Aiding decision makers to reopening of places of worship

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Abstract

Objective: Our research objective is to work with leaders of houses of worship in the local community to assess options for the physically reopening of places of worship.

Method: This study consists of two parts. The first part consists of working with a leader of a house of worship to formulate a decision process based on the priorities of the organization and its physical size and population. The second part involves the modeling of the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) virus spread within a physical space to provide the leadership of the house of worship an estimate of the outcomes of deciding on various courses of action. The model is a modification of a standard virus model developed for the NetLogo programming environment.

Results: The team worked with a large local church in Pennsylvania to physically reopen a worship service. Based on the questionnaire data, the congregation did not prefer the strongest form of the SARS-CoV-2 virus mitigation (mask wearing and social distancing) but favored either mask required and no social distancing or masks optional and social distancing. The team simulated conditions representative of the church and found that social distancing is the key factor to mitigate spread.

Conclusion: Given the preferences of the congregation, our simulation results suggested that one of the favored options would likely yield a large number of infections (>10% in a scenario with an asymptomatic carrier). This information was provided to the leadership to guide their decision-making for the coming months as poor weather will rule out outdoor worship as a viable option.

Keywords
agent-based model, analytic hierarchy process, COVID-19, decision-making, houses of worship

1 | INTRODUCTION

The purpose of this study is to aid leaders of houses of worship in their decisions to physically reopen places of worship. In communist countries like China, religious liberties to gather in-person has been vastly curtailed because of the coronavirus disease 2019 (COVID-19) pandemic (Vandenberg, 2020; Yuan, 2020). In authorized houses of worship in China, the decision to meet in person is made by the government. On the other hand, Islamic governments and organizations have reacted in widely different ways with different motivations (Hanna, 2020). The Saudi Arabian government has curtailed traffic to its pilgrimage sites, including a curfew on Mecca and Medina and has urged Muslims to postpone plans to make the Hajj in 2020. Hamas, the Islamist party ruling Gaza, banned public gatherings and Friday prayers. Unlike the examples of China and the Islamic governments and organizations, houses of worship in
the United States are more decentralized and often have more autonomy to make decisions.

As the first wave of the pandemic swept through the United States, stay-at-home orders nationwide caused houses of worship to postpone in-person gatherings. As states and counties in the United States begin to reopen in-person gatherings, many questions confront leaders in places of worship. For example, the State of Pennsylvania has entered a Green Phase, meaning that occupancy in businesses may increase to 75% of capacity (Wolf, 2020). The meaning for places of worship is less clear. As federal and state guidance for communities of faith is careful not to infringe on rights protected by the First Amendment of the Constitution and other federal laws, including the Religious Freedom Restoration Act of 1993 (RFRA), places of worship need to make decisions to reopen that balance the need to physically worship together with the need to keep the physical safety of the congregants.

In a recent paper by Dennerlein et al. (2020), an integrative health total worker health (TWH) framework for keeping safe and healthy during COVID-19 was presented. The framework is based on emerging workplace practices to reduce worker exposure to COVID-19. Key points in the paper include using participatory approaches, employing data-driven evaluation of an organization’s priorities, and reliance on leadership commitment. For this study, the investigators implemented data collection through questionnaires to the congregation. The responses enabled the research team to assess the preferences of the congregation with respect to the COVID-19 safeguards (mask wearing and social distancing) as well the consistency of the responses.

The research team worked with a large church with multiple campuses in the Central Pennsylvania region. We focused on the physical reopening of the main campus with over 800 congregants. Our study consisted of two parts. The first involved working with the pastor of the church to formulate a decision process based on the priorities of the organization and its physical size and population. Through working with the leader, the team developed a method using the analytic hierarchy process (AHP) that was implemented via questionnaires to the congregation. The responses enabled the research team to assess the preferences of the congregation with respect to the COVID-19 safeguards (mask wearing and social distancing) as well the consistency of the responses.

