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Modeling the spread of COVID-19 on construction workers: An agent-based approach

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ARTICLE INFO

ABSTRACT

As the spread of COVID-19 has continued since December 2019, stay at home orders around the globe have changed how we live our lives, mostly from physical to virtual interactions, such as going to college and doing our jobs; however, some activities are basically impossible to perform virtually, such as construction activities. Thus, the construction sector has been highly disrupted by the current pandemic. The construction sector represents a key component of countries' economies—it is approximately 13% of global GDP—as such, having the availability to perform construction activities with a minimum spread of COVID-19 may help to the financial response to the pandemic. Given this context, this study aims to understand the potential impact of COVID-19 on construction workers using an agent-based modeling approach. Activities are classified as being of low-medium–high risk for workers, and the spread of COVID-19 is simulated among construction workers in a project. This study found that the workforce from a construction project may be reduced by 30% to 90% due to the spread of COVID-19. Understanding how COVID-19 may spread among construction workers may assist construction project managers in creating adequate conditions for workers to perform their job, minimizing the chances of getting infected with COVID-19.

1. Introduction

The current pandemic due to the COVID-19 has impacted the world and our societies in its entirety. As social distancing remains the primary way to minimize the pandemic's spread, economic activities involving human interactions have been switched by online activities, such as shopping, attending schools and universities, and working from home (McKinsey, n.d.; Lund et al., 2020). However, some activities that play a fundamental role in our society are impossible to be performed online, such as construction. Consequently, the construction sector has been highly disrupted by the spread of COVID-19 by delaying and halting construction projects under development (ENR, 2020a) and by interrupting the supply chain and shortage of workers due to quarantines (ENR, 2020b). For instance, a survey deployed by the Associated General Contractors of America (AGC) showed that 28% of respondents (i.e., AGC members) reported halted or delayed projects due to COVID-19 in the United States (ENR, 2020b).

As the propagation of the COVID-19 is mostly through the interaction of people, interactions among construction workers are going to play a key role during the reopening of construction projects. Especially, taking into account that social distancing initiatives to prevent the spread of the virus may impact the number of construction workers allowed on the construction field, how these workers can perform their job, and how project managers forecast the workforce of a project. The existing literature of workforce management in construction projects has underscored the importance for project managers to have the ability to forecast and plan the workforce needed to complete a construction project (Fard Fini et al., 2018; Gomar et al., 2002; Srour et al., 2006), as well as the fact that the conditions in which construction workers do their job influence their performance (Ayodele et al., 2020; Goodrum, 2004; Jaselskis et al., 2008; Lee et al., 2020; Shen et al., 2015). Now, given the unprecedented context currently faced with the pandemic, the way construction workers are managed during the development of construction projects is likely going to change. As such, the management of the construction workforce should expand from the traditional objectives–i.e., an efficient workforce utilization to manage a productive and cost-effective project (Randolph Thomas and Horman, 2006)–and incorporate how the transmission of COVID-19 may influence the workforce performing different construction activities throughout a construction project.

Given the stay at home orders and social distancing context, in field data collection methods are highly limited, as such a modeling approach

is used in this study to simulate how the COVID-19 can be spread among construction workers involved in different types of activities during a construction project in terms of getting the virus (i.e., low, medium, high risk). Different modeling techniques—such as linear programming (Srour et al., 2006), dynamic programming (Fard Fini et al., 2018), structural equation modeling (Shen et al., 2015), and agent-based modeling (Ahn et al., 2013; Ahn and Lee, 2015)—have been used in the workforce management literature to understand how construction workers interact. Agent-based modeling (ABM) has been identified as a technique capable of modeling workers' behavior individually, analyzing emergent workers' group behavior, and creating multiple scenarios to test policies and interventions (Araya, 2020).

As COVID-19 continues to spread all over the world recent studies have started to report and discuss how to improve safety management due to COVID-19 (de Bruin et al., 2020; Lindhout and Reniers, 2020; Varotsos and Krapivin, 2020). As such, this study aims to study the influence of the potential transmission of COVID-19 among workers while interacting during a construction project using an agent-based modeling approach. Understanding how COVID-19 may be spread among workers participating in a construction project may assist project managers, contractors, and subcontractors in managing their workforce and the successful development of construction projects in the current pandemic context.

