

Sustainability through Optimal Design of Buildings for Natural Ventilation using Updated Comfort and Occupancy Models

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Abstract

This paper explores the benefits of incorporating natural ventilation (NV) simulation into a generative process of designing residential buildings to improve energy efficiency and indoor thermal comfort. Our proposed workflow uses the Wave Function Collapse algorithm to generate a diverse set of plausible floor plans. It also includes post-COVID occupant presence models while incorporating adaptive comfort models. We conduct four sets of experiments using the workflow, and the simulated results suggest that multi-mode cooling strategies combining conventional air conditioning with NV can often significantly reduce energy use while introducing only slight reductions in thermal comfort.

Introduction

Buildings account for roughly 30% of global final energy use and over 55% of global electricity consumption (IEA 2019; IEA 2022). Between 1990 and 2016, the energy consumption for space cooling in buildings more than tripled, and the cooling load is the primary contributor to rising energy demand in the building sector. Furthermore, about 70% of the air conditioning (AC) units sold annually are for residential buildings, and their output capacity accounts for 70.3% (848 GW) of the total output capacity of AC units across building types (IEA 2018). Strategies for reducing cooling loads in residential buildings have the potential to significantly mitigate energy consumption and carbon dioxide emissions in the building sector.

Passive techniques are some of the oldest ways to enhance occupants' thermal comfort and decrease energy demand from heating and cooling loads (Tejero-González et al. 2016; Cheng et al. 2018). Despite their long-standing history, these techniques remain promising due to their low installation and operating expenses, minimal carbon dioxide emissions, high durability, and low noise levels, in comparison to mechanical systems (Prajongsan and Sharples 2012; Zhang et al. 2021).

Natural ventilation (NV) is among the most potentially

beneficial passive cooling techniques available for improving energy efficiency, indoor thermal comfort, and air quality in residential buildings (Mushtaha et al. 2021; Fereidani, Rodrigues, and Gaspar 2021; Laurini et al. 2018; Wen et al. 2023). NV systems consist of purpose-built openings for ventilation, such as wind-induced airflow, the buoyancy (stack) effect, or hybrid ventilation, to provide convective heat dissipation and increase evaporative heat loss from human bodies (Prajongsan and Sharples 2012; Zhang et al. 2021). NV has been shown to significantly decrease building energy use in many countries with varying climate features. For instance, in Spain, combining the air-conditioning system with NV resulted in a reduction of up to 29.5% of HVAC operating hours (Castaño-Rosa, Rodríguez-Jiménez, and Rubio-Bellido 2018). In Andalusian schools, NV systems reduced annual primary energy usage by 18% to 33% (Gil-Baez et al. 2017). Additionally, NV contributed to a 24% reduction in energy use of air conditioning systems in Hong Kong (Gil-Baez et al. 2017; Yik and Lun 2010). NV is therefore seen as a key passive cooling technique that can help minimize energy consumption compared with conventional AC systems.

Designing an effective NV system remains difficult due to its dependence on the climate and various design variables, such as outdoor temperature, wind direction, building shape, orientation, plan layout, and window size (Wen et al. 2023; Cheng et al. 2018; Zhou et al. 2014). Evaluating NV performance can be challenging due to its complexity, making it difficult for architects and stakeholders to make design decisions and adopt NV systems. Moreover, buildings designed and constructed for conventional cooling can be challenging to later modify to support NV systems (Tejero-González et al. 2016). For this reason, integrating NV simulation with an automated generative geometry modeler may be helpful as a mean of exploring diverse building forms with high NV performance during the early design stage (Wen et al. 2023; Chen, Yang, and Sun 2016; Malkawi et al. 2016; Li and Chen 2021).

This paper aims to advance the modeling of NV solutions

by exploring a simulation-based workflow with the following features: 1) the utilization of the Wave Function Collapse (WFC) algorithm to generate mid-rise residential buildings with a diverse set of floor plan layouts; 2) the incorporation of up-to-date occupant presence models that reflect post-COVID behavior in residential buildings; and 3) the adoption of thermal comfort models that account for the thermal sensations of residential building occupants as reported in the literature. We envision the presented workflow as a step toward creating a generative tool for planning and optimizing naturally ventilated buildings during the early design stage. As a preliminary step toward this goal, we conduct four sets of simulation-based experiments using the workflow across various climate zones to assess the impact of different building layouts, orientations, and cooling strategies on energy consumption and occupant comfort in buildings. The experiments provide insight into the use of WFC-based geometry generation when comparing a) conventional AC strategies, b) NV strategies, and c) multi-mode (MM) strategies that combine AC and NV.

Related Work

Recently, simulation tools have been combined with generative geometry modeling tools to explore optimal combinations of multiple design parameters (Grygierek and Ferdyn-Grygierek 2018; Weerasuriya et al. 2019; Omrani et al. 2017). This process involves iterative evaluation and feedback on the impact of NV on building performance, with the goal of finding an optimal building design. For example, Zhou et al. (2014) explored optimal building orientation and spacing to reduce the age of indoor air, while Grygierek and Ferdyn-Grygierek (2018) investigated optimal combinations of building orientation, glazing type, window area, and thermal insulation (Zhou et al. 2014; Grygierek and Ferdyn-Grygierek 2018). Yoon et al. (2020) focused on exploring window-opening positions to optimize NV performance, while Ameer et al. (2020) explored window-opening areas (Yoon et al. 2020; Ameer, Kharbouch, and Mimmet 2020). Yin et al. (2023) optimized window type, window position, opening fraction, and furniture placement to maximize the air change rate in a room (Yin et al. 2023). The recent NV-related generative modeling research mainly focused on building characteristics, such as window dimension and position, or building orientation; however, only few studies considered occupant-related factors to precisely evaluate NV, including occupant comfort models and occupancy schedules.

To reflect precise occupants' thermal comfort and occu-

pancy schedules, several comfort and occupancy models have been proposed. One of the standardized comfort models is the Predicted Mean Vote (PMV), which predicts the mean value of a large group of people by considering indoor temperature, thermal radiation, relative humidity, air velocity, occupants' metabolic rate, and clothing insulation (ASHRAE 2005). However, this model estimates occupants' comfort based on the heat balance model, ignoring the psychological dimension of adaptation, increasing gap between the estimated and actual comfort temperature in naturally ventilated buildings where occupants control operable windows (De Dear and Brager 2002). To overcome this limitation, ASHRAE RP-884 collected 21,000 sets of raw field data, and used statistic analysis to develop regression models for "adaptive comfort". These models showed higher accuracy for predicting thermal comfort in naturally ventilated buildings than the PMV model; however, they may have limitations when applied to naturally ventilated or multi-mode residential buildings due to the relatively small number of such building in the dataset (De Dear et al. 2020). Moreover, an extensive review conducted by Kim and de Dear (2021) concluded that the adaptive comfort model consistently outperformed the PMV model with a better alignment between the occupants' actual comfort votes in multi-mode buildings and predicted comfort values although occupants in the multi-mode buildings have reported higher satisfaction levels and wider comfort ranges than existing standardized models.

