Towards Safer Work Environments During the COVID-19 Crisis: A Study of Different Floor Plan Layouts and Ventilation Strategies Coupling Open FOAM and Airborne Pathogen Data for Actionable, Simulation-based Feedback in Design

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Abstract
As work environments struggle to reopen during the current COVID-19 pandemic, it is crucial to establish practical decision-aiding tools. While a strong emphasis has been placed on determining generic guidelines to reduce the risk of airborne viral spread, there is a lack of free and easy-to-use simulation workflows to quantify indoor air quality and the risk of airborne pathogens indoors at a spatial resolution that can take into account floor-plan layouts, furniture, and ventilation inlet-outlet positions. This paper describes the development of a new, free, early design tool that allows designers and other stakeholders to simulate and compare airborne viral concentrations under different indoor conditions. The tool leverages OpenFOAM-based Computational Fluid Dynamics (CFD) and a passive scalar simulation approach to allow architects and interior designers to quantify airborne pathogens’ exposure. The tool is integrated into the popular Rhino3d & Grasshopper CAD environment to facilitate its application in fast-paced design processes. We demonstrate good agreement compared to a CFD benchmark test. Further, we validate newly developed COVID-19 capabilities by comparing our results to an existing restaurant case study that included tracer gas measurements and validation using Fluent (Ansys).

Practical Implications
Always simulate IAQ and potential SARS-CoV-2 concentration of space on a case-to-case basis. Avoid poorly ventilated rooms. Consider inlet and outlet positions, furniture layout and allow modelers to consider potential negative implications of multi-occupant zones serviced by a single air conditioning unit.

Introduction
Urgency
As offices, businesses, and schools worldwide reopen and COVID-19 restrictions are lifted, ensuring indoor spaces’ health and safety is more important than ever. Americans, on average, spend approximately 90% of their time indoors, where the concentrations of pollutants, ranging from biological contaminants such as bacteria and viruses to building materials, can be up to 2 to 5 times higher than typical outdoor concentrations (Assessment, 2009; US EPA, 2017), making indoor air quality a critical factor for the design of safe and healthy buildings.

Key Innovations
- Definition of the Airborne Pathogen Concentration (APC): a spatial and case-specific metric to evaluate the concentration of small SARS-CoV-2 airborne particles in indoor spaces.
- Easy-to-use, early design simulation methodology, and tool implemented in a popular CAD environment to facilitate spatial indoor air quality (IAQ) and APC analysis during the design of floor-plan and furniture layouts and ventilation inlet-outlet positions.
- A case study demonstrating the application Eddy3D (Indoor) on redesigning a safer restaurant floor plan layout.
and thermal comfort of a building. Although the integration of IAQ performance feedback in the design process is increasingly important, CFD integration into computational design workflows remains largely unexplored. While researchers have successfully integrated CFD in design workflows, creating tools such as RhinoCFD plugin for Rhino (CHAM | RhinoCFD, 2020), Butterfly plugin for Rhino (Ladybug Tools | Butterfly, 2020), Fast Fluid Dynamics (FFD) solver validated for limited design problems (Zuo and Chen, 2007) and Envi-Met (‘ENVI-met Software Elements - Wind and Sun’, 2021) limitations such as cost, fluid dynamics and programming knowledge remain a barrier to a broader implementation of CFD in design workflows. Eddy3D (Kastner and Dogan, 2020) is an example of an accessible and easy-to-use CFD design tool in Rhino/Grasshopper but currently only supports outdoor wind analyses. The goal of our research is to create an equally easy-to-use and accessible tool for indoor simulations.