2. Research background

The workforce management's literature in construction is discussed in this study in the context of two main groups, studying the workforce as a resource that can be planned, forecasted and optimized (e.g., Fard Fini et al., 2018; Sing et al., 2016; Sing et al., 2012a, 2012b); and a second group of studies understanding challenges faced by the workforce in the construction site, such as safety, wage differentials, and workers turnover (e.g., Ayodele et al., 2020; Goodrum, 2004; Shen et al., 2015).

2.1. The workforce as a resource

The construction workforce is one of the most variable resources involved in construction projects (Halpin et al., 2017; Sing et al., 2016). One of the main challenges that the construction industry and its companies face in this regard is the shortage of skilled labor (Karimi et al., 2018), as such, multiple models and techniques have been proposed to improve the accuracy and certainty of the workforce supply and demand for construction companies. Srour et al. (2006) proposed a model to optimize the strategic investment in the workforce's training and allocation on multiple construction projects. Specifically, Srour et al. (2006) proposed a model capable of account for a strategy to train the construction workforce, hire new workers when needed, and allocate them across different construction projects. This model allowed the workforce's optimization to human resource professionals from a strategic standpoint (Srour et al., 2006). Similarly, Gomar et al. (2002) studied multiskilled workforce's optimal allocation in construction projects. The authors found that although projects benefit from having multiskilled workers, the benefits are marginal beyond having 20% of the multiskilled workforce (Gomar et al., 2002).

Models have also been proposed specifically to understand the workforce supply and demand to find an equilibrium point. Interestingly the variables used to develop these models greatly differ. While models focused on the supply side were based on workforce attributes—e.g., age and skills (Sing et al., 2012a)— the models focused on the demand for the construction workforce were based on the economic conditions around the forecasting process (Sing et al., 2012b). More recently, Sing et al. (2016) argued that due to the large variety of factors influencing workforce forecasting needs for construction, a dynamic approach is required to improve the accuracy of workforce forecasts. Namely, Sing et al. (2016) proposed a system dynamics model to forecast the

construction workforce supply and demand, and the effect of training policies on the workforce equilibrium. More recently, the literature has begun to discuss the need to incorporate workers' career plans on workforce planning (Shahbazi et al., 2019). Some studies have claimed that including workers' career plans may improve project performance (Lim and Loosemore, 2017; Loosemore and Lim, 2017). Shahbazi et al. (2019) proposed a model to maximize productivity and construction workers' career opportunities; however, maximizing workers' career opportunities came with a small productivity loss.

In summary, existing studies have emphasized the important role of planning/forecasting the construction workforce for the successful development of construction projects. As such, given the current pandemic that project managers and the workforce have faced and will face in the foreseeable future, it is necessary to understand how the potential spread of COVID-19 among construction workers may influence workforce planning.

2.2. Challenges faced by the construction workforce

The shortage of skilled construction workers represents one of the main problems of the construction industry (Azeez et al., 2019; Goodrum, 2004). Multiple researchers have explored challenges that construction workers face while working on a construction project that may disincentivize a productive project performance, such as safety environment (Shen et al., 2015), language barriers (Oswald et al., 2019), and turnover (Ayodele et al., 2020). In this literature review, we discuss some of the challenges related to cultural aspects; nonetheless, the focus is on the safety challenges as these may provide insights about how to manage the workforce in the current pandemic context.

Studies regarding cultural challenges faced by the workforce have included differences in wages based on ethnicity (Goodrum, 2004), language barriers (Oswald et al., 2019), and absenteeism (Ahn et al., 2013). For example, Goodrum (2004) found that Hispanic construction workers were paid lower wages compared with non-Hispanic workers. Additionally, Goodrum and Dai (2005) found that Hispanic workers were related to more hazardous construction occupations, which led to more injuries and fatalities. When it comes to construction workers' absenteeism, it has been found that the social norms and interactions among workers play a key role in decreasing absenteeism among workers (Ahn et al., 2013).

