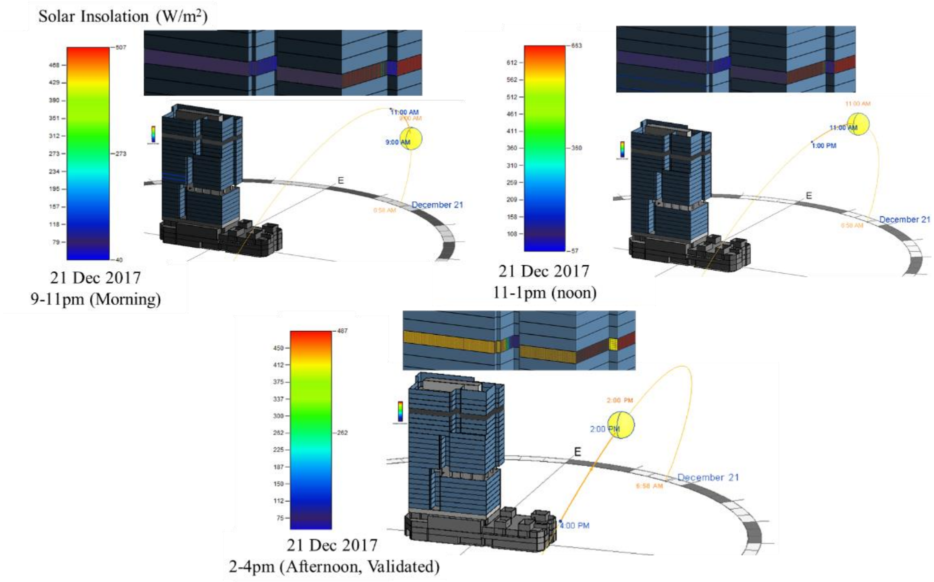

Figure 4: Solar Analysis Results at Different Times of the Day

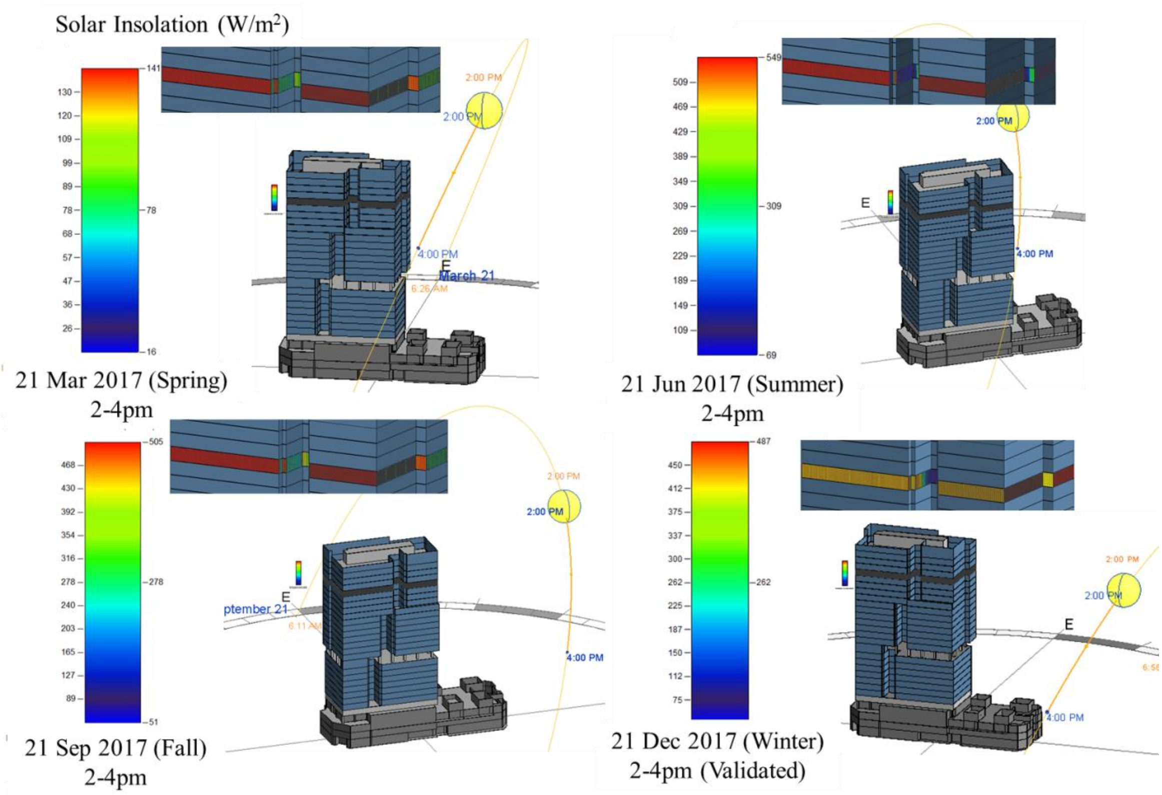

Figure 5: Solar Analysis Results in Different Days of the Year

3. Results and Discussions

3.1 Airflow Pattern Variation Induced by Different Door Gap Sizes

Figure 6 compares air velocity variations in the tenant area of the office floor at the halfway level of the door gap for different door gap sizes. When door gap size is < 3% of door height, air is trapped in the tenant area as the air velocity becomes close to zero when passing through the door gap. The velocity at the return diffuser on the right is also higher in the cases with door gap size < 3% of door height. This is because the air can only exit the tenant area via return diffusers. For the cases with door gap size > 3% of door height, a sharp increase in air velocity to > 0.6m/s was observed. This shows that the cases where door gap size > 3% of door height simulate air passing through door gap more accurately. For the region between two supply