The need for indoor air assessment tools for design and decision-making has become particularly evident in the current global pandemic. The international call to action on airborne transmission in early March (Morawska and Milton, 2020) underscores the importance of simulating the spread of airborne viral particles in indoor environments, as airborne microdroplets released during exhalation, talking, and coughing is small sufficient to remain aloft in the air pose a risk of exposure at tens of meters from an infected individual. The size of carrier fluid droplets (0.2 μm -100 μm) is critical as it determines settling velocity and time, distance of travel, and deposition location in the respiratory system (Stilianakis and Drossinos, 2010). While coughing and sneezing produce larger airborne particles (100-1000 μm diameter) that settle within 1 s (Somsen et al., 2020), small particles (1–10 μm), produced when breathing, decay within 8 to 14 minutes (Stadnyskyi et al., 2020). Once airborne, small droplets dehydrate, slowing their fall (Wells, 1934) ranging between 30 to 177 min depending on microclimate boundary conditions (Smither et al., 2020), including ventilation rates (Somsen et al., 2020), thermal and radiation environment. In addition to decay rate, other factors such as airflow pattern direction make viral transmission risk assessment a highly spatial and case-specific modeling problem. Reported transmission routes at a restaurant in Guangzhou, China (Lu et al., 2020; Li et al., 2021) demonstrate the importance of simultaneously simulating seating arrangements and ventilation systems. Forensic analysis of the restaurant layout, seating arrangements, and smear samples from air-conditioning inlets and outlets led to the belief that the transmission was likely due to a nearby air-conditioner and insufficient outside Air Changes per Hour (ACH). As demonstrated in the Guangzhou episode, source and distribution path of ventilation play a key role in the potential for virulent air circulation. This study presents three innovations that facilitate the analysis of different design strategies and their impact on potential indoor viral concentrations:

- An optimized and accessible CFD workflow to simulate Indoor Airflow on a case-to-case basis.
- A methodology that allows unspecialized users to visualize, quantify and compare viral air concentration of design strategies leveraging OpenFOAM and ParaView.
- A case study demonstrating the application of the workflow towards the redesign of a safer indoor space.

This paper implements IAQ, SARS-CoV-2 particle spread simulation capabilities and workflows into the existing tool. We implement steady-state interior Reynolds-averaged Navier–Stokes (RANS) CFD simulations with the ‘buoyantSimpleFoam’ solver utilizing a passive scalar method to evaluate "Age-of-Air" and derived particle concentration fields such as CO₂. The Age-of-Air is the mean time a particle takes to travel from an inlet to the simulation domain's measurement point. It is commonly used to calculate air-change effectiveness and identify ‘dead ventilation zones’ in buildings. Age-of-Air is a variable that is highly variable in 3D space and provides information that cannot always be elicited by evaluating simple velocity fields.

Since exhaled breath is the vehicle for the airborne release of SARS-CoV-2 and other infectious particles as well as the primary internal source of CO₂ in buildings, we leverage CO₂ concentration tracers as a proxy for exhaled-breathe exposure in buildings to measure potential viral particle accumulation and the Risk of Viral Airborne Infection (Rudnick and Milton, 2003). Furthermore, droplet nuclei smaller than (5–10 μm) have been simulated with tracer gas such as “CO₂ or N₂O, because the settling velocity is very low” (Tang et al., 2011).

We focus on simulating small airborne particles in the range of (0.1–2 μm), also referred to as accumulation particles, (Nazaroff, 2004) which make up a large portion of indoor particle concentration and have minimum deposition rate (Gao and Niu, 2007) that can be neglected in simulation (Zhang and Chen, 2006) and have the most similar behavior to tracer gas (Bivolarova et al., 2017). Our focus on small particles is further supported by the correlation between viral airborne transmission paths, infectious dose, and severity of disease. While large droplets are sprayed onto the body, a form of contact transmission, aerosols are inhaled into the respiratory system (Roy and Milton, 2004) (Wells, 1934) (Xie et al., 2007) (Tellier et al., 2019) and can be more harmful (Morawska et al., 2009).

Existing guidelines suggest that increasing ventilation rates and air distribution can often be cost-effective means of reducing indoor pollutant levels. (Stewart et al., 2020) However, it is unclear how the orientation and arrangement of ventilation systems are most beneficial and the impact of furniture layout and other larger scale objects in the space on airflow patterns. In this paper, we demonstrate and deploy our fast IAQ tool for COVID-19 safety to study the spread at the Guangzhou restaurant and evaluate the impact of spatial and case-specific designs to answer questions as:
Methods

Airborne SARS-CoV-2 Design Metric

The early design decision-making tool and workflow allows designers to evaluate and compare potential distribution and concentration of small viral SARS-CoV-2 airborne particles in indoor spaces. The metric, Airborne Pathogen Concentration (APC), describes how much space can be considered "well-ventilated" based on Age-of-Air and CO₂ concentration simulations. To ensure accessibility and readability of the simulations, the authors developed a viral concentration scalar field in Eddy3D that allows users to gain visual feedback to easily locate underperforming and poorly ventilated areas of the design when viewing the OpenFOAM simulation results in Paraview. Thus, the tool allows an iterative process, where relationship between localized air quality and floor plan design can be studied.

