DESIGN OPTIMIZATION THROUGH CFD-ABMS INTEGRATION FOR CONTROLLING VIRUS SPREAD

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Abstract. In the wake of the pandemic, the interplay between humans, architecture, and viruses has emerged as a critical area of study. Aerosol transmission particularly within indoor environments is a key factor contributing to infections. However, contemporary research frequently isolates individual strategies such as ventilation, crowd control, protective measures, and emergency protocols, often overlooking a more comprehensive perspective. To bridge this gap, we introduce an integrated design framework for parametric environment that synergizes Computational Fluid Dynamics (CFD) and Agent-based Modeling (ABM). Furthermore, compared to large-scale environments such as cities, there is also less understanding of infection control in interior spaces. This study employs simulations to track the movement of viral particles in airflow and model spatial occupancy by workflow, providing insights into both overall particle transmission trend and spatial occupancy trends. The integration of these dual aspects facilitates a thorough assessment of transmission dynamics. Our findings, based on this integrated approach, offer recommendations for optimizing circulation patterns and spatial zoning, aiming to provide adaptability and flexibility in architectural design.

Keywords. Computational Fluid Dynamics (CFD), Agent-based Modeling (ABM), Infection Control, Post-Pandemic Design, Design Integration, Design Optimization

1. Introduction

1.1. ARCHITECTURE IN THE POST-PANDEMIC ERA

In the current post-pandemic context, spatial usage patterns are undergoing transformations beyond the medical sector. This shift has sparked interdisciplinary discussions, including concepts for future hospitals and the development of rapidly deployable modular wards. Extensive research highlights the pivotal role of architectural configuration and materials in infection control (Zimring et al., 2013).

Contemporary approaches to architecture and infection control predominantly

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focus on isolated strategies like ventilation and crowd management, lacking a comprehensive view. While significant research has explored infection spread in large-scale spaces like cities and regions, most infections occur within buildings (Gomez et al., 2020). In contrast to contact transmission, the dispersion of aerosols has been confirmed as a key transmission route for Covid-19 (Zhang et al., 2020). Direct alterations in architectural design or reduced spatial occupancy for infection prevention are often impractical (Perry et al., 2022). Hence, proactive architectural planning, adaptations in space utilization, and flexible designs are vital (Shangi et al., 2020).

1.2. PARAMETRIC ENVIRONMENT

The analysis of architectural ventilation and human spatial usage has gained significance in the post-pandemic era due to increased awareness of infection control. In domains like ventilation and spatial usage, expertise in Computational Fluid Dynamics (CFD) is essential, usually necessitating the involvement of engineers or professionals skilled in CFD analysis. Quantitative studies and analyses can be performed via data-driven approaches based on Agent-based Modeling (ABM). In recent times, architectural design has evolved into an integrative task, requiring preliminary integration before consulting specialists, ensuring design decisions and receiving immediate feedback (Nguyen and Peter, 2020).

Currently, there is still a gap exists in existing software for integrating these professional insights (Gomez et al., 2021). The advantage of parametric environments such as Rhino Grasshopper (GH) lies in their open-ended architecture, enable comparison of results and design optimization by adjusting design parameters. Compared to other tools, architects find them more accessible for learning and application.

1.3. PROJECT GOAL

To enhance design efficiency by minimizing transitions between different software environments and various specialties, this research aims to establish a comprehensive design framework integrating CFD and ABM methods within a parametric environment. By layering CFD and ABM methodologies, the framework seeks to provide a holistic assessment of transmission trends within spaces. Designers can thus gain insights into the potential impact of design parameters, enabling optimization and informed recommendations (see Figure 1).