Interestingly, the cultural challenges faced by workers also influence the safety of workers. Oswald et al. (2019) found that the interpretation of safety instruction can be negatively impacted when safety videos are translated from its original language.

The construction sector has long been recognized as one of the most dangerous activities for the workers involved (Alwasel et al., 2017); thus, in recent decades, safety-related workforce challenges have been largely studied in the literature (Mohammadi et al., 2018). Interestingly, the conditions faced by the workforce have been identified as one of the main factors influencing the safety performance of construction projects (Mohammadi et al., 2018). The way construction workers perceive their environment influences how safely they interact and how safely they behave (Abbas et al., 2018; Shen et al., 2015). Notably, when workers understand and perceive construction activities as too risky or leading to frequent injuries, workers can simply decide to leave the workforce, as it has been found with masonry workers (Alwasel et al., 2017). The quantification of hazard exposure to workers can help project managers minimize activities perceived by the workforce as insecure or too risky (Luo et al., 2016).

The existing literature underscores that the conditions in which construction workers do their job highly influence their performance in construction projects. Consequently, given the current pandemic context faced by the construction sector, it is fundamental to understand the potential impact that COVID-19 may have among construction workers interacting during a construction project. As the pandemic has continued to spread all over the world some studies have researched

how to improve safety aspects due to the spread of COVID-19 (de Bruin et al., 2020; Varotsos and Krapivin, 2020); however, we also need to understand the potential influence of COVID-19 on construction workers while interacting during a construction project.

3. Methods

3.1. Agent-based modeling (ABM)

Agent-Based Modeling (ABM) is a modeling approach to represent complex systems composed of individual elements or agents (Macal and North, 2010). Individual agents are the main components of the systems modeled with ABM as these agents can interact under the same system environment (Macal and North, 2010). The modeling of agents is through the definition of rules that govern agents' behaviors and interactions among them. The definition of rules provides flexibility to modeling different agents' behaviors, which accounts for agents' heterogeneity. Precisely, due to the heterogeneity of agents and the ability to interact under the same environment, the system behaviors emerge during the simulations (Bonabeau 2002). The heterogeneity of agents and their interactions leads to emerging system's behaviors that capture systems' complexity (Macal and North, 2010).

3.2. Agent-based modeling (ABM) in construction engineering and management

Multiple studies have implemented agent-based modeling in the context of construction engineering and management (Ahn et al., 2013; Araya et al., 2020; Choi and Lee, 2018; Marzouk and Al Daour, 2018). As ABM facilitates the implementation of modeling approaches focused on the individual elements—i.e., bottom-up—this attribute fits with the study of construction engineering and management processes that involve the participation of construction workers (Araya, 2020), such as crew interactions during construction operations (Watkins et al., 2009), and construction workers' safety behaviors (Choi and Lee, 2018). Given the ability of ABM to model agents' interactions under the same environment and the key role of construction workers' interaction in spreading COVID-19 on construction projects, this study proposes the implementation of ABM to understand the potential impact of the spread of COVID-19 among construction workers.

3.3. Model formulation

Fig. 1 abstracts the model and its components for the analysis. One
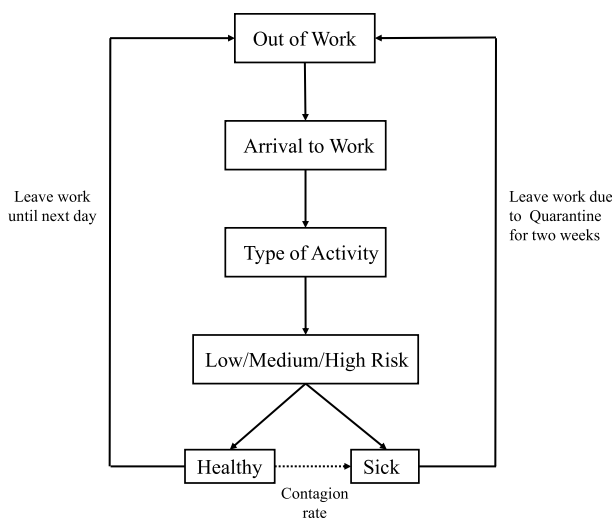