diffusers, air circulation increases as door gap size increases in general. The case where door gap size is 5% of door height has the fewest blue areas, hence the airflow here is stronger than in other cases. This implies that the 5% case has better mixing of air in the tenant area.

Figure 7 compares air velocity variations in the corridor along the centerline of the door gap for different door gap sizes. The CFD results show how air passes through door gaps in all cases. Similar to the results shown in Figure 5, only the cases with door gap size > 3% of door height are able to simulate the sharp increase in velocity. Moreover, higher air velocity is observed in the corridor in the cases where door gap size > 3% of door height than the others. Air movement is more prominent in the corridor and hence air is more thoroughtly mixed.

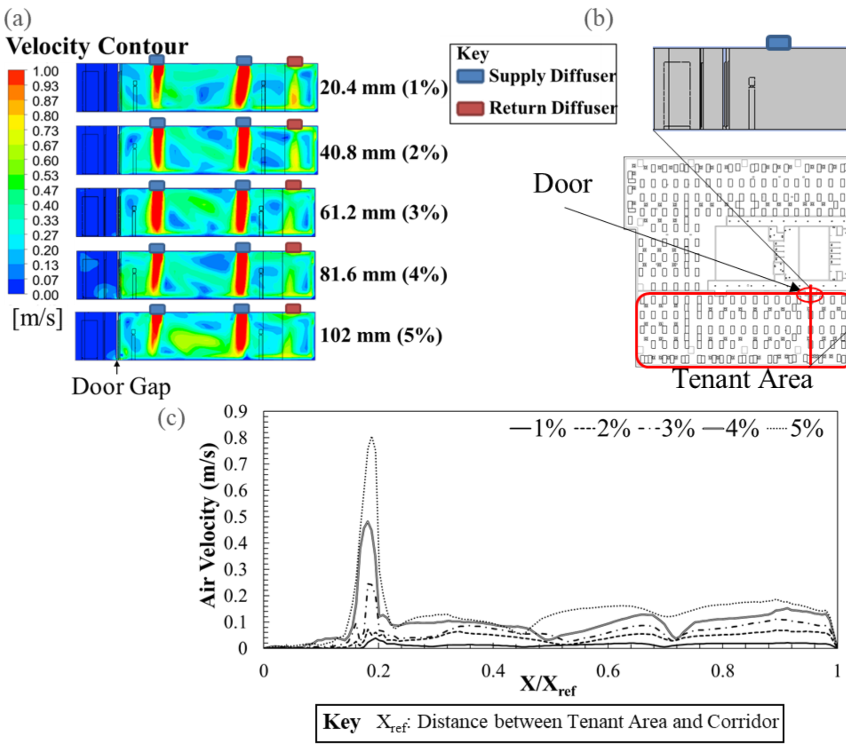

Figure 6: (a) Vertical Variations of Air Velocity for Different Door Gap Sizes in (b) Tenant Area; and (c) Comparison Different Door Gap Sizes among at the Height of the Centre of the Door Gap