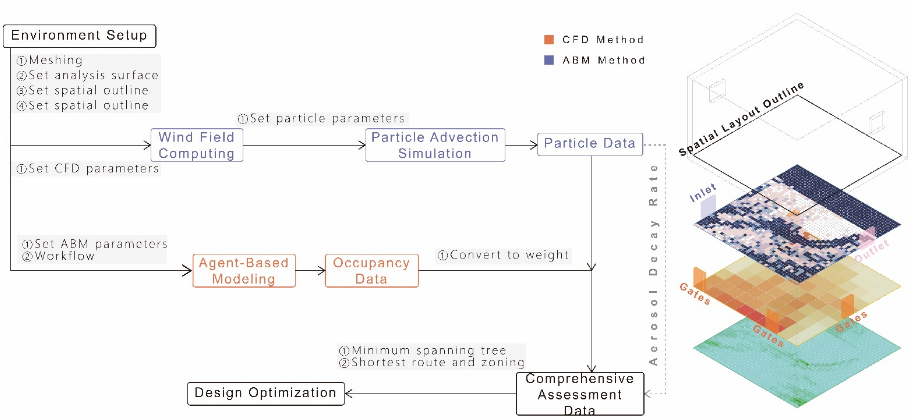


Figure 1. The flowchart and CFD-ABM design framework.

2. Methodologies

Through our literature review, it reveals that post-pandemic architectural design often employs CFD or ABM methodologies to investigate ventilation modes and assess infection risks related to varying behavioural patterns in spaces. In our proposed design framework, we integrate transmission trends of viral particles (SARS-CoV-2) in spatial environments with occupancy trends, overlaying these two layers while considering temporal factors.

In our model, the spatial plane is divided into a two-dimensional grid, representing the width and length of the space. The grid not only signifies the spatial continuity but also allows computational simplification based on the chosen grid size, thereby enhancing computational efficiency (Gomez et al., 2019). Numerical values in each grid cell correspond to computational model results. The chosen space is the ground floor of a campus building, specifically the institute hall, measuring 105.48m^2 with a height of 3.5m. The model, based on this space (see Figure 2), includes spatial environment parameters like meshing, spatial outline definition, analysis surface setting, and grid setting.

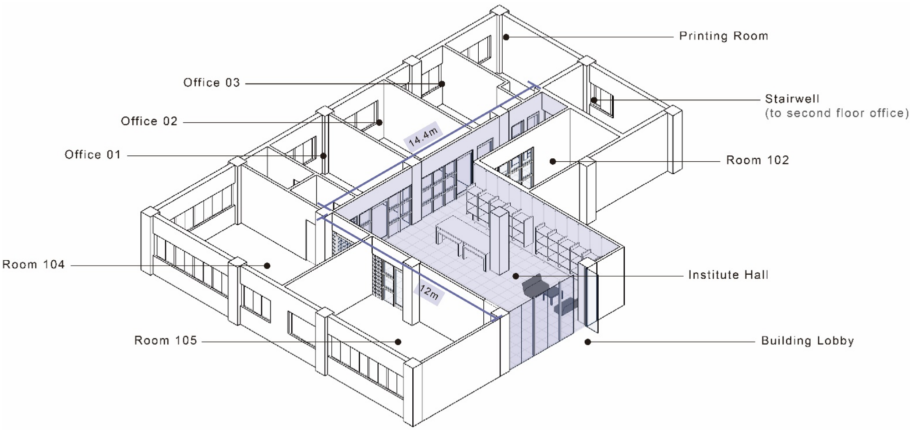


Figure 2. Localized area on the ground floor of the campus building. The shaded part represents the analysis area. The rightmost door connecting the institute hall and the building lobby remains consistently open. The windows in the stairwell and the door connecting it are also consistently open.