The second part involved the modeling of COVID-19 spread within a physical space to provide the leadership of the church an estimate of infection based on various courses of action for reopening worship. The research team surveyed research on transmission of the SARS-CoV-2 virus, which causes COVID-19, to build an agent-based model using input factors of duration of event, exposure dose limit to cause infection, number of infectious individuals, number of congregants, social distancing, indoor or outdoor gathering, masking or no masking, symptomatic or asymptomatic, and air changes per hour (ACH). The outcome of each simulation run included the number of newly infected individuals. The model is a modification of a standard virus model developed for the NetLogo programming environment.

### 1.1 Estimating COVID-19 spread using agent-based modeling

In a recent article, Holman et al. (2020) explored the use of agent-based modeling in ergonomics to adapt to the densely inter- and intraconnected socio-technical systems that are prevalent today. While their focus was on work systems within a Fourth Industrial Revolution (such as cyber-physical systems), we can extend their focus on organizational systems such as houses of worship in the midst of a COVID-19 pandemic. According to Wilensky and Rand (2015),

Agent-based modeling (ABM) is a computational modeling paradigm that enables us to describe how any agent will behave. The methodology of ABM encodes the behavior of individual agents in simple rules so that we can observe the results of these agents’ interactions. (p. 22)

In part, the effectiveness of the ABM paradigm comes from the restricted scope of the modeled system. For example, ant colonies have been modeled with simple rules to forage for food (Wilensky, 1997) to demonstrate complex colony behavior.

Existing epidemiology models, however, mostly address larger phenomenon such as spread in a region (Adam, 2020; Ivorra et al., 2020; Li et al., 2020) or are concerned with laboratory studies to investigate droplet travel distance or aerosol accumulation (Beggs, 2020; Jayaweera et al., 2020). The spread models typically seek to explain how quickly people move between states of susceptibility (S) to the virus to becoming infected (I) to either recovery (R) or death. These are called SIR (or SEIR where E stands for exposed but not yet infected) type models.

Before we can design and build an agent-based model of COVID-19 spread in a church building or an outdoor gathering space, we need to review existing findings and incorporate them into our model. Models that predict spread of the SARS-CoV-2 virus in a region are helpful in the S and I states because our focus is in the spread during a particular gathering. Models investigating droplet and aerosol spread are helpful to inform dosage and distances for our situation. Even these extensions will be simplified representations of reality, but can serve to highlight differences between various options of gathering a group together (WHO, 2020). We consider the following parameters for our model of transmitting SARS-CoV-2:

A. Mode of transmission;
B. Effects of mask wearing and social distancing;
C. Environmental conditions; and
D. Initial Infectious population.

#### 1.1.1 Mode of transmission

The WHO (2020) has outlined three main forms of SARS-CoV-2 transmission: contact and droplet, airborne, and fomite.
Contact transmission occurs through direct, indirect, or close contact with infected people through infected secretions such as saliva and respiratory secretions or their respiratory droplets, which are expelled when an infected person coughs, sings, sneezes, or talks. Respiratory droplets are >5–10 μm in diameter.

Airborne transmission is defined as the spread of an infectious agent caused by the dissemination of aerosols that remain infectious when suspended in air over long distances and time. Airborne transmissions can occur during medical procedures that produce aerosols or through aerosols in indoor settings with poor ventilation. Aerosols are defined as droplets ≤5 µm in diameter.

Fomites are secretions or droplets produced by infected individuals who contaminate surfaces and objects. While evidence exists of SARS-CoV-2 contamination of surfaces and the survival of the virus on surfaces, there are no specific reports which have directly demonstrated fomite transmission. In addition, people who come in contact with infectious surfaces often also have close contact with the infectious person, making the distinction of transmission difficult to discern (WHO, 2020).