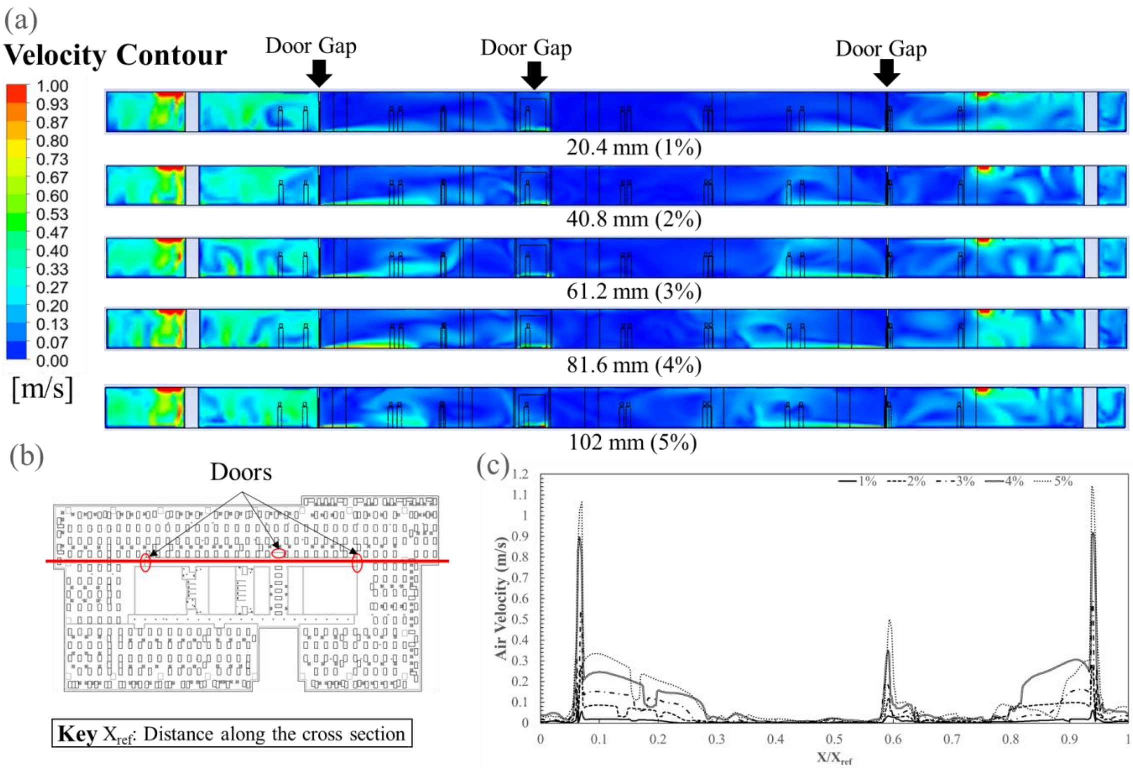

Figure 7: (a) Vertical Variations of Air Velocity for Different Door Gap Sizes in (b) Corridor; and (c) Comparison Different Door Gap Sizes among at the Height of the Centre of the Door Gaps

3.2 Temperature Variation Induced by Solar Radiation under Different Weather Conditions

Figure 8 shows the results of the temperature sensitivity analysis for solar radiation during different times of the day. The distributions of temperatures at nose level are presented. To compare the impact of solar radiation on different zones with different ventilation settings, the temperature results at P1 and P2, which are located in the tenant area and in the corridor respectively were investigated. Figures 8 (e) and 8 (f) show the normalized temperature results along the vertical direction at P1 and P2, respectively. Temperature distribution changes more significantly in the corridor than in the tenant area. As there is no MVAC system operating in the corridor, air flows to the corridor from the adjacent tenant area and lift lobby. Hence, heat is also transferred from these zones to the corridor. Since it is cooler in these zones in the 9:00-11:00 and 11:00-13:00 cases than the validated 14:00-16:00 case, the corridor also becomes cooler. In Figure 4 (f), the air is hotter near the ceiling, which is caused by the ceiling lamps.

