Proceedings of the 2021 Winter Simulation Conference
S. Kim, B. Feng, K. Smith, S. Masoud, Z. Zheng, C. Szabo and M. Loper, eds.

SPATIAL MODELS AND MASKS IN INDOOR ANALYSIS FOR THE SPREAD OF COVID-19

Zein Hajj-Ali
Gabriel Wainer

Department of Systems and Computer Engineering
Carleton University
1125 Colonel By Drive
Ottawa, ON K1S 5B6, CANADA

2021 Winter Simulation Conference (WSC) | 978-1-6654-3311-2/21/$31.00 ©2021 IEEE | DOI: 10.1109/WSC52266.2021.9715334

ABSTRACT

Face masks have been shown to slow or stop the spread of airborne COVID-19 droplets and aerosols. There is an apparent lack of research examining the effect of different types of masks used at the same time, and their impact on the spread of viral particles in a spatial sense. We introduce a rapid prototype model to overcome the issues in the available research using the Cell-DEVS formalism. We also build scenarios for the model to examine the effectiveness of all types of masks and respirators recommended by the World Health Organization on the spread of viral particles in an indoor environment.

1 INTRODUCTION

The COVID-19 pandemic has launched public health offices into a state of emergency to mitigate the effects of the virus. Several studies investigated issues such as the transmission of the virus through airborne droplets, the infection rate and accuracy of the infection tests, as well as the efficiency of different mitigation techniques (Anderson 2020; Li et al. 2020; Manski and Molinari 2020; Ueki et al. 2020). The infectious nature of the virus and the lack of a readily available treatment at the start of the pandemic pushed governing bodies to implement several different policies and recommendations to attempt to slow or stop the spread, including contact tracing, shelter-at-home orders to decrease the risk of exceeding the capacities of health systems, and social/physical distancing to decrease the transmission of viral particles.

Recommendations from the WHO (World Health Organization 2020) and local public health offices urged people to wear facemasks whenever they are unable to stay at least 1 meter from others, as well as in rooms with an unknown level of ventilation. The WHO recommends the use of face masks with at least three layers of fabric for members of the public under the age of 60 and no underlying health conditions. Medical/surgical masks are recommended for health workers, people over the age of 60 and/or underlying health conditions, and anyone with a suspected or confirmed case of the virus. The WHO also released recommendations for the use of respirators. Ueki et al. (2020) showed the effects of different types of masks on the spread of COVID-19 from person to person in a one-to-one scenario.

There is an apparent lack of research looking at the effect of different types of masks at the same time in one scenario, as well as an absence of models that study the impact of face masks on the spread of viral particles in a spatial sense. Here we show the dispersion of viral particles and the decrease in the level of viral spread with the use of face masks. This is done by utilizing a model that simulates viral particle spread in a 2D spatial environment. To study the effects of all the types of face masks recommended by the WHO. We discuss a model that measures the diffusion of viral particles in a room and run different scenarios to investigate the effect of the different types of masks in a larger closed environment.

The issues with the currently published research are threefold: (1) There is an absence of models that study the impact of face masks on the spread of viral particles in a spatial sense, which could be helpful in

978-1-6654-3311-2/21/$31.00 ©2021 IEEE

identifying solutions in buildings. (2) Most models do not include an analysis of the effects of all types of face masks recommended by the WHO during the COVID-19 pandemic. (3) There is a need to study the impact of the use of different mask types in the same setting on the spread of viral particles. We thus introduce a rapid prototype model that allows for dealing with these issues. The model allows the setting of the efficiencies of different types of face masks separately. The model can also be extended to include the efficiencies of new mask types if needed in the future. The model simulates a 2-dimensional environment and records the number of viral particles in each position. This allowed us to build scenarios that examine the effectiveness of mask use on the spread of viral particles in the environment. The model uses data from the study by Ueki et al. (2020), detailing the efficiencies of all the mask types recommended by the WHO (2020), thereby offering a complete look into the effects of mask wearing in an indoor setting during the COVID-19 pandemic. Furthermore, the scenarios built for the model explored in this paper cycle through every combination of masks that the virus spreader and susceptible individual could wear.

2 BACKGROUND

Modeling infection has been widely studied starting with the foundational Susceptible-Infected-Recovered model (SIR) first outlined by Kermack and McKendrick (1927). Epidemiologists have also simulated the spread of COVID-19 infections throughout communities, with parameters for lockdown patterns and social distancing (De-Leon and Pederiva 2020). A review article (Li 2007) found that there is a strong association between the spread of airborne infections and the level of ventilation and airflow in an indoor environment.

Some studies explored the impact of the use of face masks to diminish the spread of airborne viruses. Tracht et al. (2010) built a model to quantify the impact of wearing face masks in reducing the spread of the H1N1 virus. They found that the use of both surgical masks and N95 respirators help curtail the increase of infection rates, though the N95 respirators had a greater impact. The effects of surgical masks and N95 respirators were studied, but the authors do not consider the cotton face masks recommended by the WHO during the COVID-19 pandemic, nor did they consider the possibility of an incorrect fitting of the N95 respirators on the wearer. Eikenberry et al. (2020) used a similar method to investigate the effects of face mask use on the spread of the COVID-19 virus, although the use of different types of masks in the same scenario was not explored. They simulated 18 months of an epidemic with a modified SIR model. The findings revealed that an increase in the use of face masks significantly decreases the spread of the virus within the community. This finding holds true even with face masks of a lower efficiency. Bazant and Bush (2021) built a model to derive safety guidelines considering factors affecting the spread of the COVID-19 virus indoors. The authors focused on guidelines to mitigate the airborne transmission of the virus indoors, and examined the level of ventilation, the size of the environment, and the use of cotton and surgical face masks. The authors found that the results of the model for an indoor space were consistent with the findings of prior research in slowing the spread of the virus on the larger scale of a city or country.