2.1. CFD METHOD

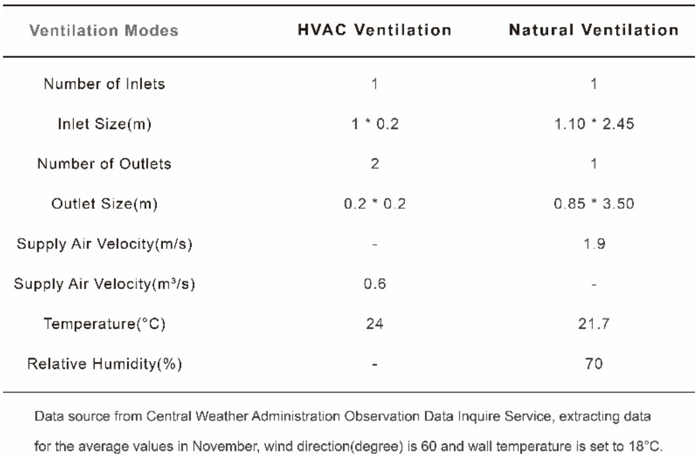
CFD, a numerical method for simulating fluid behaviours under specific conditions, offers valuable data and visualizations for designers (Hartog et al., 2000). We use the Butterfly plugin in GH for indoor airflow calculations, employing OpenFOAM for CFD simulations. The first layer of computation involves using this plugin for airflow data, supplemented by custom Python GH functions for particle transmission simulations, capturing the overall trend in the space.

2.1.1. Setting CFD Parameters

Airborne transmission risk is closely linked to ventilation rates, inadequate indoor ventilation can heighten infection risk (Ren et al., 2022). As there are currently no official standards for ventilation rates, we adopt the ideal value suggested by William Bahnfleth, setting the indoor ventilation rate at 6 air changes per hour. The HVAC supply air volume is calculated based on the ventilation rate equation:

$$Q=N*Vol$$

In this equation, where Q is airflow into the room per hour, N is the number of air changes, and Vol is the room volume. Natural ventilation, temperature, and humidity data are sourced from the Central Weather Administration Observation Service (see Table 1).



Ventilation Modes	HVAC Ventilation	Natural Ventilation
Number of Inlets	1	1
Inlet Size(m)	1 * 0.2	1.10 * 2.45
Number of Outlets	2	1
Outlet Size(m)	0.2 * 0.2	0.85 * 3.50
Supply Air Velocity(m/s)	-	1.9
Supply Air Velocity(m^3/s)	0.6	-
Temperature(°C)	24	21.7
Relative Humidity(%)	-	70

Data source from Central Weather Administration Observation Data Inquire Service, extracting data for the average values in November, wind direction(degree) is 60 and wall temperature is set to 18°C.

Table 1. Parameters for CFD simulation.

2.1.2. Particle Transmission Simulation

Building models are created with an analysis surface at 1.7m, representing breathing height. The simulation employs a Semi-Lagrangian method, following these steps (see Figure 3): (1) Using Butterfly GH for computations, we establish fixed wind field vectors. (2) Spreaders, symbolizing individuals, are uniformly placed, each with a 0.3m radius. A specific number of particles are randomly distributed within a 1.8m radius, representing the aerosol transmission range. (3) Particle advection determines their trajectories. (4) Accurate velocity vectors are obtained based on the horizontal component u and vertical component v of the wind field vectors in the surrounding four grids. (5) Particle trajectories update based on time step Δt. In this process, we assume that the fluid is incompressible and has no viscosity. The simulation shows that the space's airflow stabilizes within five minutes. The model, with 243 evenly distributed spreaders and inlet/outlet locations, simulates the overall particle transmission trend.

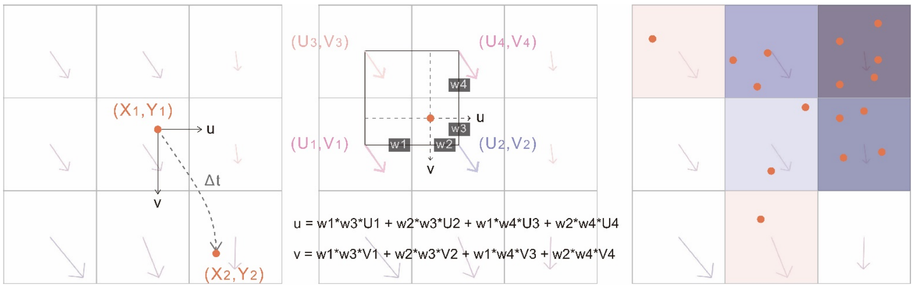


Figure 3. The light-coloured base map represents the wind field vector, with u and v as the horizontal and vertical velocity components of the particle. Particle positions are updated over Δt as time (left). w represents the weight, and the u, v velocity components of particles are computed by weighing against the adjacent four coloured wind field vectors (middle). After the simulation, the particle counts are recorded and visualized within the grid (right).