This metric has the advantage of defining regions unsafe for occupancy and comparing floor plan designs based on ventilation potential at the same time. As infectious dose for SARS-CoV-2 is still under debate, the boundaries of the metric are not absolute. Instead, the tool is used to study space and ventilation iterations relative to one another. To demonstrate the applicability and define limitations of the metric in this study, we conduct a series of restaurant design iterations.

Simulation Environment and Tools

Most indoor air quality simulation tools using CFD are only accessible to highly specialized users. This paper aims to create a simple and easy-to-use tool integrated within popular 3D modeling software and design workflows. To this end, the presented research builds on four tools for simulation and geometric modeling: OpenFOAM, ParaView, the McNeel Rhino Platform, and Eddy3D for Grasshopper. OpenFOAM is open-source software for CFD that is free and has been validated thoroughly. Paraview is an open-source visualization application that allows to view 3D CFD simulations (‘ParaView’, 2021). The Rhino3d/Grasshopper CAD environment was chosen due to its popularity amongst architects allowing for easy integration into existing design workflows. Eddy3D, an existing Computational Fluid Dynamics modeling plugin for Grasshopper using the OpenFOAM solver, is expanded to have Indoor CFD capabilities.

Indoor CFD Setup Validation

We implement steady-state interior RANS CFD simulations with OpenFOAM's "buoyantSimpleFoam", a thoroughly validated CFD code (Liman, Fellouah and Galanis, 2015). To ensure a valid set-up of the indoor case using OpenFOAM, we simulate a CFD Benchmark Test case( Nielsen et al., 2003), a Mixing Validation simulation, in the Rhino/Grasshopper environment. The test consists of a unidirectional flow field, with a wind tunnel of 2.44 m x 1.20 m x 2.46 m, circular exhaust openings 0.25 m in diameter, and located 0.6 m from the floor and the ceiling, temperature of 22°C and 76 W heat flux.

Table 1: Breathing and Violent Expiratory Behavior flow data (Shao et al., 2021) averaged over one breath per 4 seconds.

<table>
<thead>
<tr>
<th>Rate (L/s)</th>
<th>Breathing</th>
<th>Violent Expirations</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.11</td>
<td>0.11</td>
<td></td>
</tr>
<tr>
<td>Cone Angle</td>
<td>25</td>
<td>65</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>0.21</td>
<td>11.2</td>
</tr>
<tr>
<td>30mm from mouth</td>
<td>170</td>
<td>NA</td>
</tr>
<tr>
<td>Particles/L of exhaled gas</td>
<td>44</td>
<td>440</td>
</tr>
<tr>
<td>Peak particle size (µm)</td>
<td>1.5</td>
<td>NA</td>
</tr>
</tbody>
</table>

Particle Emissions Data

We implement experimental exhalation emissions to add capabilities to assess SARS-CoV-2 particle concentration. Breathing and speaking emission data including breathing and speaking flow, gas flow rate (L/s), flow speed (m/s), breathing cone angle (˚), breath frequency (1/s), particles per breath (corresponding to peak of particle size distribution in breathing experiments) for the simulation of an infected emitter is based on in situ experimental data from the University of Minnesota (Table1) (Shao et al., 2021).

Workflow

The overall structure of the workflow is as follows: the Rhino3d/Grasshopper CAD environment is used to model the Indoor Space, Inlets and Outlets, Interior partitions and furniture, and people in the space. The boundary space is modeled as a closed surface with openings corresponding to Inlet and Outlet locations, and the corresponding temperature is reported. Inlets and Outlets are modeled as surfaces with corresponding velocity vectors and are subtracted from the boundary geometry surface. Indoor partitions, furniture, and people are modeled as closed surfaces in the space and connected to the geometrical boundary. Emitter geometry is simplified and modeled as two parallelepipeds with an 8 mm diameter aperture corresponding to the mouth and nose region's location, and associated heat flux is specified.