Ueki et al. (2020) studied the efficiency of different types of face masks in inhibiting the transmission of aerosols containing COVID-19 viral particles. They constructed a transmission simulator in a biosafety level 3 test environment, utilizing two mannequin heads facing each other. One of the mannequin heads emitted a mist containing viral particles. The other was connected to a viral particle collection unit and an artificial ventilator set to mimic the steady state breathing rate of adults. The face masks tested were attached to the heads and the compressor nebulizer was set to imitate a mild cough for 20 minutes. The viral titers were then measured using the plaque assay method (Figure 1). Cotton and surgical masks were tested, as well as N95 respirators fitted correctly or not. The authors found that the masks were more protective against the virus when worn by the index rather than the susceptible individual. The study also established that none of the masks were able to completely prevent the transmission even when fitted correctly.

Modeling indoor spaces can be achieved through numerous methods. Li et al. (2010) presented a grid graph-based model that allows for the study of spatial events in an indoor environment. The authors split the floor space of the environment into a grid of 2D cells which could then be labeled with the properties of the floor plan corresponding to it. A review study (Li et al. 2019) examined several models that use Cellular Automata to model an indoor space, and the movement and behavior of crowds and crowd evacuation in that environment. Cellular Automata has also been used to model the diffusion/propagation of smoke and its effects on crowd behavior indoors during evacuation (Makmul 2021).

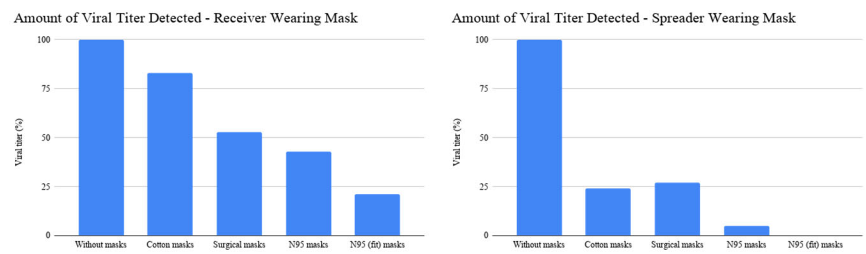

Figure 1: Mask protective efficiency against COVID-19 droplets/aerosols (Ueki et al. 2020).

The Cell-DEVS formalism has been used in various fields to model the behavior of particles or people represented as cells. Khalil et al. (2020) uses a model of CO2 production and dispersion to investigate the feasibility of using the Cell-DEVS modeling methods to determine the best placement of CO2 sensors for occupancy detection. They built and simulated the model using the CD++ toolkit, which allows for simulating DEVS and Cell-DEVS models. The results of the paper found that it was viable to model gas dispersion using the Cell-DEVS formalism. A study by Khalil and Wainer (2020) advanced the previous model and validated the results using data from real-life indoor spaces. Two laboratories were included in the study, one to calibrate the model's parameters, and the other to validate the model. The authors do not model the direction of the airflow in the environments but concluded that the model was still suitable for the use case since the results resembled the ground truth data of the physical system. Cárdenas et al. (2021) used the Cell-DEVS formalism to adapt the epidemiological Susceptible-Infected-Recovered model to work spatially to aid in the study of individual interactions and contact processes as factors of viral spread.

The models were built using Cadmium (Belloli et al. 2019), a DEVS simulator built in C++. Cell-DEVS is an extension of the DEVS formalism that allows building cell spaces. A Cell-DEVS model is composed of an n-dimensional lattice of cells, as seen in Figure 2. The complete cell space is a coupled DEVS model formed by combining the individual atomic models (Wainer 2009).

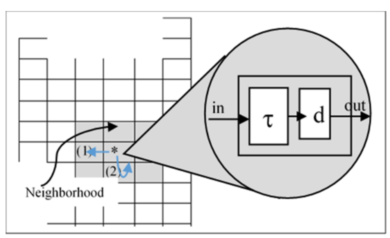

Figure 2: Cell-DEVS Models (Wainer 2009).

3 MODEL DEFINITION AND EXPERIMENTAL SETUP

Since respiratory fluid and particles of saliva can be vectors of transmission of the COVID-19 virus (Jayaweera et al. 2020), the likelihood of transmission can be dependent on several factors. The behavior of these particles, in the form of droplets or aerosols (Marr et al. 2020), can differ depending on the environment they are in and their size. Two basic classes in which we can separate the vectors include (1) ballistic droplets, and (2) infectious bioaerosols (Marr et al. 2020). Ballistic droplets are particles larger than 100 micrometers; bioaerosols are smaller than that and can stay airborne for a longer time. Both classes can cause infection through the pathways of the mouth, nostrils, or eyes.