Since the outbreak of COVID-19, traditional workplace practices and employees' workplace preferences have undergone a drastic transformation. In the United States, for example, 48% of Americans still anticipate having the option to work from home after the pandemic, which represents approximately a 30% increase compared to the pre-COVID period (Yang et al. 2022; Javadinasr et al. 2022). In the case of Canada, 32% of Canadian employees worked most of their hours from home at the beginning of 2021, while only 4% did in 2016 (Mehdi and Morissette 2021). In the Netherlands, 27% of teleworkers responded in April 2020 that they expected to work more from home in the future (De Haas, Faber, and Hamersma 2020). The growing number of teleworkers has also altered the pattern of HVAC usage and electricity consumption in residential buildings (Sirati, O'Brien, and Cruickshank 2023; Villeneuve et al. 2021). Currently, occupancy profiles from the 1989 version of ASHRAE 90.1 and ASHRAE Advanced Energy Design Guide are among the most commonly used for building energy modeling software programs (Mitra et al. 2021). However, these profiles appear outdated in light of post-

COVID occupancy patterns reported in the recent literature. We therefore strive to use up-to-date occupancy models, and we submit that this should become standard practice to ensure that the COVID pandemic’s lasting effects on daily life are reflected in building energy and comfort simulations.

In summary, despite the importance of comfort and occupancy models for evaluating NV performance, few research articles have considered post-COVID occupancy schedules and adaptive comfort models in NV simulation. To overcome this limitation, this paper integrates the following additional models with the NV simulation: 1) an updated occupancy schedule to reflect post-COVID behaviors in residential buildings and 2) alternative thermal comfort models to account for occupants’ thermal sensations inside naturally ventilated or multi-mode residential buildings.

This research encompasses four sets of experiments conducted using the developed workflow. Firstly, a large population of buildings was generated, and simulations were performed on this population to test the capabilities of the workflow. Secondly, the study investigated the impact of different cooling strategies on energy consumption and occupant thermal comfort across various climate zones. Thirdly, the research explored the influence of building orientation on energy usage. Lastly, the fourth experiment involved visually comparing the hourly changes in energy consumption and occupants’ thermal comfort among different cooling strategies to gain insight into their relative performance.

Methodology

The workflow developed for this research consists of five steps:

- 1- *Selecting the modeling parameters*: This involves determining the input parameters that are relevant to the simulation model.
- 2- *Generation of building geometries*: This step involves creating the 3D model of the building, which is necessary for the simulation process.
- 3- *Generating the simulation-ready models*: In this step, the building model is converted into a simulation-ready format. The user can choose their desired occupancy and comfort models, or they can use the default values provided by the simulation software.
- 4- *Conducting the simulation*: The simulation is run using the parameters and model created in the previous steps.
- 5- *Data analysis on the results obtained*: The results ob-

tained from the simulation are analyzed to draw conclusions and insights.

Figure 1 illustrates these steps. Each step of the workflow will be discussed in detail in the sub-sections of Section .

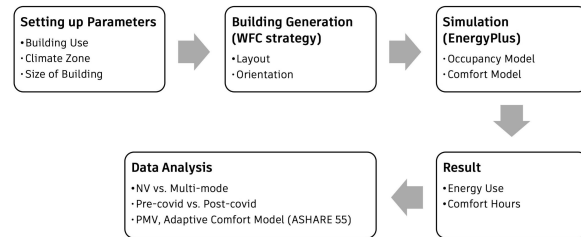


Figure 1: The workflow of the research.

Selecting the modeling parameters

Firstly, this project set up input parameters for energy and thermal comfort simulation focusing on mid-rise apartments. Over the last three decades, the share of new mid-rise apartment buildings, which have five to twelve floors, has upsurged from 6% in the 1990s to 41% of buildings under construction due to stronger demand for urban living and more expensive cost of land than before (Sarac 2019). Considering this trend in the residential building sector, the input parameters for simulating mid-rise apartments are determined based on a technical report written by the National Renewable Energy Laboratory, such as the number of people per area, infiltration rate, energy consumption from lighting per area, etc. (Deru et al. 2011)

Next, climate zones were selected to comparatively analyze the effect of climate zones on a building. Department of Energy and ASHRAE Standard 90.1-2004 classify climate zones into 16 categories based on temperature (Zone 1 to 8) and relative humidity (Zone A to C) (Deru et al. 2011; Baechler et al. 2010). Among them, this project mainly focuses on the following six cities to leverage relatively comfortable climates for enhancing indoor thermal comfort, as shown in Figure 2: Houston (2A), Phoenix (2B), Atlanta (3A), Los Angeles (3B-CA), Las Vegas (3B-other), and San Francisco (3C). As shown in Figure 3, each climate shows different patterns of outdoor temperature and relative humidity.

Generation of building geometries

To automatically generate building geometries, this project adopts the Wave Function Collapse (WFC) algorithm that enables a geometry-generation model to syn-

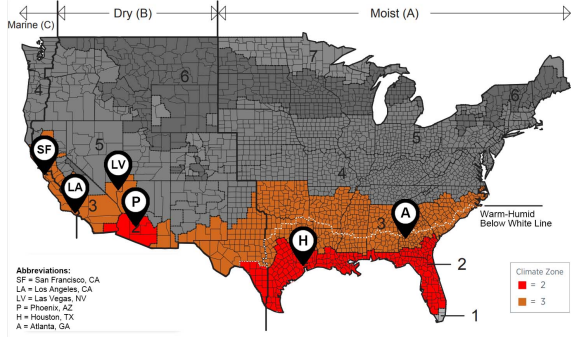


Figure 2: Selection of climate zones

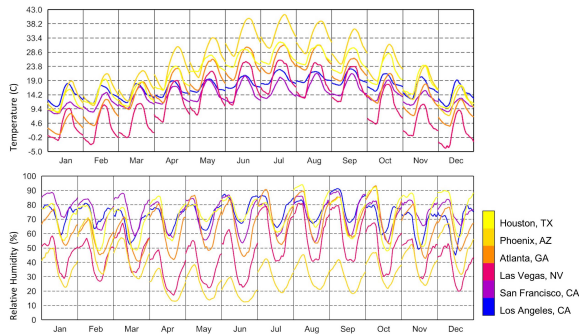


Figure 3: Outdoor temperature and relative humidity of the selected climate zones