While the WHO discusses other modes of possible transmission (such as through urine of patients), we will focus our modeling efforts on contact and airborne transmission since these forms account for the vast majority of transmissions (Jayaweera et al., 2020). Table 1 shows the number of droplet particles produced from human activities. While scientists disagree on the specific number of particles required for an infectious dose, there is general agreement that a few hundred or thousand particles would be adequate (Science Media Centre, 2020).

In addition to the particles generated, one must also consider the distance covered in the human expiratory activities as a factor for contamination. Figure 1 shows the droplets from an infected patient when sneezing, coughing, or simply exhaling.

A recent assessment on the impact of singing on SARS-CoV-2 transmission suggests that singing is comparable to coughing (COVID-19 Scientific Advisory Group, 2020).

**TABLE 1** Detailed information of droplets and aerosols generated from human expiratory activities

| Activity                        | Number of droplets and aerosols generated (1–100 µm) | Presence of aerosols (1–2 µm) | Region of origin |
|---------------------------------|------------------------------------------------------|-------------------------------|------------------|
| Normal breathing (for 5 min)    | None—few                                             | Some                          | Nose             |
| Single strong nasal expiration  | Few—few hundred                                      | Some                          | Nose             |
| Counting loudly—talking         | Few dozen—few hundred                                | Mostly                        | Front of the mouth |
| A single cough (mouth open)     | None—few hundred                                     | Some                          | Fauclial region  |
| A single cough (mouth initially | Few hundred—many thousand                            | Mostly                        | Front of the mouth |
| closed)                         |                                                       |                               |                  |
| Single sneeze                   | Few hundred thousand—few million                     | Mostly                        | Front of the mouth |
|                                 | Few—few thousand                                     | Some                          | Both from the nose and the faucial region |

Source: Duguid (1945).

**FIGURE 1** Trajectories of droplets (a) event of sneezing with droplets travelled for 6 m at a speed of 50 m/s within 0.12 s, (b) event of coughing with droplets travelled for 2 m at a speed of 10 m/s within 0.2 s, (c) event of exhaling with droplets travelled for 1 m at a speed of 1 m/s within 1 s (Source: Jayaweera et al., 2020)

**Implications:** Taken together, Table 1 and Figure 1 show that a sneezing infectious person may transmit a hundred thousand or more SARS-CoV-2 virus particles to a distance of up to 6 m. A coughing/singing infectious person may transmit a few thousand particles to a distance of up to 2 m. An infectious person simply breathing may transmit a few hundred particles to a distance of 1 m.
1.1.2 | Effects of mask wearing and social distancing

There is a steadily accumulating body of literature that show the effectiveness of masks (or respirators) when coupled with social distancing (Prather et al., 2020; WHO, 2020). The comparative effects of masks or respirators are shown in Figure 2.

When an infectious individual is wearing surgical masks, there is about 20%–30% leakage of droplets and a large portion of aerosols. With N95 and elastomeric respirators (reusable half facepiece or full facepiece tight-fitting respirators where the facepieces are made of synthetic or natural rubber material), there is about 5% leakage of droplets and a cloud of aerosols. In addition, researchers have found that homemade cloth masks are two to three times less effective in blocking transmission than surgical masks (Davies et al., 2013; Jayaweera et al., 2020). When an infectious individual is not wearing a mask or respirator, a noninfected individual in close proximity will have similar percentages of droplets and aerosols pass through his/her mask or respirator.

Implications: Combined with Section A, one can assess the viral load and the travel distance of SARS-CoV-2 under different human events.

FIGURE 2 | Trajectories of droplets in the event of an infected individual coughing with different masks or respirators worn (a) without any mask or respirator, (b) with surgical mask, (c) with N95 respirator, and (d) with reusable elastomeric respirator (Source: Jayaweera et al., 2020)

[Image: Figure 2 showing trajectories of droplets with different masks or respirators]

1.1.3 | Environmental conditions

There are many environmental parameters which affect viral load such as air temperature, humidity, sunlight, and UV radiation (Jayaweera et al., 2020). We know that aerosols will accumulate and persist for hours in a confined space with inadequate airflow. In confined areas with sufficient airflow such as an airplane cabin or a passenger car, movement of SARS-CoV-2 via plumes of aerosols is not well understood. For example, an aircraft cabin has 20–30 ACH and the filtration system consists of high-efficient particulate air (HEPA) filters. While it is conceivable for plumes of virus aerosols to enter the airflow, the actual number of recorded cases of virus transmission are few. Nevertheless, it is possible that spread of the virus can occur via large droplets as well as aerosols.