The length of time that the viral airborne pathogens can stay viable and the distance they can travel can vary between the classes, though it is accepted that ballistic droplets cannot travel more than 2 meters away from the source and are airborne for only a few seconds, while bioaerosols can stay up in the air for hours (Jayaweera et al. 2020; Marr et al. 2020). Aerosols accumulate more heavily near their source, decreasing as the distance from the source gets larger. Due to this, the conditions of the environment of viral spread, including airflow direction and speed, determine the likelihood of infection based on proximity to the source (Lu et al. 2020). The main method of transmission is through the mouth and nostrils (Marr 2020). The probability of infection also depends on the type of respiratory activity performed by the source, as well as whether they are at rest, talking, singing, or engaging in physical activity (Buonanno et al. 2020a; 2020b).

Buonanno et al. (2020a; 2020b) use the definition of a quantum presented by Wells (1955) as the dose of airborne droplet nuclei needed to infect a susceptible person. The quanta are then calculated for a range of respiratory activities, as well as inhalation rates and level of activity. The authors calculate the quanta emission rates of COVID-19 and estimate the number of infectious quanta in the viral load. They conclude that breathing while at rest emits the lowest quanta at 0.36 per hour while heavy physical activity can increase the rate to 2.4 quanta per hour. Others have studied the rate of aerosol emissions when factoring in the loudness of the source's voice, finding a positive correlation (Asadi et al. 2019).

This information was used to build our model as a Cell-DEVS with 9 different cell types: air, impermeable walls, doors, tables, chairs, ventilation, index (spreader) cells, susceptible, and infected individuals. The cell state keeps track of the time, the cell type, the number of viral particles in the cell, the flow direction, and some variables used for calculating the appropriate number of particles to emit or diffuse to neighboring cells. The index and susceptible individual cells also make use of a state variable that keeps track of the type of mask that cell is using. Each type of mask has a 'shed' variable and an 'efficiency' variable. The shed variable is the percentage of the viral particles that can pass through the mask from the index out to the environment. The efficiency variable is the percentage of the viral particles that can pass through the mask from the environment into the person wearing the mask (Ueki et al. 2020).

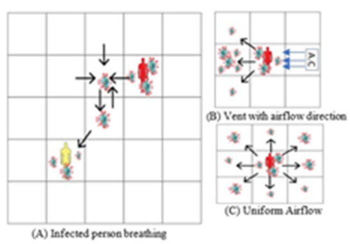

Figure 3: Conceptual model of the viral particles within the environment (Altamimi et al. 2021).

A function calculates the number of viral particles that the current cell will receive from its neighbors. It considers the number of particles sent to it by the neighbors, whether directly or through airflow. The flow describes the percentage of particles sent to an adjacent cell in the direction of the ventilation. We also compute the direction by looking at the adjacent cells and adjusting accordingly. We then calculate the number of viral particles the cell will contain next, as well as the number of particles to be sent to the neighbors. We then calculate the number of particles to be produced and emitted at that cell. We compute the number of particles that escape from the mask in use. Finally, we compute the number of particles inhaled by taking the number of particles in the cell and the 'efficiency' of each mask (Figure 3).

Table 1: Mask types with shed and efficiency values (Ueki et al. 2020).

Mask Type	Shed	Efficiency
No Mask	100%	0%
Cotton	24%	17%
Surgical	27%	47%
Incorrectly fitted N95 respirator	5%	57%
Correctly fitted N95 respirator	0%	79%

The four types of masks that were investigated (WHO 2020) were used in the model; cotton, surgical, incorrectly fitted N95 respirator, correctly fitted N95 respirator, as well as an option for no mask. The mask options with their preset shed and efficiency values can be seen in Table 1.

The processes that occur when advancing a timestep for each of the cell types are as follows:

- *Air*: The air cell calculates the direction of the airflow. It then checks the neighborhood and calculates the number of particles that will be given to it from those neighbors. It then computes the number of viral particles it will be sending to its neighbors and increases its counter variable.
- *Impermeable Wall*: Always has 0 viral particles and does not change. The impermeable walls change the direction and weight of the airflow of surrounding cells.
- *Table*: Performs the same function as the air cells in this version of the model. The table cells are mostly used for the visualization and organization of the chair and person cells. Viral particles pass through them in the same way as the air cells.
- *Chair*: The chair cells allow viral particles to pass across them in the same way as the air and table cells. They spawn the index and susceptible individual cells at the start time.
- *Ventilation*: The main behavior of the ventilation cells is to change the direction and therefore the weights of the airflow of the surrounding cells away from it.
- *Index Cell*: The index cells first calculate the direction of the airflow and checks its neighborhood to calculate the number of particles it will be given from those neighbors. Depending on the preset breathing, speaking, and coughing rate, it might emit viral particles. The number of particles emitted depends on both the type of action as well as the shed of the type of mask being worn.
- *Susceptible Individual Cell*: The cell first calculates the direction of the airflow and checks its neighborhood to calculate the number of particles it will be given from those neighbors. Depending on the preset breathing rate, it might inhale some particles, which depends on the efficiency of the type of mask being worn. If the susceptible individual inhaled a total number of particles greater than or equal to a preset infection threshold, the cell would become a newly infected cell.
- *Newly Infected Cell*: The cell behaves the as the susceptible individual cell and does not have the ability to emit particles. They represent individuals with the potential to become infected because they inhaled viral particles above the quantum.