these constrained design variations using a sparse set of input examples in a manner compatible with multi-objective search methods through variable inputs for tile weights (Villaggi, Stoddart, and Gaier 2022; Karth and Smith 2017; Sandhu, Chen, and McCoy 2019). To generate diverse variations of building layouts, the WFC algorithm combines different types of unit tiles—like end wall, side wall, corridor, core, and empty tile—based on rules learned from the provided input samples. First, a series of 300 WFC solutions was generated using a randomized sampling of tile input weights and a 40 x 40 output dimension, each containing multiple candidate building layouts. Second, 553 individual unique building layouts were automatically extracted from the generated solutions using graph-based methods with rotational variants and candidates containing no building cores discarded. Third, feature characteristics were computed for each unique building layout, including counts of building tiles, corners, building cores, building envelope tiles, and individual apartments. Additionally, a series of geometric descriptors were computed including the minimal bounding box area, the normalized aspect ratio, and the

compactness of the design (a ratio of building tiles to bounding box area). Figure 4 illustrates the generation process using the WFC.

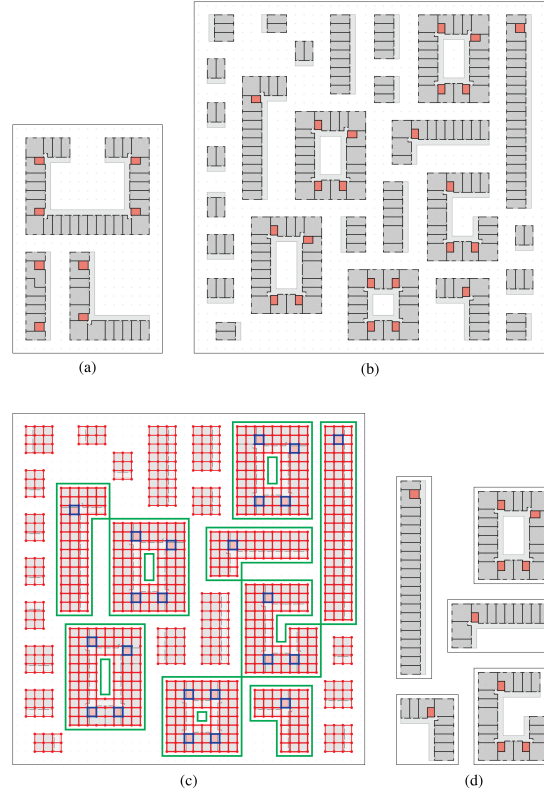


Figure 4: (a) Input example for training WFC model, indicating reference building configurations; (b) Output 40x40 solution from WFC solver containing multiple building layout candidates; (c) Tile grouping using graph analysis with red edges indicate building tile connections, blue edges indicate building core connections, and green outlines indicate valid layouts (containing at least one building core) for extraction; (d) Examples of isolated and extracted building layouts.

From the computed 553 unique candidates, a subset of 189 layouts containing 10 to 15 apartment units was isolated to compare similarly-sized buildings with different layouts to analyze the influential factors on NV. An issue with simulating layouts containing fully-enclosed void space, primarily ring-shaped buildings, led to the exclusion of 13 layouts. After excluding the failed geometries, 176 building layouts are prepared for generating simulation-ready models. As shown in Figure 5, we selected four different types of buildings with open cor-

ridors for the analysis and comparisons: single-loading corridor, double-loading corridor, L-shaped corridor, and court-yard type. This is because corridors play a significant function in directing outdoor air into the building and facilitating cross ventilation (Aflaki et al. 2015; Siew et al. 2011).

Generating the simulation-ready models

As shown in Figure 6, Grasshopper in Rhinoceros software, Ladybug, and Honeybee plug-ins are used for automating the generation of energy models from the building geometries, and we set up EnergyPlus-based simulation environments combining alternative assumptions for building orientation, heating and cooling strategies, occupancy schedules, and thermal comfort models.

To compare the influence of air-conditioning mode, natural ventilation mode, and multi-mode systems, different parameters are applied: 1) for the air-conditioning mode, all the windows are closed and HVAC system is turned on to ensure the indoor temperature between 21.7°C and 24.4°C, which are setpoints suggested by the NREL technical report (Deru et al. 2011); 2) for the natural ventilation mode, the HVAC system is turned off, and windows are opened or closed to ensure the room temperatures between 21°C and 28°C. Windows are opened or closed only when outdoor temperature is at least 3°C lower than indoor temperature as the main purpose of the window operation is for space cooling. The windows are operated while the outside temperature is in the range of 18°C to 25°C. 3) for the multi-mode, windows are operable same as NV mode. HVAC will be running if the indoor temperature is lower than 20°C or higher than 29°C. We assumed a 1-degree buffer zone between the temperature thresholds of HVAC and NV modes to avoid unnecessarily frequently switching between AC and NV modes around the temperature thresholds.

To apply realistic pre-COVID and post-COVID occupancy patterns, occupancy schedule data was obtained from Mitra et al. (2021). For developing pre-COVID US residential occupancy profiles, the researchers set up their dataset based on the American Time Use Survey and Current Population Survey conducted by the US Census Bureau; for the post-COVID residential occupancy profiles, they implemented field survey data. This dataset provides occupancy fraction information prior to, during, and after the COVID-19 pandemic period, and each group is subdivided into weekday/weekend and high/middle/low-income levels. As a preliminary study, we mainly focus on the occupancy fractions for the three periods with middle-income levels, as shown in Figure 7.

The occupancy fraction value ranges from 0 to 1, where 0 represents no occupant is at home; 1 represents all occupants present.

For evaluating occupants' comfort based on the simulated indoor environment, PMV and adaptive comfort models are adopted, and their approaches are different. The PMV model estimates comfort values based on the heat balance model by considering indoor temperature, thermal radiation, relative humidity, air velocity, occupants' metabolic rate, and clothing insulation (ASHRAE 2005). On the other hand, the adaptive comfort model calculates the optimal comfort temperature based on the mean outdoor dry bulb temperature (De Dear and Brager 2002).