2.2. ABM METHOD

ABM, a computational model where each agent has unique states, behaviours, and decision-making processes, is widely used to simulate social phenomena in urban and architectural contexts (Batty, 2001). In GH, the Pedsim plugin simulates agent movement and behaviour. ABM in this study models pedestrian flow, forming the computational model's second layer and determining spatial occupancy trends.

2.2.1. Setting ABM Parameters

Agents' parameters include roles (students and office staff) and behaviours (staying and moving). During break times, students exhibit three behaviour modes: (1) Remain in the classroom. (2) Leave and return to the institute hall. (3) Visit a halfway point of interest in the institute hall before returning. Post-class, everyone exits the institute hall. Students without classes (student in room 104) and office staff can leave and return during breaks.

2.2.2. Spatial Occupancy

Workflow adjustments and comparisons aid in understanding flexible spatial usage patterns (Ortner and Tay, 2021). Our simulation uses existing workflow data to model spatial usage, involving: (1) Agents finding the shortest path to their destinations. (2) Agents deciding on additional behaviours en route. (3) Continued movement towards destinations. Given the substantial time intervals in common pedestrian density heatmaps, our ABM model divides time into 30-minute segments to examine spatial occupancy patterns within each time segment. This allows for a comparison with the earlier viral particle decay rates, with a focus on the 13:00 period for detailed assessment (see Figure 4).

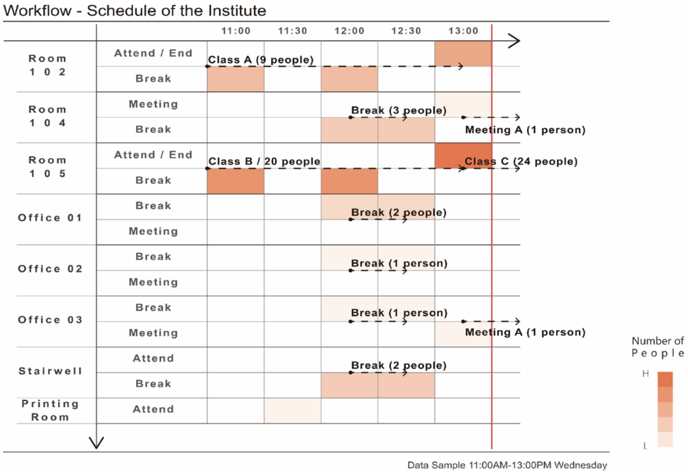


Figure 4. Spatial activity flow sample within the institute, where colours indicate whether agents engaged in entering or exiting the institute hall at that specific time point. The corresponding spaces can be cross-referenced with the earlier architectural model, with colour depth representing the number of agents. Dashed arrows represent the duration of activities, and the red line represents the time segment chosen for assessment in this study.

2.3. CFD-ABM METHOD

The third layer involves overlaying particle transmission and spatial occupancy trends (see Figure 5) to obtain a comprehensive transmission assessment. The framework includes: (1) Converting spatial occupancy data into weights, based on the number of times a single grid has been visited divided by the highest visited count. (2) Refining the grid for data alignment between layers (see Figure 6). (3) Adding the third dimension, time, to the two-dimensional grid, combining the previously influenced virus particles from earlier times, affected by decay rates, and allowing for the comprehensive assessment transmission trend.