The experimental setup is based on the model presented above, and it uses the initial configuration of tables and chairs found in Lu et al. (2020). The base scenario was validated with the data found in that study and based on the initial simulation results, the studies considering the use of masks were split into two sets. All the scenarios occur when the restaurant environment is fully occupied, i.e., all the chairs have persons in them. They all involve one infected person that spread the virus placed close to the middle of the environment. In the first group of scenarios, all wear the same type of mask, the only difference between the scenarios being the type of mask worn in each. The second set of scenarios has the virus spreader wearing a different mask than the susceptible individuals. The full implementation of the model and scenarios is available online (Hajj-Ali 2021).

The scenarios presented here are set up using JSON files that describe the size of the environment, the initial values of each cell, and some variables including breathing rate, coughing rate, and efficiency of each mask. The JSON scenarios can be used to run the models in the Cadmium Cell-DEVS Simulation Environment (Belloli et al. 2019) and the DEVS Web Viewer (St-Aubin et al. 2018). This environment allows executing web-based simulations and visualizations, and numerous simulation cases without the need of modifying the underlying models.

The model was used to execute several simulation scenarios, described in detail in upcoming sections. All the cells start with no viral particles in them, and all the cells representing spreaders and susceptible individuals have an initial number of inhaled particles of 0. The environment is represented by an area of 31x28 cells, the outer border of which is lined with impermeable walls and two areas of ventilation 5 cells long. 14 tables of various sizes were created, with a total of 54 chairs. A chair close to the center of the environment was occupied with an index cell, while the other 53 chairs were occupied with susceptible individuals. The model used a Moore neighborhood with a range of 1 (9 near neighbors). All variables were kept constant between scenarios, except for the type of mask used by index and susceptible individual cells.

The first set of scenarios consider a restaurant fully occupied (Figure 4), and all the individuals wear masks of the same type. There is only one index case, represented as an index cell in the middle of the room. The scenario is run multiple times changing only the type of mask all the persons in the room are wearing. In total, 5 scenarios were considered:

1. All persons not wearing masks.
2. All persons wearing cotton masks.
3. All persons wearing surgical masks.
4. All persons wearing incorrectly fitted N95 respirators.
5. All persons wearing correctly fitted N95 respirators.

The second group of scenarios considered that the tables were fully occupied, with an index placed in the same position as in the first set of scenarios. The index wears a mask of a different type than the mask being worn by all the susceptible individuals. The scenario is run multiple times while only changing the type of masks being worn by the index and the susceptible individuals. All unseen combinations of type of mask worn by the index and the type of masks worn by the susceptible individuals were tested.

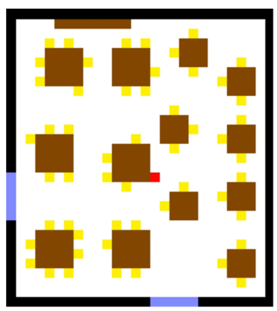

Figure 4: Layout of the simulation scenario.

4 SIMULATION OF MASK WEARING INDOORS

When visualizing the simulation, we present three views of the environment. The view on the left shows the type of each cell at that time step. The view in the middle shows the concentration of viral particles in the environment at each cell. The view on the right shows the concentration of viral particles inhaled by each susceptible individual. All simulations are run for a little over 114 minutes of simulated time. On a machine with a processor running at 4.60 GHz, each scenario takes around 8.5 minutes to complete.

4.1 Same Mask Type

Initially, we study a case when both the spreader and the susceptible individuals are not wearing masks. At the first instance of emission of viral particles from the index (Figure 5a), the particles reached a position 6 cells above the index, with no spreaders having inhaled any particles. Halfway through the simulation at 52 minutes (Figure 5b), the dispersion of the particles reaches 23.2% of the area. It can also be seen that there are 9 susceptible individuals that inhaled enough particles to become infected, as well as 2 more that are close to the threshold of infection. At 114 minutes the particles cover 32.1% of the area with a maximum distance from the source of 15 cells, and 3 more susceptible individuals had become infected. In total, 18 of the 53 susceptible individuals had inhaled some quantity of viral particles after 114 minutes (Figure 5c).

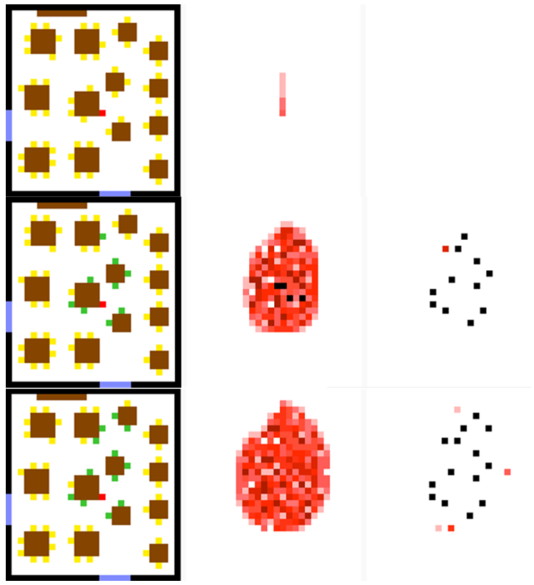

Figure 5: Simulation results; no one wearing masks: (a) initial spread; (b) 52 minutes; (c) 114 minutes.