Conducting the simulation

The workflow provides simulation results as two metrics: energy use intensity (EUI) and percentage of neutral time (PNT). EUI is the total energy consumption per year divided by the gross floor area of the building. That is, the low EUI of the building represents high energy performance. On the other hand, PNT represents the percentage of time when the comfort level is within acceptable limits that vary depending on comfort models. These two metrics are mainly used for comparatively analyzing the performance of the energy models with different heating/cooling strategies, comfort models, and occupancy models. Please note that the PNT results shown in the paper are based on Adaptive Comfort Model (ACM); this model has shown higher accuracy for predicting thermal comfort in naturally ventilated buildings and better reflects the psychological dimension of occupants' adaptation inside their homes than the PMV model (De Dear and Brager 2002).

Results

Simulating a set of buildings with diverse forms and orientations

This first study involved taking the 176 generated building layouts and simulating their performance for each of the 12 orientation angles. The investigated models included generated layouts that were oriented at angles ranging from 0 through 330 degrees with a step size of 30 degrees.

Figure 8 illustrates the Aspect Ratio, Footprint, Facade, and Compactness measures of the generated building population; the x-axis of the images shows the ID-number of the buildings in this population. In this context, Aspect Ratio refers to the normalized aspect ratio

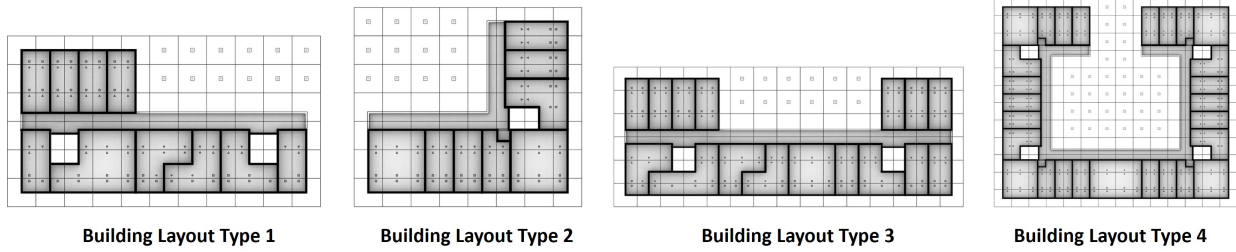


Figure 5: The four building layout types selected for the analysis.

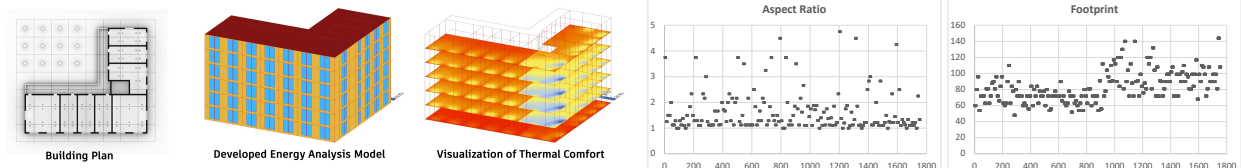


Figure 6: The sample building layout, its developed energy analysis model, and thermal comfort results.

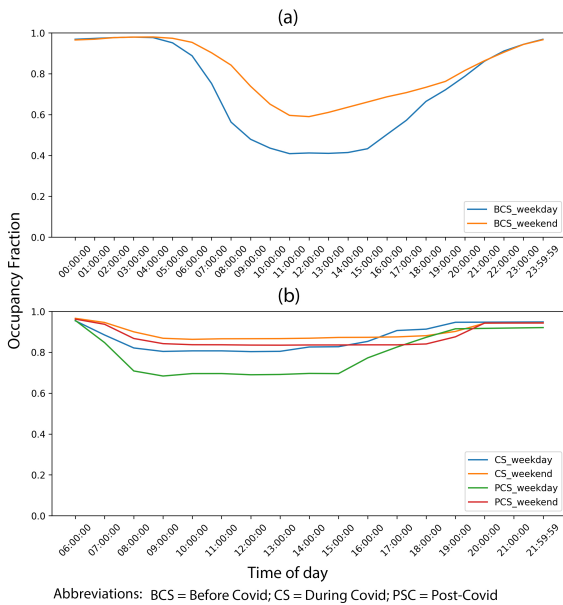


Figure 7: Average occupancy schedule before, during, and after COVID-19 pandemic on weekdays and weekends (regenerated based on the collected data from Mitra et al. (2021))

for the building footprint, calculated as the maximum of the width and length divided by the minimum. Footprint refers to the minimal bounding box area of the building pattern (width multiplied by length including open space). Facade refers to the count of tiles correspond-

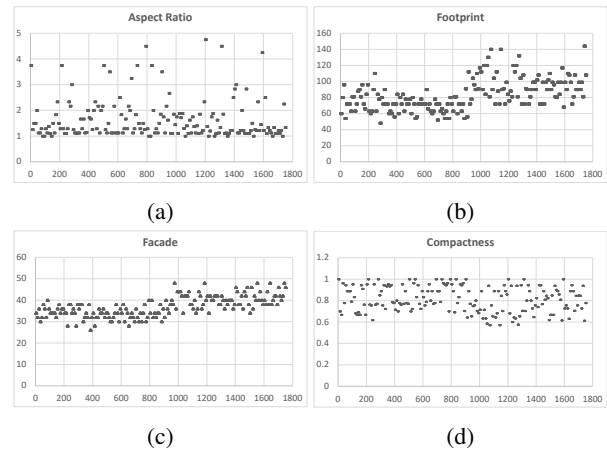


Figure 8: (a) Aspect Ratio, (b) Footprint, (c) Facade, (d) Compactness values for all generated and modeled buildings. The x-axis of the plots represents the ID-numbers of the buildings in the population.

ing to the building envelope, i.e., the outer perimeter of the buildings. Compactness refers to the percentage of the footprint occupied by building tiles, calculated as the count of tiles corresponding to building elements divided by the footprint.

The simulations were run for all the buildings using the MM cooling strategy. The simulations were conducted for the Phoenix, AZ location, which is classified as climate zone 2B (hot and dry). The occupancy presence model considered a post-COVID scenario and households with a middle-income level.

The results obtained for EUI are displayed in Figure 9, showing a 10% difference in EUI within the dataset. The study also observed a 16% and 22% difference in the Predicted Mean Vote (PMV) and Adaptive Comfort model, respectively, for the buildings' PNT, obtained based on Adaptive Comfort Model. The results obtained for PNT are not shown here.