In indoor environments, such as a church where the ACH is between 8 and 12 (ASHRAE, 2013), we can approximate the spread of SARS-CoV-2 via plumes of aerosols. Our consideration of aerosol transmission is dependent on the viral load of an aerosol over time. For example, an ACH of 12 represents air within a space being replaced every 5 min.

While the vast majority of cases being reported have been in indoor environments (Qian et al., 2020), the potential for outdoor transmission still exists. Qian et al. (2020) studied 318 outbreaks in China and came upon only one outbreak in an outdoor environment involving two cases (individuals). In the one outbreak outdoors, the individuals were engaged in a one-on-one conversation. We know that sunlight and UV radiation degrades the infectivity of influenza virus in droplet and aerosols. We also know that high relative humidity causes a loss of viability of SARS-CoV-2. Jayaweera et al. (2020) summarizes the impacts of a number of environmental factors on the virus. In addition, natural air currents in the outdoors diminishes the potential of aerosol build up although droplets expelled through sneezes or coughs of infectious individuals remain potent.

Implications: Incorporating airflow in an indoor context, we modify Table 2 to show the number of particles per exposure of a healthy person. This is shown on Table 3. We assume events such as sneezing and coughing will persist no longer than the interval at which air is replaced. We take into consideration ACH rates of 10 and 12.

For outdoor exposure, we assume airborne transmission via aerosols and fomites to be negligible. We also assume the viral load of contact transmissions to be diminished by environmental factors.
TABLE 2  Droplets expelled for different human events when masked or not (n represents an integer factor)

| Facial covering | Human event                | For transmitter | For receiver | Sneezing | Coughing/singing | Exhaling |
|-----------------|----------------------------|-----------------|-------------|-----------|------------------|----------|
| None            | None                       | 100 K × n, 6 m  | 1 K × n, 2 m| 100 × n, 1 m| 630 × n          | 63 × n   |
| Cloth           | None                       | 63 K × n        | 630 × n     | 63 × n    | 630 × n          | 63 × n   |
| None            | Cloth                      | 63 K × n        | 630 × n     | 63 × n    | 630 × n          | 63 × n   |
| Cloth           | Cloth                      | 39.7 K × n      | 397 × n     | 39.7 × n  | 397 × n          | 39.7 × n |

1.1.4 | Initial infectious population and assessment of a positivity rate for a geographical area

Determining the probability that someone attending a church is infected (i) at a church function depends on three variables: the size of the population (p), the size of the church group (g), and the number of infectious people (c). The equation is:

\[ i = 1 - \left(1 - \frac{c}{p}\right)^{\frac{g}{g}}. \]  

The population of the county being considered is 160,000 (p) and the capacity limitation for an indoor gathering currently is 250 (g). If there are currently 70 active cases in the county (c), then the chance of someone attending the gathering being infected is 10%.

In addition, it is important to assess the percentage of all COVID-19 tests conducted that are positive to differentiate the transmission of COVID-19 in a particular geographical area. The way percent positivity (pp) is calculated by the Centers for Disease Control is (CDC, 2020b):

\[ pp = \frac{\# \text{ of positive tests}}{\# \text{ positive tests} + \# \text{ negative tests}}. \]  

2 | CONGREGATION PREFERENCE ASSESSMENT USING THE ABSTRACTION HIERARCHY PROCESS

The process of assessing congregational preferences involve working with the leadership of a house of worship to structure decision criteria that reflects the priorities of the organization. The research team chose the Analytic Hierarchy Process (AHP) as a technique that facilitates both the hierarchical structuring of decisions as well as the formation of a quantitative questionnaire for soliciting preference information to inform those decisions (Saaty & Vargas, 1990). The research team administered the questionnaire to the congregation and analyzed the results to determine congregational preferences.