The next scenario considers that both the index and the susceptible individuals are wearing cotton masks. At the first instance of emission of viral particles from the index, the particles only reached the position directly adjacent above the index (Figure 6a). Again, at 52 minutes into the simulation, the dispersion of the particles had reached 7.2% of the area of total possible cells (Figure 6b).

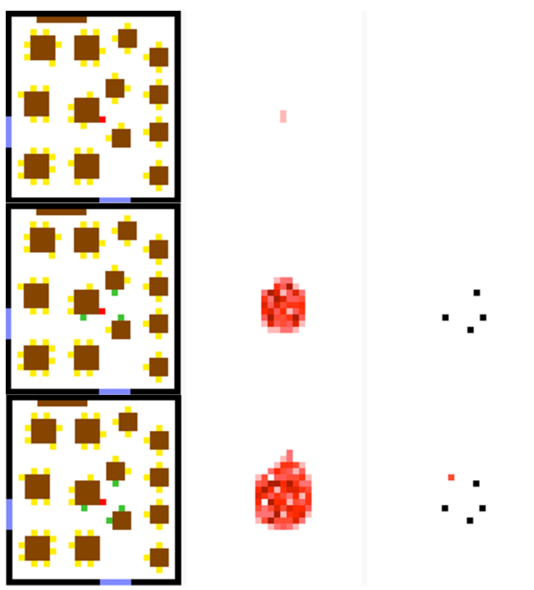

Figure 6: Everyone wearing cotton/surgical masks: (a) initial spread; (b) 52 minutes; (c) 114 minutes.

We can see that there are 3 susceptible individuals that had inhaled enough particles to become infected, and 1 more that is close to the infection threshold. At 114 minutes into the simulation there are a total of 5 susceptible individuals that had inhaled the viral particles, including 4 that had become infected (Figure 6c). The particles covered 11.9% of the environment, at a maximum distance of 8 cells from the index. Both the number of infected susceptible individuals and the area covered by the viral particles had decreased by around two thirds when all the persons were wearing cotton masks compared to not wearing any masks.

The next scenario considered that both the index and the susceptible individuals were wearing surgical masks. Although the efficiency of the surgical masks is significantly greater than that of the cotton masks the scenarios return identical results. Over 114 minutes, the spread of the viral particles in the third scenario follows the same pattern as that of the second. There are also 4 infected susceptible individuals at the end of the simulation, with only 1 more having inhaled any viral particles, and an area covered of 11.9%. This is due to the similarity in the shed values of the cotton and surgical face masks, 24% and 27% respectively.

The final two scenarios consider that all the persons in the restaurant are wearing N95 respirators. One of the scenarios explores the use of incorrectly fitted respirators, while the other looks at the use of correctly fitted respirators. Both scenarios resulted in an insignificant number of viral particles emitted from the index, and therefore, no particles appear in the visualization at the end of the simulation (Figure 7). This phenomenon can be explained by the low shed values of both respirators. With shed values of 5% and 0% for incorrectly and correctly fit N95 respirators respectively, the viral particle spread is low enough after 114 minutes that no particles had been inhaled by any susceptible individuals. Therefore, the use of N95 respirators in this context is safer for those around the index than the use of surgical, cotton, or no mask.

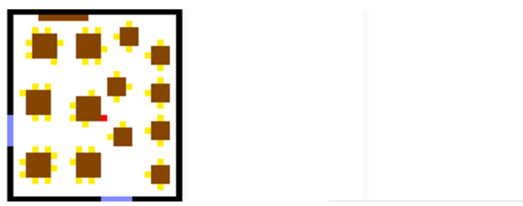

Figure 7: Visualization of the results; everyone wearing N95 respirators 114 minutes into the simulation. Note that the views in the middle and the right are blank due to the lack of viral particles in the environment.

4.2 Different Mask Types

The second group of scenarios occur when the index is wearing one type of mask while all the susceptible individuals are wearing another type. This resulted in twenty different scenarios. Eight of those scenarios have the index wearing either an incorrectly fit N95 or a correctly N95. It can be seen in the previous section that when the index wears an N95 respirator, a minimal number of viral particles are emitted. Therefore, we do not include the results of the scenarios that use of an N95 respirator for the index, as they all produce the same outcome as the one shown in Figure 7. The remaining twelve scenarios consist of four scenarios where the index is wearing no mask while the susceptible individuals are wearing one of the four masks, four scenarios where the index is wearing a cotton mask while the susceptible individuals are either wearing no mask or one of the other masks, and four scenarios where the index is wearing a surgical mask while the susceptible individuals are either wearing no mask or one of the other masks.

The spread of the viral particles in the scenarios with the index not wearing a mask all have the same size and shape of the viral particle spread in the environment as seen in Figures 8-11. The outward spread of the particles from the index in a controlled environment depends only on the shed value of the mask being worn by the index. The only difference between the simulations is the number of particles inhaled by the susceptible individuals, and accordingly, the number of susceptible individuals that become infected. When the susceptible individuals are wearing cotton masks, 12 of them became infected, the same as in the first scenario, with a total of 15 having inhaled some number of particles. 15 susceptible individuals also inhaled some viral particles when they were wearing surgical masks or incorrectly fit N95 respirators. The use of surgical masks and incorrectly fit N95 respirators only decreased the number of infected susceptible individuals by 1 to a total of 11. The scenario with the susceptible individuals wearing correctly fit N95 respirators, however, had displayed a decrease of both the number of infected susceptible individuals to 9, and the number of susceptible individuals that inhaled viral particles to 13.