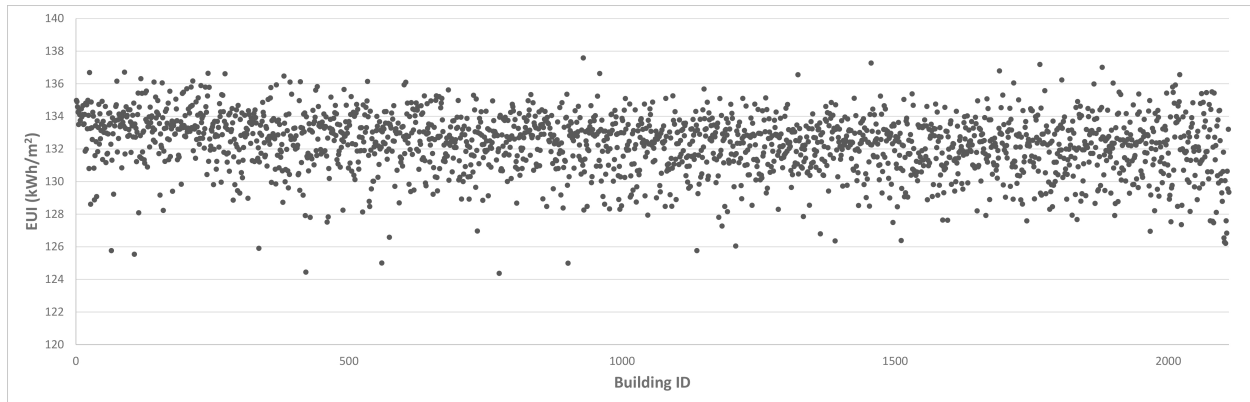


Figure 9: The EUI obtained for all of the simulated buildings, assuming: Phoenix, AZ location, MM cooling strategy, a post-COVID occupancy presence model, and middle-income households.

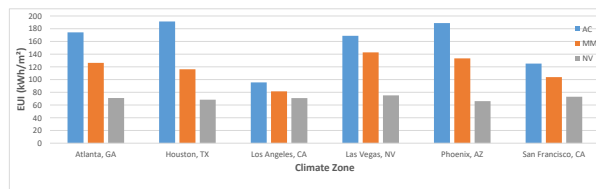


Figure 10: The EUI values obtained for the 6 climate zones, 3 cooling strategies, and Type-2 building layout. A lower EUI indicates higher energy efficiency and a more sustainable building design.

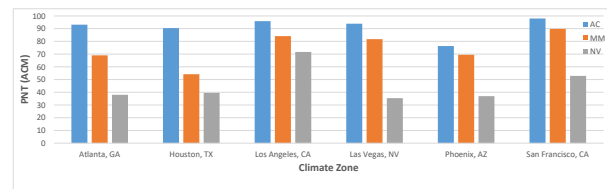


Figure 11: The PNT obtained for the 6 climate zones, 3 cooling strategies, and a Type-2 Buildings Layout. A higher PNT indicates a greater level of thermal comfort and suggests that the building design is successful in meeting the occupants' comfort needs.

Exploring 3 cooling strategies in 6 climate zones

Figures 10 and 11 provide a comparison of the EUI and PNT data obtained for 6 different climate zones. These simulations were conducted using the assumption of a post-COVID occupancy presence model and households with a medium income level. The simulations were conducted on Building Layout Type 2 shown in Figure 5.

Across all climate zones, it was observed that the NV and MM modes resulted in lower energy consumption compared to the HVAC mode. However, the use of NV and MM modes led to a decrease in PNT. Although this reduction may not be ideal, it is important to note that the acceptability of the PNT level depends on the specific region and its comfort standards.

Exploring the impact of building orientation on energy usage

The study examined the impact of building orientation on energy usage for the 4 building layouts presented in Figure 5. Figure 12 displays the EUI obtained for

these buildings when oriented at angles ranging from 0 through 330 degrees with a step size of 30 degrees. These simulations were conducted for the Phoenix, AZ location and using an AC cooling mode.

The results highlight that both the trend and level of EUI change depending on the orientation and building form. This suggests that while general rules of thumb can provide rough estimates on energy savings through building orientation, considering the specific building form can provide better estimations, even during the early stages of design.

The percentage difference in the EUI and PNT levels obtained for Type 3 Building Layout, presented in Figure 5, comparing the AC mode and MM mode at different orientations, is presented in Figure 13. The simulations were conducted for the Phoenix, AZ location.

The results show a significant reduction in EUI, approximately 40%, when the MM mode is utilized. On the other hand, the decrease in PNT is only 10%. It is important to note that the change in PNT level depends on the

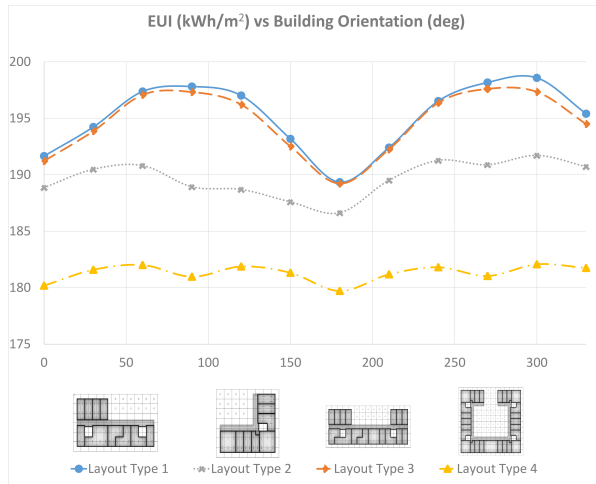


Figure 12: Impact of building form and orientation on EUI. The trend and the level of EUI change depends on the orientation as well as building form.

selected thermal comfort model. In this case, an Adaptive Thermal Comfort model was employed for the comparison and analysis.

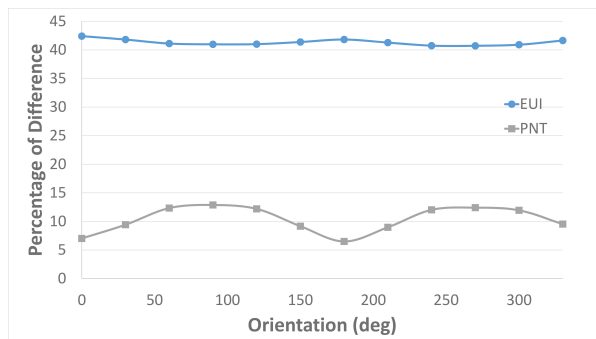


Figure 13: The percentage difference in the EUI and PNT levels obtained for a Type 3 Building Layout, comparing the AC mode and MM mode at different orientations.