Fig. 1. Abstraction of Problem.

type of agent is included in the model—i.e., construction workers. These agents basically transition between being out of work and being at work. The simulation process starts when construction workers agents arrive to work, these are classified according to the type of activities they will perform during the day in low/medium/high risk activities regarding the contagion of COVID-19. As such, construction activities involving a high level of interaction with other construction workers are classified as high risk, activities with a minimum interaction and exposure to other workers are classified as low risk, and activities that are not classified as neither low or high risk, are classified as medium risk. Moreover, a contagion rate is assigned to the different type of activities to capture the possibility that healthy workers can get sick at work by interacting with other co-workers. The contagion rate differs for each type of activity—low, medium, high risk—to reflect how likely is for a worker agent to get sick while interacting at work. Once a worker's agent is identified as sick, the agent must leave the project and go to a quarantine for two weeks.

As limited information exists regarding the spread of COVID-19 among construction workers, three levels of activities—low/medium/high risk—are used to represent different levels of exposure from workers to the risks associated with COVID-19. These three levels of activities were used as previous studies in literature had done when studying construction workers and evaluating risks on construction projects (Ahn et al., 2013; Gebrehiwet and Luo, 2019; Sanni-Anibire et al., 2020).

3.4. Model implementation

The simulation process begins with the arrival of construction worker agents to work at the construction project. Once worker agents are at work these are distributed among different types of activities classified as low, medium, and high risk regarding the spread of COVID-19. Important to note, this model does not specify which construction activities are low/medium/high risk for workers. By doing this, the model can be flexible enough to be applied to different types of construction projects, as long as the project manager is able to identify and classify the activities that construction workers will perform as low/medium/high risk regarding the spread of COVID-19.

While workers are performing their activities there is a contagion rate that reflects how contagious is the activity they are performing. Therefore, worker agents can stay healthy or get sick at work. If a construction worker agent is identified as sick, then the agent transitions to the state "out of work" due to a mandatory quarantine of two weeks that sick agents must do before returning to work. An explanation of the construction worker agents and the parameters and variables used in the model are shown in Table 1.

The modeling process simulates 100 construction workers agents involved in one construction project throughout their working days. That means that workers are simulated to arrive to the project between 7 and 8 am, and to leave the project between 5 and 6 pm from Monday to Friday. The model simulates working days, so a month of simulated time

Table 1
Object class and associated parameters, variables, and rules.

Object Class	Function	Parameters and Variables	Examples of decision rules and formulas
Construction workers	Simulation of individual behavior of workers during a construction project regarding the spread of COVID-19	Time of arrival to work Time to leave work Level of risk activities performed by workers Percentage of workers sick rate of contagion among construction workers	Level of contagion among construction workers based on the level of risk of the activities that a worker agent is performing in the project

is approximately 24 h by 20 working days, which is 480 h. The results presented in this study consider a total simulation time of three working months, or 1440 h. The argument to select a three-month of simulation period was to have enough simulated result so to identify trends and emerging behaviors among construction workers agents in the model.

In order to address the research question of this study, the model includes two main variables, the distribution of low/medium/high risk activities among construction workers agents, and the rate of infection of each type of activity. These variables define how frequent construction workers will transition from a healthy state to a sick state in the construction project. Given the limited information regarding the impact of COVID-19 among construction workers, and the difficulties to collect actual data in construction projects, the impact of these parameters was tested by using different values and comparing the results. Specifically, eight models arranging a multiple set of values for these parameters are presented in the results section, which aim to capture low, medium, and high values for these parameters. Ultimately, the proposed model was implemented using the object orienting programming tool AnyLogic (AnyLogic, n.d.).

3.5. Verification and validation

To ensure that the model is verified and validated the author followed an iterative process from the model formulation through the model simulation (Sargent, 2004). The conceptual validation and model assumption of the model occurred though discussions with two different subject matter experts (SME)—a construction manager with more than 25 years of experience, and a construction worker with more than 30 years of experience; both had to work several months after the pandemic had started until their corresponding projects were stopped due to the pandemic. Ultimately, the computerized model validation was done by running sensitivity analyses on model parameters.