Once the geometry, ventilation speed, temperature, and heat flux are specified in the Rhino/Grasshopper environment, the simulation is run. The simulation reports data slices at user-selected probing locations and graphs that can be viewed in the ParaView: Age-of-Air (AOA) and SARS-CoV-2 concentration.
floor plan and 18 normalized predicted concentration values from the respective analysis (Li et al., 2020). The COVID-19 spreading event occurred on the third floor of a five-floor, air-conditioned building without windows. On the day of the event, 91 people, of whom 83 customers, sitting at 15 tables approximately 1 m apart, and eight staff members were in the space. Ten out of 83 customers, including one infectors, became ill with COVID-19, all of whom were sitting at three tables (A, B, C) located near patient A1 and within the flow of air conditioner 1, located above table C. Family A was seated for 1 hour and 22 minutes. Families A and B were each seated for an overlapping period of 53 minutes and families A and C for an overlapping period of 73 minutes.

The case study is recreated in the Rhino CAD environment. Dimensions reported by the case study include dimensions of the space, exhaust fans' position, occupant locations, and furniture. The restaurant has a near-rectangular plan with a restroom, elevator, and fire stair located on the south. There are five fan coil AC units, four along the east-facing wall, and one near the fire stair. Measured ventilation rates are not reported in the case study. We extrapolate three possible rates (230, 320, 400 $m^3/h$) based on AC unit type and test them for the best results.

There are four exhaust fans located along the west-facing wall and one located in the restroom. At the time of the incident, only the fan in the restroom was functioning. Therefore, it is the only fan modeled in our simulation. Tables are distinguished into four types based on shape and size and modeled as extrusions with 5 cm thickness. People and chairs are modeled as one and simplified into two parallepipeds: Body and chair (1.07 x 0.3 x 0.4), and head (0.22 x 0.22 x 0.22).

Emitters are modeled as two parallelepiped with an 8-mm diameter aperture corresponding to the mouth and nose region's location, and respective heat flux is specified (Figure 1).

### Restaurant Design Case Study

We conduct a case study of the restaurant, comparing the influence of variations in furniture and partition layout, table distancing, and occupancy on indoor air quality and potential SARS-CoV-2 concentrations.

1. **Influence of Plastic Partitions**: Plastic Partitions are placed between tables in their existing position in order to analyze the effect of temporary barriers.
2. **Influence of Furniture Layout and De-densification**: Viral accumulation in the base case is compared to that of a de-densified space. The base case is de-densified, and tables are removed from the space, leaving only 47 occupiable seats compared to 83 in the original case. The furniture is organized such that there are two tables per AC unit.

### Results

**Indoor CFD Setup Validation**

The case setup used in the paper is validated by comparing velocity measurements at eight grid points (Figure 3-4) with corresponding velocities in the Mixing Validation Benchmark test as well as through visual correspondence (Figure 2). Velocities are measured along the plane at $z=0$ m and $x=1.69$ m with two inlet ventilation rates, corresponding to high (0.5 m/s) and medium (0.2 m/s) flow rate.

![Figure 2: Simulation of the Mixing Ventilation Benchmark Tests with 0.2 m/s inlet velocity.](https://doi.org/10.26868/25222708.2021.30632)
is not the most precise due to a simplification of the mannequin mesh, the error is acceptable within the bounds of its intended use: the early-design stage, where meshes are not precisely defined or fixed beyond simple volumes.

**Figure 3: Comparison of normalized velocity measurements of the Mixing Ventilation Benchmark Tests and our simulations (Eddy3D) at z(m)=0, x(m)=1.69, y(m)=0.275, 0.550, 0.825, 1.100, 1.375, 1.650, 1.925, 2.200; with 0.2m/s (left) and 0.5m/s (right) inlet velocity.**

**SARS-CoV-2 Simulation Validation**

The validation of the precision and efficacy of Eddy3D (Indoor) viral capabilities is carried out by comparing SARS-CoV-2 concentrations simulated using Eddy3D with tracer gas measurements and predictions modelled with Ansys, Fluent (Li *et al.*, 2021). The study reported tracer gas measurements collected in 8 points of the Guangzhou Restaurant floor plan and 18 normalized predicted concentration values (Lu *et al.*, 2020). In the experimental setup, ethane gas was released through an 8 mm inner diameter pipe at a speed of 1.5 m/s at 32–34°C, with the pipe outlet placed in proximity of the index patient's nose, marked as A1 at table A. In our simulation, the emitter is modeled as the experimental setup, with a breathing flow of 1.5 m/s and an opening of 8 mm in diameter. Passive Scalar simulations of SARS-CoV-2 concentrations, Age-of-Air, and Velocity Streamlines are performed using Eddy3D (Indoor).