Exploring hourly EUI and PNT for 3 cooling strategies

Figure 14 provides a visual comparison of the hourly values of EUI and PNT for the month of June in a simulation case for Building Layout Type 2, assuming a San Francisco location. The results show that the MM cooling strategy reduces EUI by approximately 11% compared to the HVAC strategy, while still maintaining reasonable PNT values above 85%.

Preliminary results for Houston and Atlanta (not shown in the figure) indicate even larger potential decreases in energy consumption levels: 32.5% for Houston and 22.1% for Atlanta. However, the simulations suggest that natural ventilation alone is not sufficient to maintain the indoor climate within an acceptable range.

The images in Figure 14 illustrate the hours of the day with poor PNT levels, indicating either hot or cold sensations for the occupants, as well as the times with peak energy consumption levels. This information can be utilized in the design of smart controllers and advanced energy-saving strategies and technologies. For instance, green energies can be generated/collected and stored during specific hours of the day and used to power the MM system during hours with low PNT, optimizing both energy usage and occupant comfort.

Discussion

This research presents a developed workflow for generating, modeling, and simulating diverse building types and layouts with different orientations, specifically focusing on incorporating passive cooling techniques, such as NV, in the early design stages of sustainable household apartment buildings. The workflow consists of five steps: selecting modeling parameters, generating building geometries using the WFC algorithm, converting the models into a simulation-ready format, conducting the simulations, and analyzing the obtained results. The workflow offers a range of simulation options, including different ventilation methods (NV, MM, AC), occupancy presence models, and thermal comfort assessment models. The simulation results are evaluated in terms of the EUI, representing energy consumption per square foot per year, and the PNT, representing the percentage of time when occupants experience a comfortable indoor environment.

The research experiments in this project aimed to provide insights into the impact of utilizing different cooling strategies and support the design of more energy-efficient and comfortable residential buildings. The experiments assessed the impact of cooling strategies on energy consumption and thermal comfort by comparing air-conditioning, natural ventilation, and multi-mode cooling strategies, considering various parameters. To address the limitations of existing studies in evaluating NV performance, the research integrates updated occupancy schedules to reflect post-COVID behaviors and alternative thermal comfort models for assessing occupants' thermal sensation in naturally ventilated or multi-mode residential buildings.

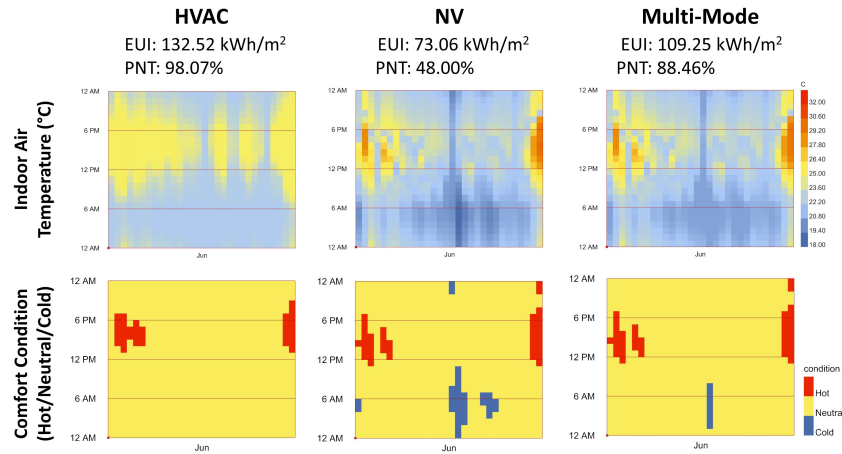


Figure 14: A visual comparison of the hourly values of EUI and PNT for the month of June in a simulation case for Layout Type 2, assuming a San Francisco location

The first research experiment generated and simulated a large set of buildings. The results highlighted that the large pool of data generated by the simulations can be challenging for humans to digest. While optimization engines can assist in the process of optimal design selection or knowledge inference, they are probably not sufficient on their own. Therefore, AI-driven technology has the potential to greatly benefit designers and stakeholders in tailoring specific buildings by rapidly exploring different options for larger design projects and surfacing near-optimal designs. The technology can also be utilized to extract and present knowledge from the data in various interactive formats, including text, images, and video, to aid decision-making processes. Moreover, a few high-performing building design options can be selected with and passed on to the next design stages. Further detailed analysis can be conducted on these cases by providing additional design information available in later design stages. The selected cases can also be moved to high-fidelity analysis tools such as computational fluid dynamics (CFD) for more detailed analysis.

The second research experiment indicated that both the NV and MM cooling strategies result in lower energy consumption compared to the conventional HVAC mode across all of the examined climate zones. On the hand, the use of NV and MM modes lead to a decrease in PNT, and it is important to observe that NV alone may not adequately maintain the indoor climate within an acceptable range. Our results suggest that implementing the MM mode could lead to substantial improvements in energy efficiency, with a noteworthy decrease in EUI of about 18% to 40%. Although there is a slight reduction in ther-

mal comfort (PNT-ACM) compared to the AC mode, it is important to consider the overall trade-off between energy efficiency and occupant comfort. It is worth noting that the acceptability of the reduced PNT level depends on the specific region and its comfort standards. The contribution of MM mode to energy saving is aligned with previous research works. González-Lezcano and Hormigos-Jiménez (2016) reported 13% saving of total cooling energy combining HVAC with NV in social housing in Spain, and Weerasuriya et al. (2019) and Yik and Lun (2010) showed 8-27% and 25-50% reduction of the energy consumption of residential buildings in Hong Kong, respectively. However, the proposed workflow has room to increase energy savings by optimizing window size, window position, thermal insulation, etc. Additional design variables will be included for improving energy efficiency in future work.

The third experiment shows that considering the orientation and form of a building is highly advisable for accurate estimations of energy savings during the early design stages. While general rules of thumb provide rough estimates, the research demonstrates that the trend and level of EUI vary based on these factors. It is important to consider the interaction between building form and orientation when aiming for energy efficiency. Simply relying on general guidelines for building orientation may not be sufficient, as the specific form of the building can have a notable influence on the EUI. Therefore, a comprehensive approach that takes into account both building form and orientation is necessary to achieve accurate estimations and optimize energy performance during the early design process.