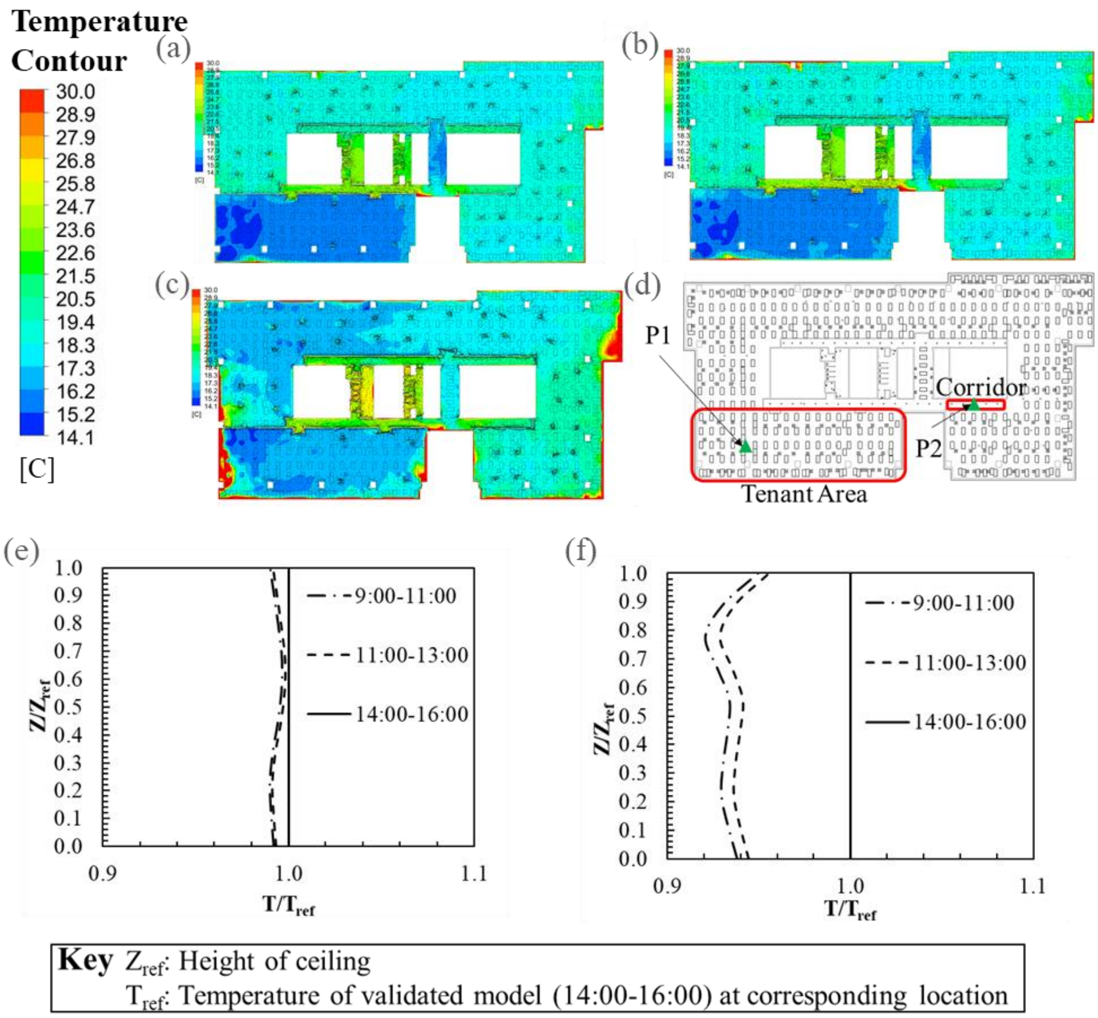

Figure 8: Temperature Distributions at Nose Level at Different Times of Day: (a) 9:00-11:00; (b) 11:00-13:00; and (c) 14:00-16:00; and Comparison of Normalized Temperature at Points Marked on (d) Floor Layout: (e) P1 in Tenant Area and (f) P2 in Corridor