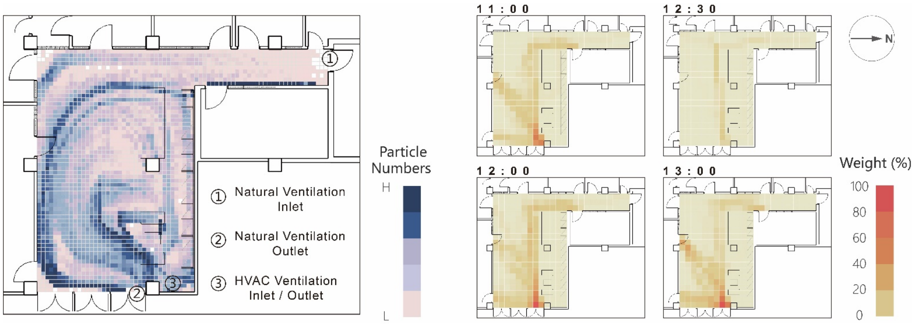


Figure 5. First Layer: Particle transmission trend (left). Second Layer: Spatial occupancy trends in different time segments (right).

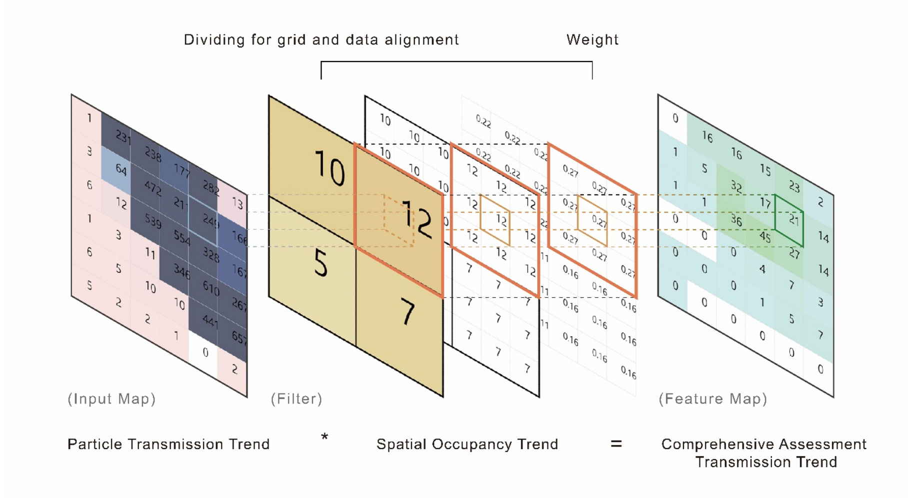


Figure 6. Refining the grid to align the data between the two layers, and obtaining the comprehensive assessment transmission trend by multiplying the particle transmission trend with the spatial occupancy trends transformed into weights.

3. Result

The overlaid layers reveal significant differences from individual layers (see Figure 7). This comprehensive assessment informs design strategies and optimizations. From the trend distribution, we employ the Minimum Spanning Tree (MST) algorithm to identify efficient paths within the space. The process includes: (1) Filtering the overlaid results based on assessed trend levels to form a Spanning Tree, with edges between points representing weights, the graph with the minimum total weight is the MST. (2) Introducing the starting and end point into the layout (spanning tree graph). (3) Edges between nodes, where edge weights can be set based on design considerations, such as distance, slope, lighting, etc. In this study, distance is used as the weight, and derives the most efficient paths from the MST graph, providing trend zoning and design recommendations after the assessment (see Figure 8).