The simulations show that Eddy3D (Indoor) has results comparable to the measured concentration and a Mean Absolute Percentage Error (MAPE) of 14.7% (Table 2). The concentration at A1, the index patient at table A, A2–A5, B1–B3, and C1–C2 is higher than concentrations in proximity to other restaurant occupants (Figure 4). Furthermore, we can see that Velocity Streamlines from Eddy3D (Indoor) (Figure 4) are comparable to those computed using CFD software package Fluent (Ansys Fluent, USA)(Li *et al.*, 2021).

Velocity plots (Figure 5) support the notion that small aerosol particles emitted from the index patient were transported to contiguous tables B and C by the nearby A/C unit. We note that both our simulations and the referenced simulations assume rapid droplet evaporation, approximate the exhaled droplet nuclei as a passive scalar, and the deposition effect is neglected.

**Table 2: Comparison of normalized tracer gas concentration measurements (Column 2)(Li *et al.*, 2021), Fluent simulation (Column 3)(Li *et al.*, 2021) and Eddy3D(Indoor) simulation(Column 4) at each table.**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
<td>0.04%</td>
</tr>
<tr>
<td>B</td>
<td>0.87</td>
<td>1.04</td>
<td>0.96</td>
<td>7.90%</td>
</tr>
<tr>
<td>C</td>
<td>0.98</td>
<td>0.93</td>
<td>0.92</td>
<td>1.49%</td>
</tr>
<tr>
<td>4</td>
<td>NA</td>
<td>1.00</td>
<td>0.83</td>
<td>16.74%</td>
</tr>
<tr>
<td>5</td>
<td>NA</td>
<td>0.62</td>
<td>0.58</td>
<td>6.09%</td>
</tr>
<tr>
<td>6</td>
<td>NA</td>
<td>0.47</td>
<td>0.50</td>
<td>6.12%</td>
</tr>
<tr>
<td>7</td>
<td>NA</td>
<td>0.42</td>
<td>0.42</td>
<td>1.12%</td>
</tr>
<tr>
<td>8</td>
<td>NA</td>
<td>0.42</td>
<td>0.25</td>
<td>40.87%</td>
</tr>
<tr>
<td>9</td>
<td>NA</td>
<td>0.32</td>
<td>0.16</td>
<td>48.48%</td>
</tr>
<tr>
<td>10</td>
<td>0.55</td>
<td>0.52</td>
<td>0.33</td>
<td>36.19%</td>
</tr>
<tr>
<td>11</td>
<td>NA</td>
<td>0.57</td>
<td>0.42</td>
<td>27.14%</td>
</tr>
<tr>
<td>12</td>
<td>NA</td>
<td>0.50</td>
<td>0.50</td>
<td>0.25%</td>
</tr>
<tr>
<td>13</td>
<td>NA</td>
<td>0.55</td>
<td>0.58</td>
<td>5.86%</td>
</tr>
<tr>
<td>14</td>
<td>NA</td>
<td>0.63</td>
<td>0.62</td>
<td>0.96%</td>
</tr>
<tr>
<td>15</td>
<td>0.58</td>
<td>0.54</td>
<td>0.50</td>
<td>7.64%</td>
</tr>
<tr>
<td>16</td>
<td>0.7</td>
<td>0.56</td>
<td>0.58</td>
<td>3.97%</td>
</tr>
<tr>
<td>17</td>
<td>0.86</td>
<td>0.50</td>
<td>0.67</td>
<td>33.14%</td>
</tr>
<tr>
<td>18</td>
<td>0.73</td>
<td>0.85</td>
<td>0.67</td>
<td>21.68%</td>
</tr>
</tbody>
</table>

**Figure 4: SARS-CoV-2 concentration distribution of the Base case computed using Eddy3D(Indoor).**

**Figure 5: Velocity of the Base case computed using Eddy3D(Indoor).**
Restaurant Design Case Study

The Guangzhou restaurant validation simulation demonstrates AC's role in SARS-CoV-2 particle transport from the infected table to surrounding tables. To demonstrate the use and efficacy of Eddy3D (Indoor) as a tool for the design of safer indoor spaces, we compare the base case with two interior design alternatives to improve the air quality and reduce SARS-CoV-2 concentrations inside the space.