2.1 | Introduction to the analytic hierarchy process

AHP is a general theory of measurement used to derive ratio scales from human judgments through multiple paired comparisons in a hierarchically structured task (Saaty, 1980). AHP has been used in human factors applications such as to rank-order computer interfaces (Mitta, 1993), to ascertain appropriate knowledge elicitation methods (Chao et al., 1999), to select attributes for designing virtual environment systems (Stanney et al., 2003), and to analyze the decision process itself in multiattribute decisions (Jin et al., 2010; Spries, 1991).

The first step in the AHP is to model the problem as a hierarchy, such as shown in Figure 2, containing the decision objective, the alternatives for reaching it, and the attributes for evaluating the alternatives. The next step is to establish priority weights among the elements (i.e., alternatives and attributes in Figure 2) of the hierarchy by making a series of judgments based on pairwise comparisons of the elements. More specifically, participants make n(n–1)/2 pairwise comparisons for n elements using a 9-point scale ranging from absolute dominance to equality. The results of the pairwise comparisons are then arranged in a reciprocal matrix,

\[ A = \begin{bmatrix} 1 & \frac{w_2}{w_1} & \cdots & \frac{w_n}{w_1} \\
\frac{w_2}{w_1} & 1 & \cdots & \frac{w_n}{w_2} \\
\vdots & \vdots & \ddots & \vdots \\
\frac{w_n}{w_1} & \frac{w_n}{w_2} & \cdots & 1 \end{bmatrix}. \]  

where \( w_j \) (j = 1, 2, ..., n) is the weight value of element j.

Given a reciprocal matrix, the next step is to compute a weight vector \( w \), which represents relative weights of the elements of the hierarchy. Saaty (1980) showed that \( w \) must satisfy

\[ Aw = \lambda_{\text{max}} w, \]  

where \( \lambda_{\text{max}} \) is the largest eigenvalue of A. Mathematically, \( w \) can be obtained by normalizing the principle eigenvector of A.

In addition to calculating priority weights, the AHP is also used to assess judgment consistency. Since small changes in a reciprocal matrix element imply a small change in \( \lambda_{\text{max}} \), the deviation of the latter from \( n \) can be taken as a measure of consistency. Saaty (1980) uses this deviation as a measure he calls the consistency index, where
\[
\lambda = \lambda_{\text{max}} - \frac{n}{n-1}.
\]  
(5)

In other words, a set of choices is most consistent if \( \lambda = 0 \). The \( \lambda \) can then be compared with a random index (RI), which is the CI value of a randomly generated comparison matrix, to determine whether any inconsistency found is acceptable. This is called the Consistency Ratio (CR). CR is then calculated as follows and the RI values for different number of \( n \) are shown in Table 4. Saaty (1980) estimated that a CR of 10% or less would be acceptable. The reasoning is that values much higher than 10% would resemble a random outcome.

\[
\text{CR} = \frac{\text{CI}}{\text{RI}}.
\]  
(6)

The method of aggregation of the preferences across all the survey participants depends on structure of the decision hierarchy (Ossadnik et al., 2016). For the current problem, where the judgments of the participants are desired, we use an arithmetic mean to aggregate individual judgments.