To investigate the seasonal effect, Figure 9 shows temperature sensitivity analysis results for solar radiation during different days of the year. The normalized temperature results at P1 and P2 are also presented in Figures 9 (e) and 9 (f). The difference in overall temperature distribution on the floor among the cases is more significant than in the cases shown in Figure 7. The temperature variation is more substantial in regions close to the curtain walls as well as in the corridors. The toilets become hotter on the 21st of June and 21st of September. This is caused by the hot air coming from the corridor. Heat accumulation is also substantial in the two cases as solar radiation is stronger in these cases than in others. Similar to the cases of different times of the day, the corridor is more sensitive to solar heat and ceiling lamps than in the tenant area. In Figure 8 (f), peaks are formed between 0.6Z and 0.8Z in the corridor for the June 21 and September 21 cases. This is because air heated by the curtain walls near the lift lobby is hotter than the air coming from the tenant area. After entering the corridor, the hot air from the lift lobby is further heated by the ceiling lamps, thereby forming the peaks.

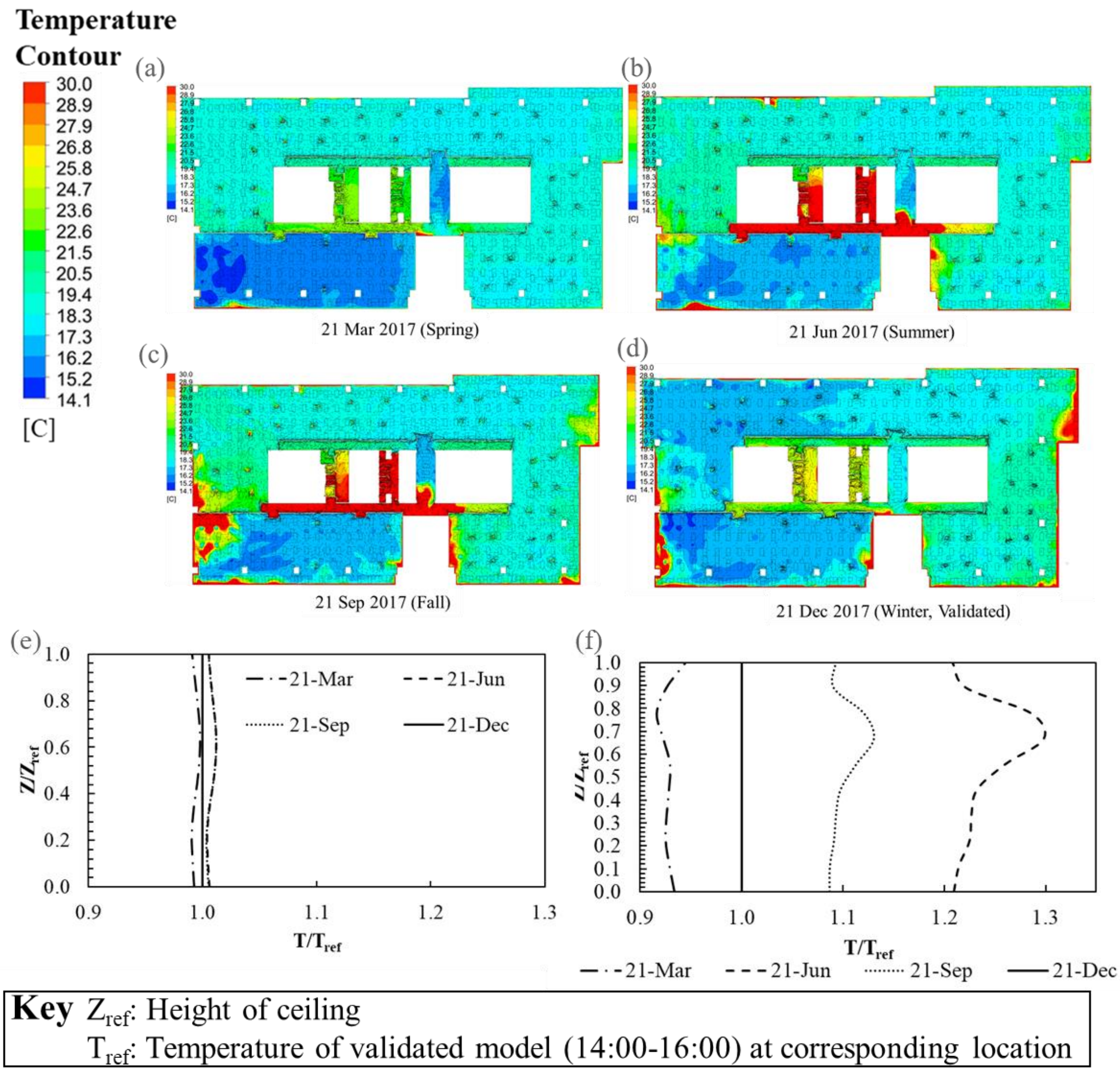

Figure 9: Temperature Distributions on Nose Level for Different Days of Year: (a) 21 Mar; (b) 21 Jun; (c) 21 Sep; and (c) 21 Dec; and Comparison of Normalized Temperature at: (e) P1 in Tenant Area and (f) P2 in Corridor

3.3 Limitations

Limitations in this study are:

1. Variability in body shapes of the office occupants was ignored. Each occupant was represented by a simplified manikin made of rectangular boxes. Airflow around the manikins was distorted.
2. The steady-state CFD simulation was conducted without occupant movements considered. The local variations in air velocity and temperature induced by movements were ignored in this study.
3. Furniture and room partitions inside the tenant areas were omitted. Hence, the deviations in airflow pattern caused by room layouts was not taken into account.

4. Conclusion and Future Study