The fourth research experiment highlights hourly simulation results and determines the hours of the day with poor PNT levels, indicating discomfort for occupants, as well as the peak energy consumption times. This information can be utilized to design smart controllers and advanced energy-saving strategies, such as generating and storing green energy during specific hours to power the MM system when the PNT is low. Such an optimization approach would aim to effectively balance energy usage and occupant comfort over time.

It should be noted that the results obtained in this work are approximate and may vary depending on specific building characteristics and simulation conditions. The goal of this work was to provide reasonable evaluations for the energy consumption and occupants' thermal comfort inside buildings at early design stages where limited design data is available.

In the future, we are planning to expand the capabilities of the developed workflow by providing more simulation options including controllers for running the MM and AC systems. In addition, we aim to develop a user interface for the workflow. On the experimental side, we are planning to develop a surrogate model based on the simulation results to let designers and decision-makers infer knowledge from the pool of the data in a more efficient way. The model could be also incorporated into a tool to speed the search for optimal sustainable designs.

Conclusion

This research introduces a developed workflow for generating, modeling, and simulating diverse building types and layouts with different orientations, with a focus on incorporating passive cooling techniques like natural ventilation (NV) in the early design stages of sustainable household apartment buildings. The workflow was used to perform four research experiments in order to evaluate the impact of cooling strategies on energy consumption and thermal comfort of occupants inside buildings.

The findings emphasize the benefits of implementing MM cooling strategy, as it significantly improves energy efficiency with a notable decrease in EUI. Although there is a slight reduction in thermal comfort compared to the AC mode, the trade-off between energy efficiency and occupant comfort must be considered. However, the study highlights that relying solely on NV may not be sufficient to maintain an acceptable indoor climate. The findings demonstrate the importance of considering the interaction between building form and orientation when aiming for energy efficiency. Simply relying on general guidelines for building orientation may not be sufficient,

as the specific form of the building can have a notable influence on the EUI.

While the use of the WFC algorithm can help generate a diversity of design options that vary in their interior layouts as well as orientation, the large amount of data produced by the ensuing simulations may be challenging for architects to interpret. To aid the decision-making process, knowledge extraction from the data and AI-driven technology could be highly beneficial for designers and other stakeholders. These technologies can provide information in interactive formats facilitating tailored building design and exploration of options for larger-scale projects.

References

- Aflaki, Ardalan, Norhayati Mahyuddin, Zakaria Al-Cheikh Mahmoud, and Mohamad Rizal Baharum. 2015. "A review on natural ventilation applications through building façade components and ventilation openings in tropical climates." *Energy and buildings* 101:153–162.
- Ameur, Mohamed, Yassine Kharbouch, and Abdelaziz Mimet. 2020. "Optimization of passive design features for a naturally ventilated residential building according to the bioclimatic architecture concept and considering the northern Morocco climate." *Building Simulation*, Volume 13. Springer, 677–689.
- ASHRAE. 2005. "Ergonomics of the thermal environment: Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria." International Organization for Standardization.
- Baechler, Michael C, Jennifer L Williamson, Theresa L Gilbride, Pamala C Cole, Marye G Hefty, and Pat M Love. 2010. "Building America best practices series: volume 7.1: guide to determining climate regions by county." Technical Report, Pacific Northwest National Lab.(PNNL), Richland, WA (United States).
- Castaña-Rosa, Raúl, Carlos E Rodríguez-Jiménez, and Carlos Rubio-Bellido. 2018. "Adaptive thermal comfort potential in mediterranean office buildings: a case study of Torre Sevilla." *Sustainability* 10 (9): 3091.
- Chen, Xi, Hongxing Yang, and Ke Sun. 2016. "A holistic passive design approach to optimize indoor environmental quality of a typical residential building in Hong Kong." *Energy* 113:267–281.

- Cheng, Jun, Dahai Qi, Ali Katal, Liangzhu Leon Wang, and Ted Stathopoulos. 2018. "Evaluating wind-driven natural ventilation potential for early building design." *Journal of Wind Engineering and Industrial Aerodynamics* 182:160–169.
- De Dear, R, J Xiong, J Kim, and B Cao. 2020. "A review of adaptive thermal comfort research since 1998." *Energy and Buildings* 214:109893.
- De Dear, Richard J, and Gail S Brager. 2002. "Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55." *Energy and buildings* 34 (6): 549–561.
- De Haas, Mathijs, Roel Faber, and Marije Hamersma. 2020. "How COVID-19 and the Dutch 'intelligent lockdown' change activities, work and travel behaviour: Evidence from longitudinal data in the Netherlands." *Transportation research interdisciplinary perspectives* 6:100150.
- Deru, Michael, Kristin Field, Daniel Studer, Kyle Benne, Brent Griffith, Paul Torcellini, Bing Liu, Mark Halverson, Dave Winiarski, Michael Rosenberg, et al. 2011. "US Department of Energy commercial reference building models of the national building stock." Technical Report, National Renewable Energy Laboratory.
- Fereidani, Nazanin Azimi, Eugénio Rodrigues, and Adélio Rodrigues Gaspar. 2021. "A review of the energy implications of passive building design and active measures under climate change in the Middle East." *Journal of Cleaner Production* 305:127152.
- Gil-Baez, Maite, Ángela Barrios-Padura, Marta Molina-Huelva, and R Chacartegui. 2017. "Natural ventilation systems in 21st-century for near zero energy school buildings." *Energy* 137:1186–1200.
- González-Lezcano, RA, and S Hormigos-Jiménez. 2016. "Energy saving due to natural ventilation in housing blocks in Madrid." *IOP Conference Series: Materials Science and Engineering*, Volume 138. IOP Publishing, 012002.
- Grygierek, Krzysztof, and Joanna Ferdyn-Grygierek. 2018. "Multi-objective optimization of the envelope of building with natural ventilation." *Energies* 11 (6): 1383.
- IEA. 2018. "The Future of Cooling." Technical Report, International Energy Agency, <https://www.iea.org/reports/the-future-of-cooling>.
- IEA. 2019. "The Critical Role of Buildings." Technical Report, International Energy Agency, <https://www.iea.org/reports/the-critical-role-of-buildings>.
- IEA. 2022. "Final energy consumption of buildings relative to other sectors." Technical Report, International Energy Agency, <https://www.iea.org/data-and-statistics/charts/final-energy-consumption-of-buildings-relative-to-other-sectors-2022>.
- Javadinasr, Mohammadjavad, Tassio Maggasy, Motahare Mohammadi, Kouros Mohammadain, Ehsan Rahimi, Deborah Salon, Matthew W Conway, Ram Pendyala, and Sybil Derrible. 2022. "The Long-Term effects of COVID-19 on travel behavior in the United States: A panel study on work from home, mode choice, online shopping, and air travel." *Transportation research part F: traffic psychology and behaviour* 90:466–484.
- Karth, Isaac, and Adam M Smith. 2017. "WaveFunctionCollapse is constraint solving in the wild." *Proceedings of the 12th International Conference on the Foundations of Digital Games*. 1–10.
- Kim, Jungsoo, and Richard de Dear. 2021. "Is mixed-mode ventilation a comfortable low-energy solution? A literature review." *Building and Environment* 205:108215.
- Laurini, Eleonora, Mariangela De Vita, Pierluigi De Berardinis, and Avi Friedman. 2018. "Passive ventilation for indoor comfort: A comparison of results from monitoring and simulation for a historical building in a temperate climate." *Sustainability* 10 (5): 1565.
- Li, Wenjing, and Qingchang Chen. 2021. "Design-based natural ventilation cooling potential evaluation for buildings in China." *Journal of Building Engineering* 41:102345.
- Malkawi, Ali, Bin Yan, Yujiao Chen, and Zheming Tong. 2016. "Predicting thermal and energy performance of mixed-mode ventilation using an integrated simulation approach." *Building Simulation*, Volume 9. Springer, 335–346.
- Mehdi, Tahsin, and René Morissette. 2021. "Working from home: Productivity and preferences." *Statistics Canada= Statistique Canada*.
- Mitra, Debrudra, Yiyi Chu, Kristen Cetin, Yu Wang, and Chien-fei Chen. 2021. "Variation in residential occupancy profiles in the United States by household income level and characteristics." *Journal of Building Performance Simulation* 14 (6): 692–711.