### 2.2 Developing an AHP model for assessing congregation priorities

To assess the priorities of the congregation, the church leadership and the team focused on viable options to the church in terms of a physical gathering. The church, like many others since the beginning of the pandemic, had developed a significant online program. Therefore, while a physical gathering is desirable, it is not a necessary element of the weekly worship service if prohibited by safety considerations. The research team developed the following options for physical gathering as follows:

A. Indoor worship gathering with social distancing and masks optional.

B. Indoor worship gathering with social distancing and masks required.

C. Indoor worship gathering with no social distancing and masks required.

D. Outdoor worship gathering with social distancing and masks required.

E. Outdoor worship gathering with social distancing and masks optional.

The primary objective for all the options is the worship experience. A survey was sent via electronic mail to the congregation of the church with a distribution list of over 2000 people. The survey consists of all pairwise combinations of the five options along a 9-point scale. A sample question using Options A and B is shown in Figure 3. The team received 226 responses of which 219 were complete and could be used in the data analysis. The church is one of the largest in Centre County, Pennsylvania. According to the U.S. Census Bureau, the race demographic of the county consists primarily of White (87.9%), Black or African American (3.8%), Asian (6.4%), and Hispanic or Latino (3%). The percentage of high school graduate or higher among persons at least 25 years old is 94.3% and the percentage of bachelor’s degree holder is 44.7%.

### 2.3 Analysis of congregation priorities

The weights were calculated per individual and we used an arithmetic mean to aggregate individual judgments. We used the ahpsurvey package (Cho, 2019) for R to perform the calculations. The results are shown in Figure 4 and reflect that the congregation prefers to worship indoors but not with the restrictions of masking and social distancing. The least preferred options include gathering outdoors. The mean consistency ratio was 0.149. While this value is slightly higher than the estimated threshold by Saaty (1980), we submit that the results show a clear preference pattern.

To better aid the leadership of the church in their decision-making, we next focus on the ramifications of selecting a particular option to return to physical gathering.

#### TABLE 4 Random index (RI) for \( n = 1–9 \)

|   | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI | 0.00| 0.00| 0.58| 0.90| 1.12| 1.24| 1.32| 1.41| 1.45|

Q1. When worshipping which option is more important?

**A:** Gathering indoors with social distancing and optional mask wearing

**B:** Gathering indoors with social distancing and mandatory mask wearing

![Survey question comparing Options A and B](image)
We use the NetLogo programming environment (Wilensky & Rand, 2015) for our model of virus spread in an indoor or outdoor space within a time span measured in minutes. The model interface is shown in Figure 5. The interface was modified from an early virus model (Wilensky, 1998). A congregant in the church is represented as an agent in the shape of a human figure. Agents occupy space, known as patches, in the model that corresponds to the physical footprint of a church. At each time step, known as a tick, each agent exchanges air (breathe, cough/sing, and sneeze) and moves randomly within the space. In the figure, a healthy individual is colored green, an infected individual is represented by red, and an infectious individual is shown as violet.

3 | AGENT-BASED MODEL DEVELOPMENT

We use the NetLogo programming environment (Wilensky & Rand, 2015) for our model of virus spread in an indoor or outdoor space within a time span measured in minutes. The model interface is shown in Figure 5. The interface was modified from an early virus model (Wilensky, 1998). A congregant in the church is represented as an agent in the shape of a human figure. Agents occupy space, known as patches, in the model that corresponds to the physical footprint of a church. At each time step, known as a tick, each agent exchanges air (breathe, cough/sing, and sneeze) and moves randomly within the space. In the figure, a healthy individual is colored green, an infected individual is represented by red, and an infectious individual is shown as violet.
The controls of the interface enable the user to manipulate the population, the regulations enforced, the environment, and the characteristics of SARS-CoV-2. For population, the user can determine the number of healthy agents in the congregation, the initial number of infectious agents, and whether the infectious are symptomatic. For regulations, the user can establish social-distancing, masking requirement, whether singing is allowable. For environment, the user can set the ACH in the place of worship and the amount of time spent at the place. In terms of the characteristics of the virus, the user can set the dose required to contract COVID-19 and the incubation period needed for an infected agent to become infectious.