The first design iteration considers the influence of Furniture Layout and Plastic Partitions. Plastic partitions are laid out between tables without considering movement and table accessibility. Partitions are placed such that tables with occupants closer than 6ft are separated by partitions, while tables more than 6ft apart are not separated by partitions.

Velocity (Figure 7) and SARS-CoV-2 concentration (Figure 6) plots show that the air movement is significantly altered by adding plastic partitions. While virus concentrations are lower in proximity of table B, as airflow from the air conditioner is blocked by the partition, concentrations in proximity of tables 17, 16 and 13 are higher when partitions are added to the space. This simulation demonstrates that plastic partitions do not always ameliorate IAQ and SARS-CoV-2 concentrations, and supports the need to model spaces on a case-to-case basis.

The third case study analyses the influence of Furniture Layout and De-densification. The base case is de-densified, and tables are removed from the space, leaving only 47 occupiable seats compared to 83 in the original case. The furniture is organized such that multiple tables are not aligned along the same AC unit ventilation direction. We compute SARS-CoV-2 concentration (Figure 8) and Velocity Streamlines (Figure 9) for each design iteration using Eddy3D (Indoor) and compare them to the Base Case and Partition restaurant design simulations.

While the high SARS-CoV-2 concentrations in the de-densified case are primarily located near table A and gradually decrease with the distance, high-concentrations in the de-densified case are not uniform and less predictable (Figure 8).

Velocity in the Base case and De-densified case are similar (Figure 10). However, concentrations are significantly different. The results suggest that furniture plays a large role in air distribution and the spreading of the virus.

Furthermore, SARS-CoV-2 concentrations are overall lowest in the Base case and higher in De-densified case, as there are fewer obstacles to the diffusion of the virus (Figure 10). From the Partition case is it clear that plastic barriers increase concentration in proximity of the emitter, with exception of Table B, which is effectively blocked from the AC units’ airflow.
The results have shown that Eddy3D (Indoor) yields reliable results for indoor air studies. The precision with a 0.125m/s RMSE for the velocity values is caused by the simplification of the mannequin mesh and is acceptable within the bounds of the precision of the underlying simulation engine OpenFOAM. The results of the restaurant case study yield reliable results for the concentration of airborne infection. Concentration values yield a MAPE of 14.7%, which is acceptable within the bounds of OpenFOAM. As expected, Air Stagnation and Airborne Infection Concentration are identified in the proximity of infected occupants.

Future Improvement

The authors plan to consider natural ventilation in addition to mechanical ventilation in the future development of the tool.

A common drawback of design tools and corresponding metrics is difficulty in judging and comparing computed results. The authors plan to mitigate this inconvenience by generating a database of viral assessments, ranging in floor plan shape, layout, and ventilation strategy. This tool could be accompanied by a guide to compare designs with an optimum case.

How the tool should not be used

As data and research on SARS-CoV-2 evolve, this tool should be considered work-in-progress and reflect current data and knowledge as such a tool should not be considered a perfect airborne transmission model. Furthermore, as an infectious dose for SARS-CoV-2 is still under debate, the metric's limitations are not absolute. Instead, the tool is used to study space and ventilation iterations relative to one another and to identify improvements throughout the early design process. The authors plan to integrate such boundaries when they become available.

Conclusion

The novel approach to integrate indoor airflow pattern and viral transmission risk assessment into CAD software allows tackling highly spatial and case-specific modeling problems. From a design standpoint, the tool revolutionizes the way IAQ can be analyzed and integrated into early design workflows. Furthermore, the tool introduces airborne viral assessment into the design repertoire, allowing designers to study the effect of floor plan designs and layouts, ventilation strategies on indoor air quality and health.

Acknowledgment

We thank Khaled Hashad (Cornell University) for insightful discussions on particle deposition. We further would like to thank the Hunter R. Rawlings III Cornell Presidential Research Scholars Program and the Cornell Atkinson Center for funding this research.

References


Figure 10: SARS-CoV-2 concentration of the Base case, Partition and De-densified restaurant floor plan.