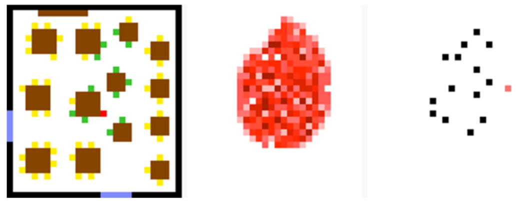

Figure 8: Index not wearing a mask; others wearing cotton masks.

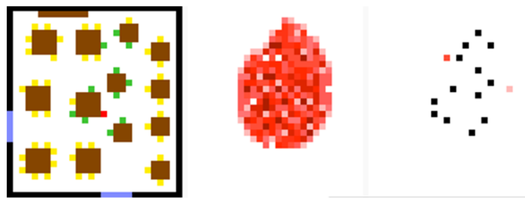

Figure 9: Index not wearing a mask; others wearing surgical masks.

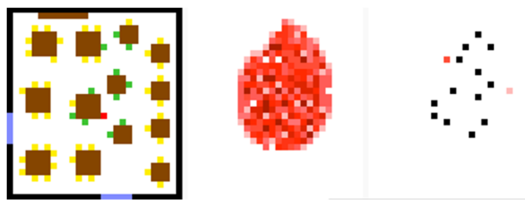

Figure 10: Index not wearing a mask; others wearing incorrectly fit N95 respirators.

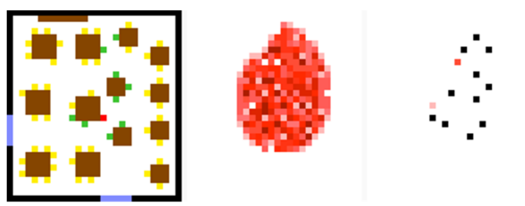

Figure 11: Index not wearing a mask; others wearing correctly fit N95 respirators.

As seen in the previous section, the scenario when the index is wearing a cotton mask returns an identical viral spread pattern to the scenario when the index is wearing a surgical mask due to the similar shed values of both mask types. We present the visualizations of both types of masks that the index wears in one figure for each type of mask that the susceptible individuals wear in the scenario (Figures 12-15).

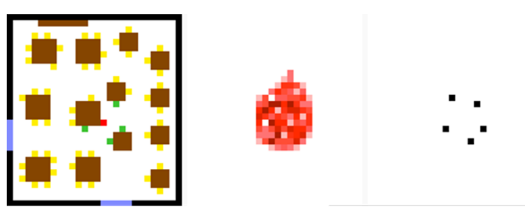

Figure 12: Index wearing cotton/surgical mask; others not wearing masks.

After running the simulation for 114 minutes, we can see that the number of susceptible individuals that become infected stays constant at 4, regardless of the mask worn. The number of susceptible individuals that have inhaled viral particles also stays the same, except in the case of the susceptible individuals wearing correctly fit N95 respirators. When looking at the scenarios in order of susceptible individual mask type efficiency, Figure 16 down to Figure 19, we can note that the number of inhaled particles seen in the right-side view decreased.

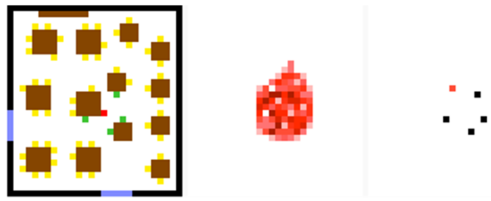

Figure 13: Index wearing cotton/surgical mask; others wearing cotton masks.

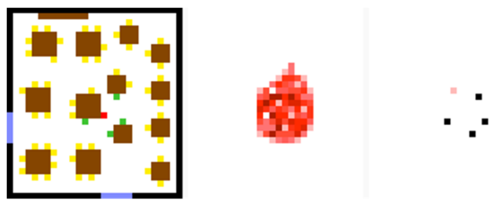

Figure 14: Index wearing cotton/surgical mask; others wearing incorrectly fit N95 respirators.

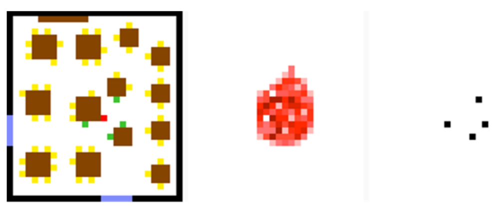

Figure 15: Index wearing cotton/surgical mask; others wearing correctly fit N95 respirators.

4.3 Discussion

Table 2 summarizes the results of our simulation studies. We can see a larger decrease in new infections when masks with higher efficiencies were used by the index rather than the susceptible receivers. When a mask was not worn by the index, the number of infections ranged from 9 to 12, however, when a cotton or surgical mask was worn by the index, the number of infections stayed constant at 4, despite the difference in efficiencies in the masks worn by the susceptible receivers. The area of the environment reached by the viral particles diminished by two thirds when a cotton or surgical mask was worn by the index, from 32.1% to 11.9%. Of note are the effects of the N95 respirators. Though the use of N95 respirators by susceptible individuals did not completely protect them from infection, the respirators did decrease the likelihood of particle inhalation. When the respirators were worn by the indexes, there was a perfect stop in the spread of the viral particles, thereby keeping everyone else present in the environment safe.