3.1 | Basic agent properties

Each agent can be either healthy, infected, or infectious. A healthy agent can be infected, and an infected agent can become infectious after an incubation period. The population begins with a number of healthy individuals and a number of infectious individuals. A healthy agent can become infected if it has accumulated a viral load (via contact or airborne transmission) that exceeds a specific exposure dose. Once infected, an agent can become infectious after a specific incubation period. Because the model simulates time on a scale of minutes, and recovery occurs on a scale of days, no accommodation is made for infected agents to become healthy again.

3.2 | Infection and viral load

The mechanisms of transmission include proximity of an infectious agent to another agent and the viral load that is shed by the infectious agent. To parameterize the viral load, we combine the mitigating effects of masking (see Table 3) with the impact of airflow through the space (see Table 4). A decision tree for setting model parameters is shown in Figure 6. Each terminal node contains the viral load shed by an infectious agent per ACH condition. If an infectious agent is symptomatic, the viral load produced by sneezing overrides the type of activity allowed (i.e., singing). Moreover, the effective distance the load is carried is to twice the distance of normal exhalation due to sneezing and coughing at 12 feet. Also, the impact of being outdoors include an ACH of 60 and a reduced viral load by a factor of X. For this study, we assume that viral load is impacted by sunlight, UV radiation, and humidity so that X = 2. It is difficult to arrive at a specific factor for parameters to calculate viral load since SARS-CoV-2 is a relatively new virus. Our assumptions are based on the review of the literature in Section 1 of this article.

![Decision Tree](image)

**FIGURE 6** Viral load exposure per minute. An infectious symptomatic individual will override the impact of singing since sneezing behavior surpasses coughing/singing in terms of droplets expelled (Table 3). The normal range of virus spread is 6 feet. In the case of a symptomatic individual, the distance traveled by expelled droplets will double the normal range. When outdoors, ACH is assumed to be 60 and the load carried will be reduced by a factor of X. The viral load is calculated in terms the average droplets expelled during the time span before the volume of air is replaced. ACH, air changes per hour.
We assume that all congregants are masked in the masking-required condition or all are not masked otherwise. We also assume that all infectious agents are either symptomatic or not depending on the condition established.

### 3.3 Simulation execution and results

The research team executed 100 simulation runs per model condition reflecting the physical gathering options contained in the church questionnaire. Based on the low probability of having a congregant in Central Pennsylvania who is infectious (see Equation 1) in July of 2020, we set the number of initial infectious agents to one. To estimate the initial infected population in different geographical region or for a different time, the research team recommends that the percent positivity for the region under consideration be calculated. The simulation time was set to 60 min to represent the duration of a typical worship service. The exposure limit was set low at 100 as a cautious position to detect infections. Since the indoor worship space is a relatively new facility, we set the ACH to 10. We set the number of agents/people in the worship space to 250 per state guidelines (Wolf, 2020). The results of the runs are shown in Table 5.

The worst outcome is estimated in the indoor gathering without social distancing condition. Even when masking is required, the estimated number of infected agents after 60 min is 34 in the asymptomatic case and 130 in the symptomatic case. Therefore, if an indoor gathering is preferred, it is recommended that social distancing be strictly enforced. The best outcomes are projected in the outdoor options.

A graphical representation of the percent of infected individuals out of 250 total worshippers is shown in Figure 7. Also, as a measure of comparison, the condition of indoor gathering with no social distancing and masks optional was added. Based on the simulation outcomes, the impact of a symptomatic infectious person in an indoor gathering is notable—even comparable to meeting indoors with no mitigation safeguards.