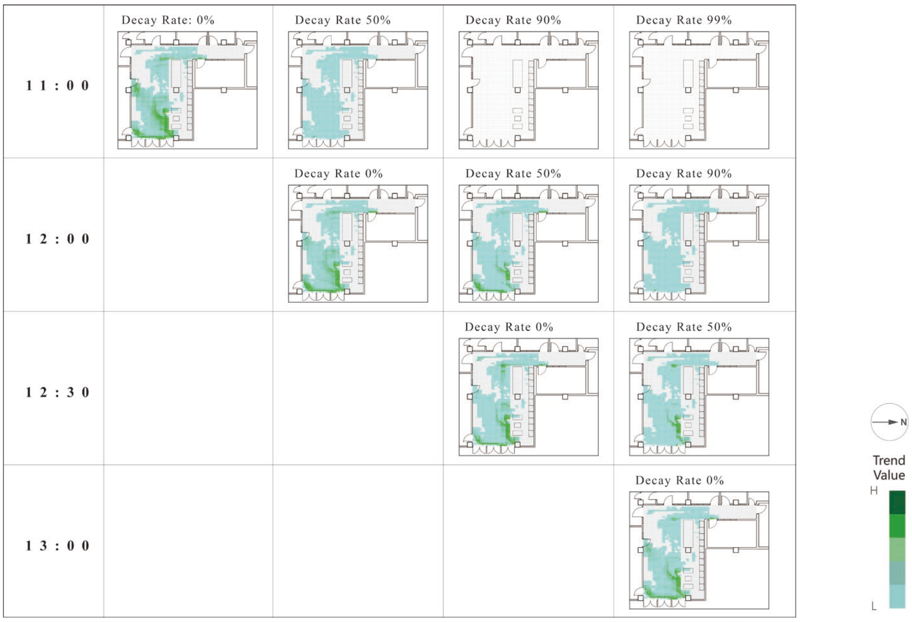


Figure 7. Third layer: Comprehensive assessment transmission trends. The bottom of each straight column, representing a decay rate of 0%, illustrates the current time segment's comprehensive assessment transmission trend, incorporating the influence of trends from previous time periods. The timeline in this figure can be cross-referenced with the earlier workflow figure's timeline.

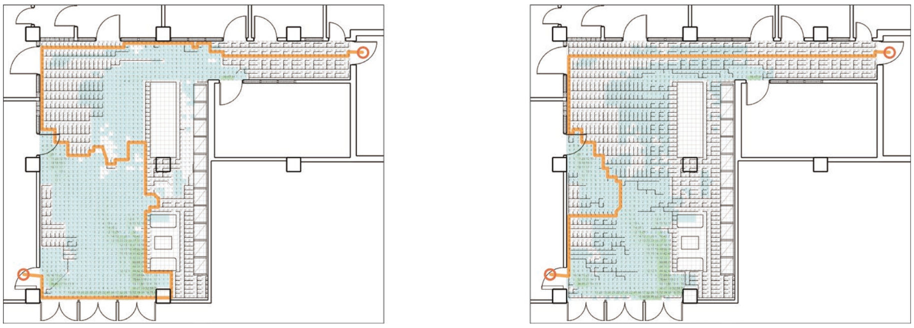


Figure 8. Regions with trend values of 0% (left) and 5% (right) were selected to generate a spanning tree graph. The thin black lines in the graph represent the MST, and recommendations for routes were generated based on specified points (the orange line and points).

4. Conclusion and Future Works

This study introduces a design framework suitable for parametric environments, integrating CFD and ABM methods to comprehend the combined impact of airflow and spatial occupancy on infection trends. CFD methods extend beyond fixed wind field calculations, using Python GH to apply wind field data in particle simulations. While guiding users along these routes may deviate from common sense, the design framework remains critical for early-stage decisions, activity zone planning, and open-space configurations (e.g., mobile cabin hospital layouts). The integration overlays two data layers, offering insights into design impacts on transmission trends, applicable in various architectural projects. On one hand, it discusses the possibility of airborne transmission in the space through CFD. On the other hand, it simultaneously formulates strategies for the utilization of space by individuals and how to avoid the singularity of circulation. Currently, both of these aspects are still under further development.

However, limitations exist. In CFD simulations, precise values for infectious dose and virus shedding are elusive, complicating the determination of necessary virus quantities for infection or released by infected individuals. The intensive computation demands of this hybrid approach currently limit simulations to two-dimensional environments, as such simulations are resource-intensive and time-consuming, this is also the reason why many simulation tools are not accepted by architects or designers (Su and Yen, 2014). Addressing these computational challenges is also a crucial issue.

Future research will focus on overcoming these challenges, comparing transmission trends under different ventilation modes and occupancy strategies, and validating CFD simulations with more agent data to refine model accuracy. This research aims to inform effective infection control across diverse design approaches, inspiring designers to embrace integration across various fields and methodologies, fostering adaptability and flexibility in architectural design.

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