We can see from the results that the type of mask worn by the infected indexes is much more important to the safety of the susceptible individuals in the environment than the type of mask worn by the susceptible individuals themselves. Although the better performing masks do make a difference in the number of inhaled particles and slightly decreases the number of new infections, specifically when the index does not wear any mask, the use of any type of mask by the index cells has a much greater impact. The drastic decrease in infected susceptible individuals when moving from a scenario where the index does not wear a mask to a scenario where the index wears an N95 respirator, or to a lesser extent a cotton or surgical mask, is apparent. When looking at the susceptible individuals that were in a position near the index, the use, or lack of, of any mask other than an N95 respirator did not change the outcome. This can be seen to be in line with the recommendations provided by the WHO (2020) during the COVID-19 pandemic in that mask use is not to be used in lieu of the concept of physical distancing, but in conjunction with it.

Table 2: Results of all scenarios.

Mask worn by virus index	Masks worn by susceptible individuals	Susceptible individuals that have inhaled viral particles	Susceptible individuals that have become infected	Area reached by viral particles
None	None	18	12	32.1%
	Cotton masks	15	12	
	Surgical masks	15	11	
	Incorrectly fit N95	15	11	
	Correctly fit N95	13	9	
Cotton mask and surgical mask	None	5	4	11.9%
	Cotton masks	5	4	
	Surgical masks	5	4	
	Incorrectly fit N95	5	4	
	Correctly fit N95	4	4	
Incorrectly fit N95	All masks	0	0	0%
Correctly fit N95				0%

5 CONCLUSIONS

We presented a model that simulates viral spread spatially in a 2D indoor environment. The model was built to consider the efficiencies of different mask types. This allowed for the simulation of scenarios to explore the effects of wearing face masks on the spread of airborne viral infections in an indoor setting. Using data on the specific efficiencies of face masks recommended for use during the COVID-19 pandemic, we were able to study the impact of different mask wearing combinations on the spread of the virus in a restaurant-like setting. The limitations of the model mean that both the incorrectly and correctly fit N95 respirators returned similar results when worn by the indexes, and that they do not allow for the visualization of the small number of viral particles emitted in those cases. This is not true in a real-world setting, and further study and modifications to the model can be made to better represent this. The results show that more emphasis should be placed on the type of mask being worn by someone with symptoms or a suspicion of having the virus than the type of mask being worn by susceptible people trying to protect themselves. As expected, the type of masks with a higher efficiency in the one-to-one studies are also more efficient when looking at an environment that contains more people. The use of any mask greatly decreased the chance of infection and the spread of the viral particles, as opposed to not wearing a mask. Currently we are exploring the use of the Cell-DEVS formalism to develop a 3D environment for more in-depth study of the effects of viral particle spread in an environment.

REFERENCES

Altamimi, T., H. Khalil, V. S. Rajus, R. Carriere and G. Wainer. 2021. "Cell-DEVS models with BIM integration for airborne transmission of COVID-19 indoors". *Symposium on Simulation in Architecture and Urban Design SimAUD* 2021 (virtual).

Anderson, R. M., H. Heesterbeek, D. Klinkenberg, and T. D. Hollingsworth. 2020. "How will country-based mitigation measures influence the course of the COVID-19 epidemic?". *The Lancet* 395(10228):931-934.

Asadi, S., A. S. Wexler, C. D. Cappa, S. Barreda, N. M. Bouvier, and W. D. Ristenpart. 2019. "Aerosol emission and superemission during human speech increase with voice loudness". *Scientific Reports* 9:2348.

Bazant, M. Z. and J. W. M. Bush. 2021. "A guideline to limit indoor airborne transmission of COVID-19". *Proceedings of the National Academy of Sciences* 118(17):e2018995118.

Belloli, L., D. Vicino, C. Ruiz-Martin, and G. Wainer. 2019. "Building Devs Models with the Cadmium Tool". *Proceedings of the Winter Simulation Conference* 2019, December 8th-12th, Maryland, United States of America, 45–59.

Buonanno, G., L. Stabile, and L. Morawska. 2020a. "Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment". *Environment International* 141:105794.

Buonanno, G., L. Morawska, and L. Stabile. 2020b. "Quantitative assessment of the risk of airborne transmission of SARS-CoV-2 infection: Prospective and retrospective applications". *Environment International* 145:106112.

Cárdenas, R., K. Henares, C. Ruiz-Martin, and G. Wainer. 2020. "Cell-DEVS Models for the Spread of COVID-19". *Cellular automata for research and industry ACRI* 2020, December 2nd-4th, Łódź, Poland, 239-249.

De-Leon, H., and F. Pederiva. 2020. "Particle modeling of the spreading of coronavirus disease (COVID-19)". *Physics of Fluids* 32:087113.