### Table 5 Simulation outcomes for options in congregation-preferred order

| Option in order of congregation priority | Number of infected per one infectious asymptomatic carrier | Number of infected per one infectious symptomatic carrier |
|-----------------------------------------|----------------------------------------------------------|---------------------------------------------------------|
| A. Indoors worship gathering with social distancing and masks optional | $\mu = 1.01, \sigma = 0.1$ | $\mu = 9.44, \sigma = 4.01$ |
| B. Indoors worship gathering with social distancing and masks required | $\mu = 1.05, \sigma = 0.22$ | $\mu = 9.12, \sigma = 4.01$ |
| C. Indoors worship gathering with no social distancing and masks required | $\mu = 34.09, \sigma = 5.52$ | $\mu = 129.66, \sigma = 7.77$ |
| D. Outdoors worship gathering with social distancing and masks required | $\mu = 1, \sigma = 0$ | $\mu = 1.05, \sigma = 0.22$ |
| E. Outdoors worship gathering with social distancing and masks optional | $\mu = 1, \sigma = 0$ | $\mu = 1.05, \sigma = 0.22$ |

Note: Initial condition of each option includes one infectious agent. Each simulation run concluded after 60 min and the final number of infected (including the infectious agent) was recorded. Outcomes formatted as the mean and standard deviation per 100 simulation runs.

![Comparison of means of percentage of simulated infected individuals and whether infectious individual is symptomatic. Options are choices A–E for congregation members. Included as a measure of comparison is the mean number of infected for the group with no social distancing and no mask wearing while indoors.](image-url)
4 | DISCUSSION

To assist leaders of houses of worship in their decisions to physically reopen places of worship, the research team developed a process consistent with the framework presented by Dennerlein et al. (2020) as follows:

1. Work with the leadership of the house(s) of worship to determine viable alternatives;
2. Create a questionnaire for the congregation(s) based on these alternatives in a pair-wise comparison structure;
3. With the help of the leader(s), solicit congregants to complete questionnaires;
4. Analyze questionnaire data using AHP to assess the preferences of the congregation(s) and the consistency of the ratings; and
5. Estimate the spread of COVID-19 in a congregational gathering based on the preferences of the congregation(s).

The team worked with a large local church in Pennsylvania to physically reopen a worship service. We determined viable options and created a questionnaire to solicit feedback from the congregation. We analyzed the questionnaire data and computed the priority of the options. Using ABM, we found that one of the preferred options of the respondents of the questionnaire would likely yield a large number of infections (>10% in a scenario with an asymptomatic carrier). This information was provided to the leadership to guide their decision-making for the coming months as poor weather will rule out outdoor worship as a viable option.

5 | CONCLUSIONS

The objective of this study effort is to assist leaders of houses of worship in a local community to assess options for the physical reopening of places of worship. While this study was conducted in the United States, we suggest that the framework can be applied in situations where houses of worship have autonomy to determine policy on physical gatherings. However, we do not recommend simply applying our ABM results in all contexts because our modeling assumption may not generally hold. For example, as N95 masks become more widely available, the mitigating effects of masks will improve. Also, the number of initial infectious individuals will vary from low-risk to high-risk areas.

While we are confident that we adequately developed the agent-based model, we would like to point out some limitations of our study:

1. The research team submits that 100% adherence to mask wearing (assumed for Options B, C, D) or social distancing (assumed for Options A, B, D, E) is idealistic. Nevertheless, our assumptions can serve as boundary conditions from which to assess states which are less ideal. For example, if social distancing is modeled, we can compare the outcomes under Option D with the no social distancing model (Option C).
2. The team proposed a couple of different tools to determine an initial infectious population for the model. However, we also acknowledge that outside factors such as Christian nationalism influence incautious behavior (Perry et al., 2020) and may skew this estimate.
3. The ABM assumes infection based on a viral dose limit. As more of the population becomes infected (and recovers), the degree of immunity and reinfection within the congregation needs to be considered and modeled as more information about COVID-19 becomes available.

As states within the United States reopen, guidance to business and state agencies can be applied with consistency (Wolf, 2020). However, because of the need to respect the First Amendment rights of its citizens, places of worship are given latitude to create their own guidelines. Tools such as the ones presented in this article are needed to enable the leadership at places of worship to make reopening decisions that balance the need to physically worship together with the need to keep the physical safety of the congregants.

DATA AVAILABILITY STATEMENT

The data and models used for this project are available upon request.

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