- Mushtaha, Emad, Tareq Salameh, Sahar Kharrufa, Taro Mori, Abdelsalam Aldawoud, Rawan Hamad, and Tareq Nemer. 2021. "The impact of passive design strategies on cooling loads of buildings in temperate climate." *Case Studies in Thermal Engineering* 28:101588.
- Omrani, Sara, Veronica Garcia-Hansen, Bianca Capra, and Robin Drogemuller. 2017. "Natural ventilation in multi-storey buildings: Design process and review of evaluation tools." *Building and Environment* 116:182–194.
- Prajongsan, Pimolsiri, and Steve Sharples. 2012. "Enhancing natural ventilation, thermal comfort and energy savings in high-rise residential buildings in Bangkok through the use of ventilation shafts." *Building and environment* 50:104–113.
- Sandhu, Arunpreet, Zeyuan Chen, and Joshua McCoy. 2019. "Enhancing wave function collapse with design-level constraints." *Proceedings of the 14th International Conference on the Foundations of Digital Games*. 1–9.
- Sarac, Florentina. 2019. "High-Rise Apartment Buildings and Mid-Rise Buildings Are Overshadowing Low-Rises for the First Time in 3 Decades." RentCafe, <https://www.rentcafe.com/blog/apartmentliving/high-mid-rise-residential-buildings-overshadowing-low-rise/>.
- Siew, CC, AI Che-Ani, NM Tawil, NAG Abdullah, and M Mohd-Tahir. 2011. "Classification of natural ventilation strategies in optimizing energy consumption in Malaysian office buildings." *Procedia Engineering* 20:363–371.
- Sirati, Melina, William O'Brien, and Cynthia A Cruickshank. 2023. "Household energy and comfort impacts under teleworking scenarios via a zoned residential HVAC system." *Journal of Building Performance Simulation*, pp. 1–15.
- Tejero-González, Ana, Manuel Andrés-Chicote, Paola García-Ibáñez, Eloy Velasco-Gómez, and Francisco Javier Rey-Martínez. 2016. "Assessing the applicability of passive cooling and heating techniques through climate factors: An overview." *Renewable and Sustainable Energy Reviews* 65:727–742.
- Villaggi, Lorenzo, James Stoddart, and Adam Gaier. 2022. "Harnessing Game-Inspired Content Creation for Intuitive Generative Design and Optimization." *Design Modelling Symposium Berlin*. Springer, 149–160.
- Villeneuve, Hannah, Ahmed Abdeen, Maya Papineau, Sharane Simon, Cynthia Cruickshank, and William O'Brien. 2021. "New insights on the energy impacts of telework in Canada." *Canadian Public Policy* 47 (3): 460–477.
- Weerasuriya, Asiri Umenga, Xuelin Zhang, Vincent JL Gan, and Yi Tan. 2019. "A holistic framework to utilize natural ventilation to optimize energy performance of residential high-rise buildings." *Building and Environment* 153:218–232.
- Wen, Liwei, Kyosuke Hiyama, Yu Huang, and Xueting Qin. 2023. "A framework for rapid diagnosis of natural ventilation effect during early design stage using Thermal Autonomy." *International Journal of Green Energy* 20 (7): 752–766.
- Yang, Longqi, David Holtz, Sonia Jaffe, Siddharth Suri, Shilpi Sinha, Jeffrey Weston, Connor Joyce, Neha Shah, Kevin Sherman, Brent Hecht, et al. 2022. "The effects of remote work on collaboration among information workers." *Nature human behaviour* 6 (1): 43–54.
- Yik, Francis WH, and Yu Fat Lun. 2010. "Energy saving by utilizing natural ventilation in public housing in Hong Kong." *Indoor and built Environment* 19 (1): 73–87.
- Yin, Xin, Mohammed W Muhieldeen, Ruzaimah Razman, and Jonathan Yong Chung Ee. 2023. "Multi-objective optimization of window configuration and furniture arrangement for the natural ventilation of office buildings using Taguchi-based grey relational analysis." *Energy and Buildings*, p. 113385.
- Yoon, Nari, Mary Ann Piette, Jung Min Han, Wentao Wu, and Ali Malkawi. 2020. "Optimization of window positions for wind-driven natural ventilation performance." *Energies* 13 (10): 2464.
- Zhang, Haihua, Dong Yang, Vivian WY Tam, Yao Tao, Guomin Zhang, Sujeeva Setunge, and Long Shi. 2021. "A critical review of combined natural ventilation techniques in sustainable buildings." *Renewable and Sustainable Energy Reviews* 141:110795.
- Zhou, Chaobin, Zhiqiang Wang, Qingyan Chen, Yi Jiang, and Jingjing Pei. 2014. "Design optimization and field demonstration of natural ventilation for high-rise residential buildings." *Energy and Buildings* 82:457–465.