3.6. Case study

Given the global impact of COVID-19 and with the aim to maintain the model as flexible and transferable as possible, no specific location was selected for the project in which workers agents interact in the model. 100 construction workers agents are used in the model, as this number has been suggested in the literature as a common setting while studying construction workers behaviors (Ahn et al., 2013). Table 2 shows the variables and values used in the case study presented in this study.

Eight scenarios are developed using the proposed model, Table 3 shows the value of the parameters for the eight different scenarios. Cases a and b were run to assess the influence of the distribution of activities by risk level, as well as the rate of infection regarding the spread of COVID-19 among construction workers.

3.7. Limitations

As with any study, this one has limitations. It is acknowledged that the model formulation and implementation of agent-based modeling may oversimplify the real-life conditions under study. Specifically, the classification of activities—i.e., low/medium/high risk—to be performed by construction workers does not refer to specific construction activities. Although this model attribute reduces the specificity of the findings of this study, it also gives the modeling approach more flexibility to apply it to different construction projects where each project manager can identify which activities are low/medium/high risk for the construction workers. Another limitation is the lack of actual data from a real project to simulate construction workers' behaviors in the model; however, given the pandemic context and the corresponding difficulties in collecting data in real projects, a modeling approach is thought to provide valuable insights for construction managers in a safe manner. Furthermore, multiple cases were included to account for a wide range

Table 2
Model's parameters and variables used in the case study.

Parameter/Variables	Value Range	Justification/References
Population of worker agents	100	• A common setting to understand construction workers behaviors during a construction project (Ahn et al., 2013).
Percentage of activities classified as low risk	40–70%	• As limited information exists regarding the spread of COVID-19 among construction workers a range of values is used to model workers contagion rate (Varotsos and Krapivin, 2020).
Percentage of activities classified as medium risk	30–40%	
Percentage of activities classified as high risk	0–20%	• A range of values for these parameters are used to represent a wide variety of potential cases (Ahn et al., 2013).
Rate of infection during construction activities	0–40%	• As limited information exists regarding the spread of COVID-19 among construction workers a range of values is used to model workers contagion rate (Varotsos and Krapivin, 2020).
Arrival time to work Leaving time from work	7–8 am 5–6 pm	• Assumption of the arrival from construction workers based on a 45 work-hours week, a longer work-hours week may have detrimental effects on construction workers (ENR 2010).
Quarantine duration	Two weeks/ 14 days	• Duration of the quarantine if infected with COVID-19 (ENR 2020c)

Table 3
Parameters' values for the scenarios developed with the model.

Description	Case a		Case b	
Scenario	Distribution of activities (L/M/H risk)	Contagion rate (L/M/H) risk activities	Distribution of activities (L/M/H risk)	Contagion rate (L/M/H) risk activities
1	50%/35%/15%	0%/10%/20%	50%/35%/15%	0%/20%/40%
2	70%/30%/0%		70%/30%/0%	
3	60%/30%/10%		60%/30%/10%	
4	40%/40%/20%		40%/40%/20%	

Note: L: low risk; M: medium risk; H: high risk.

of possible scenarios in the model to minimize the impact of limited real-life data availability due to the pandemic.

4. Results

Figs. 2 and 3 show the number of sick workers during the simulation for scenarios 1 through 4 for cases a and b, respectively. Figs. 4, 5, 6 and 7 show the number of sick workers for cases a and b for each scenario.