Eikenberry, S. E., M. Mancuso, E. Iboi, T. Phan, K. Eikenberry, Y. Kuang, E. Kostelich, A. B. Gumel. 2020. "To mask or not to mask: Modeling the potential for face mask use by the general public to curtail the COVID-19 pandemic". *Infectious Disease Modelling* 5:293-308.

Hajj-Ali, Z. 2021. Scenarios for "Spatial Models and Masks in Indoor Analysis for the Spread of COVID-19". https://github.com/ZeinHajjAli/Cell-DEVS-Mask-Effects, accessed 26th June 2021.

Jayaweera, M., H. Perera, B. Gunawardana, and J. Manatunge. 2020. "Transmission of COVID-19 virus by droplets and aerosols: A critical review on the unresolved dichotomy". *Environmental Research* 188:109819.

Kermack, W. O., and A. G. McKendrick. 1927. "Contributions to the Mathematical Theory of Epidemics". *Proceedings of the Royal Society of London* 115(772):700-721.

Khalil, H. and G. Wainer. 2020. "Modeling Carbon Dioxide Dispersion Indoors". *Cellular automata for research and industry ACRI* 2020, December 2nd-4th, Łódź, Poland, 226-236.

Khalil, H., G. Wainer, and Z. Dunnigan. 2020. "Cell-DEVS Models for CO2 Sensors Locations in Closed Spaces". *Proceedings of the Winter Simulation Conference* 2020 (virtual).

Li, Y., G. M. Leung, J. W. Tang, X. Yang, C. Y. H. Chao, J. Z. Lin, J. W. Lu, P. V. Nielsen, J. Niu, H. Qian, A. C. Sleigh, H.-J. J. Su, J. Sundell, T. W. Wong, P. L. Yuen. 2007. "Role of ventilation in airborne transmission of infectious agents in the built environment - a multidisciplinary systematic review". *Indoor Air* 17(1):2-18.

Li, X., C. Claramunt, and C. Ray. 2010. "A grid graph-based model for the analysis of 2D indoor spaces". *Computers, Environment and Urban Systems* 34(6):532-540.

Li, Y., M. Chen, Z. Dou, X. Zheng, Y. Cheng, and A. Mebarki. 2019. "A review of cellular automata models for crowd evacuation". *Physica A: Statistical Mechanics and its Applications* 526:120752.

Li, H., F. Y. Leong, G. Xu, Z. Ge, C. W. Kang, and K. H. Lim. 2020. "Dispersion of evaporating cough droplets in tropical outdoor environment". *Physics of Fluids* 32:113301.

Lu, J., J. Gu, K. Li, C. Xu, W. Su, Z. Lai, D. Zhou, C. Yu, B. Xu, and Z. Yang. 2020. "COVID-19 Outbreak Associated with Air Conditioning in Restaurant". *Emerging Infectious Diseases* 26(7):1628-1631.

Makmul J. 2021. "A pedestrians flow model during propagation of smoke: Microscopic and macroscopic approaches". *Safety Science* 133:105006.

Manski, C. F. and F. Molinari. 2021. "Estimating the COVID-19 infection rate: Anatomy of an inference problem". *Journal of Econometrics* 220(1):181-192.

Marr, L., S. Miller, K. Prather, C. Haas, W. Bahnfleth, R. Corsi, J. Tang, H. Herrmann, K. Pollitt, J. Ballester, and J. L. Jimenez. 2020. FAQs on Protecting Yourself from COVID-19 Aerosol Transmission – Version 1.87. https://tinyurl.com/FAQ-aerosols, accessed 21st December 2020.

St-Aubin, B., O. Hesham, and G. Wainer. 2018. "A Cell-DEVS visualization and analysis platform". *Proceedings of the 50th Summer Computer Simulation Conference* 2018, Berlin, Germany.

Tracht, S. M., S. Y. Del Valle, and J. M. Hyman. 2010. "Mathematical Modeling of the Effectiveness of Facemasks in Reducing the Spread of Novel Influenza A (H1N1)". *PLoS ONE* 5(2):e9018.

Ueki, H., Y. Furusawa, K. Iwatsuki-Horimoto, M. Imai, H. Kabata, H. Nishimura, Y. Kawaoka. 2020. "Effectiveness of Face Masks in Preventing Airborne Transmission of SARS-CoV-2". *mSphere* 5(5):e00637-20.

Wainer, G. 2009. *Discrete-Event Modeling and Simulation: A Practitioner's Approach*. 1st ed. Boca Raton: CRC Press.

Wells, W.F. 1955. "Airborne Contagion and Air Hygiene: An Ecological Study of Droplet Infection". *Journal of the American Medical Association* 159(1):90.

World Health Organization. 2020. Coronavirus disease (COVID-19) advice for the public: When and how to use masks. https://www.who.int/emergencies/diseases/novel-coronavirus-2019/advice-for-public/when-and-how-to-use-masks, accessed 21st December 2020.

AUTHOR BIOGRAPHIES

ZEIN HAJJ-ALI is a master's student at the Department of Systems and Computer Engineering at Carleton University (Ottawa, ON, Canada). His email address is zeinhajjali@sce.carleton.ca.

GABRIEL A. WAINER is Professor at the Department of Systems and Computer Engineering at Carleton University (Ottawa, ON, Canada), where he is now Full Professor. He is a Fellow of SCS. His email address is gwainer@sce.carleton.ca