The paper proposed a workflow to use a BIM multi-zone model to conduct a sensitivity analysis on air velocity and temperature to different door gap sizes and solar radiation under different weather conditions. The workflow was illustrated with a typical office floor. The sensitivity analysis on air velocity for different door gap sizes was conducted for door gap size of 1-5% of the door panel. The results show that a door gap size > 3% of the door panel is able to simulate the sharp increase in velocity when air is passing through the door gaps. As for the temperature sensitivity analysis results for solar radiation during different weather conditions, the zone without an MVAC system installed becomes more sensitive to solar radiation than the zone with an MVAC system operating. For future studies, how sensitive airflow is in different zones to different ventilation settings should be investigated. Moreover, how human movements, furniture and room partitions inside tenant areas alter the airflow pattern should be studied.

5. References

ANSYS INC (2018). Fluent User's Guide.

ASHRAE (2013). Handbook of Fundamentals. Atlanta: American Society of Heating, Refrigerating and Air Conditioning Engineers.

AUTODESK INC (2015). Autodesk Insight Frequently Asked Questions.

AUTODESK INC (2018). Revit.

GILANI, S., MONTAZERI, H., BLOCKEN, B. (2016). CFD simulation of stratified indoor environment in displacement ventilation: Validation and sensitivity analysis. Build. Environ. 95, pp. 299-313.

KALLIOMAKI, P., SAARINEN, P., TANG, J. W., KOSKELA, H. (2016). Airflow patterns through single hinged and sliding doors in hospital isolation rooms - Effect of ventilation, flow differential and passage. Build. Environ. 107, pp. 154-168.

KWOK, H. H. L., CHENG, J. C. P., LI, A. T. Y., TONG, J. C. K., LAU, A. K. H. (in press). Improving the Accuracy of Multi-zone Indoor Temperature CFD Simulation Under Limited Information Using Solar Analysis and BIM. CIB WBC 2019.

LEE, S., PARK, B., KURABUCHI, T. (2016). Numerical evaluation of influence of door opening on interzonal air exchange. Build Environ 102, pp. 230-242.

MENTER, F. R. (1994). 2-Equation Eddy-Viscosity Turbulence Models for Engineering Applications. Aiaa J 32, pp. 1598-1605.

NIELSEN, P. V. (2015). Fifty years of CFD for room air distribution. Build Environ 91, pp. 78-90.

SABERIAN, A., SAJADIYE, S. M. (2019). The effect of dynamic solar heat load on the greenhouse microclimate using CFD simulation. Renew Energ 138, pp. 722-737.

SHAN, W. Y., RIM, D. H. (2018). Thermal and ventilation performance of combined passive chilled beam and displacement ventilation systems. Energ Buildings 158, pp. 466-475.