5. Discussion

The proposed agent-based model simulates the spread of COVID-19 among construction workers. The results of this study show that the highest peak of sick construction workers is obtained for the scenarios 4a and 4b, with approximately 70% and 90% of construction workers sick, respectively (Figs. 2 and 3). Conversely, the scenarios with the lowest peaks of sick construction workers were 2a and 2b. Interestingly, even though scenarios 2 had the lowest peaks of sick workers, the percentage of sick workers still was between a 30%-50% range (Figs. 2 and 3), which is a considerable percentage from the workforce involved during a construction project. These results can be expected as both scenarios 4
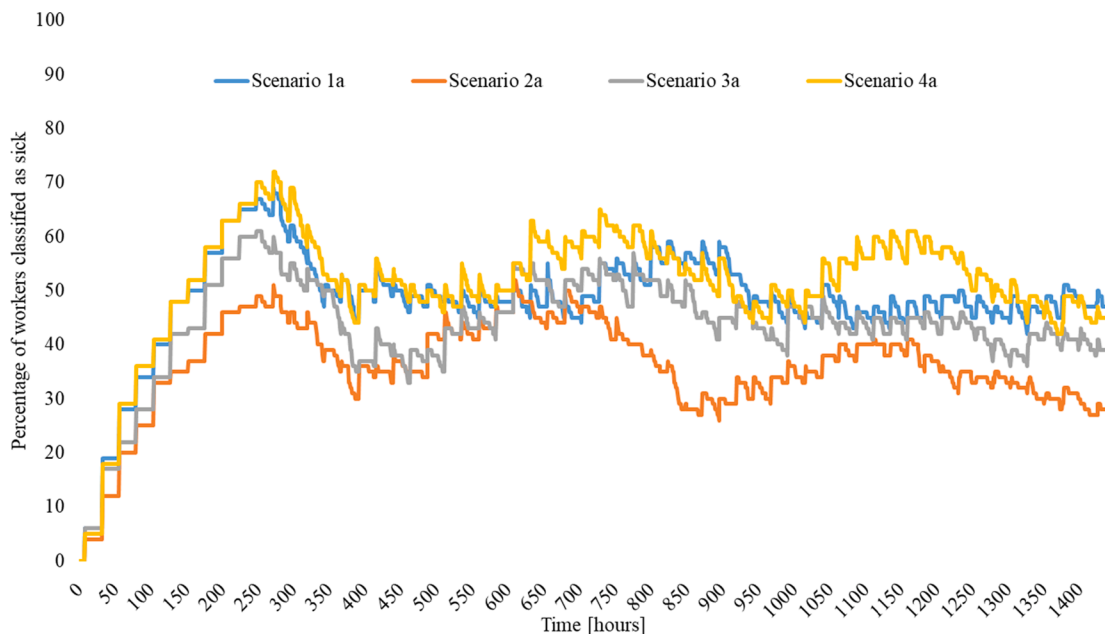
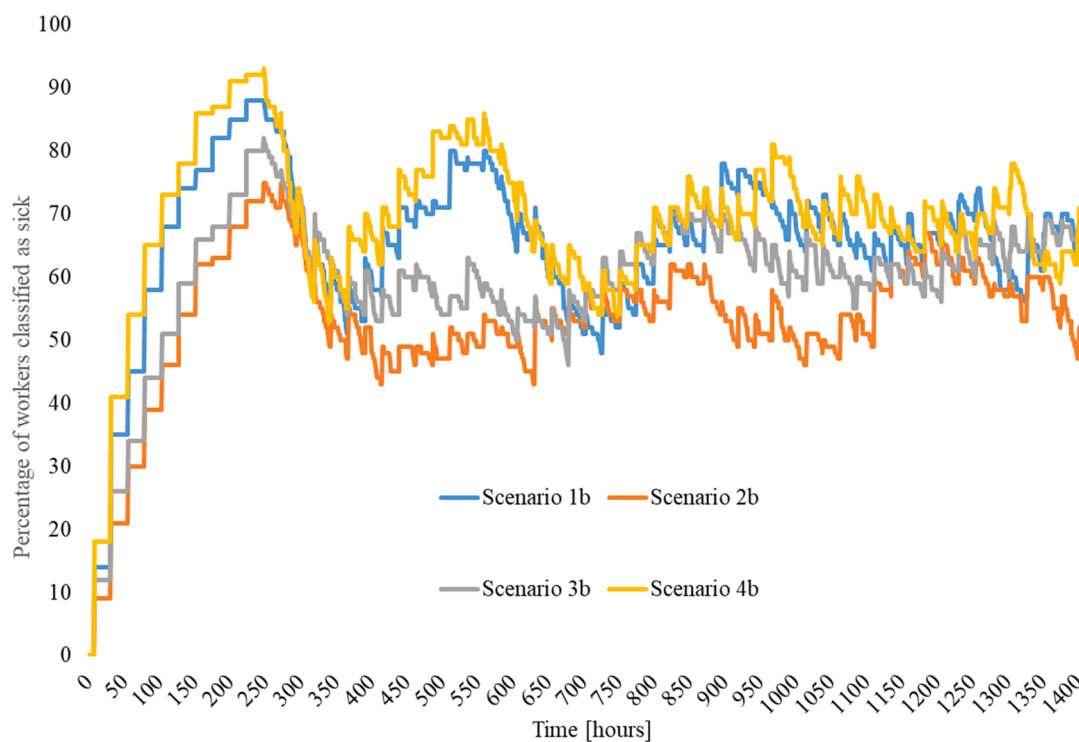Fig. 2. Models' results for scenarios 1a, 2a, 3a, and 4a.

Fig. 3. Models' results for scenarios 1b, 2b, 3b, and 4b.

had the highest percentage of activities classified as of high-risk for construction workers, while scenarios 2 had the lowest percentage of high-risk activities (Table 3). Similarly, when comparing the results of scenarios b versus scenarios a, it can be observed that when the rate of contagion is higher, the number of sick workers also increases. Although this is an intuitive result, this study contributes to quantifying how much more workers are classified as sick when increasing the contagion rate among workers. In general, the difference between scenarios a and b, is approximately 20% more sick workers at the peak for all four scenarios b (Figs. 4–7).

As such, this study's results reinforce the importance of the level of risk of activities that construction workers will perform regarding the contagion of COVID-19. The level of risk that construction workers assume when working on a construction project will be directly related to how much interaction among workers exists during the activities. Given the limited information about what construction activities are the most and least risky for construction workers, at least during the first stages of construction projects re-opening, how to classify the construction activities will likely be a task assigned to construction managers and safety engineers. However, is important to emphasize that it is recommended
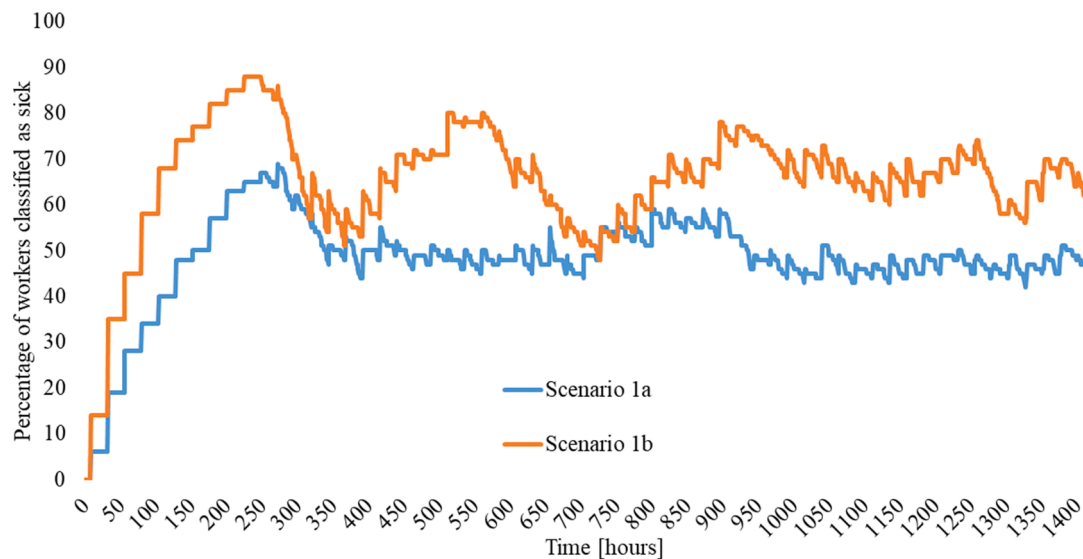
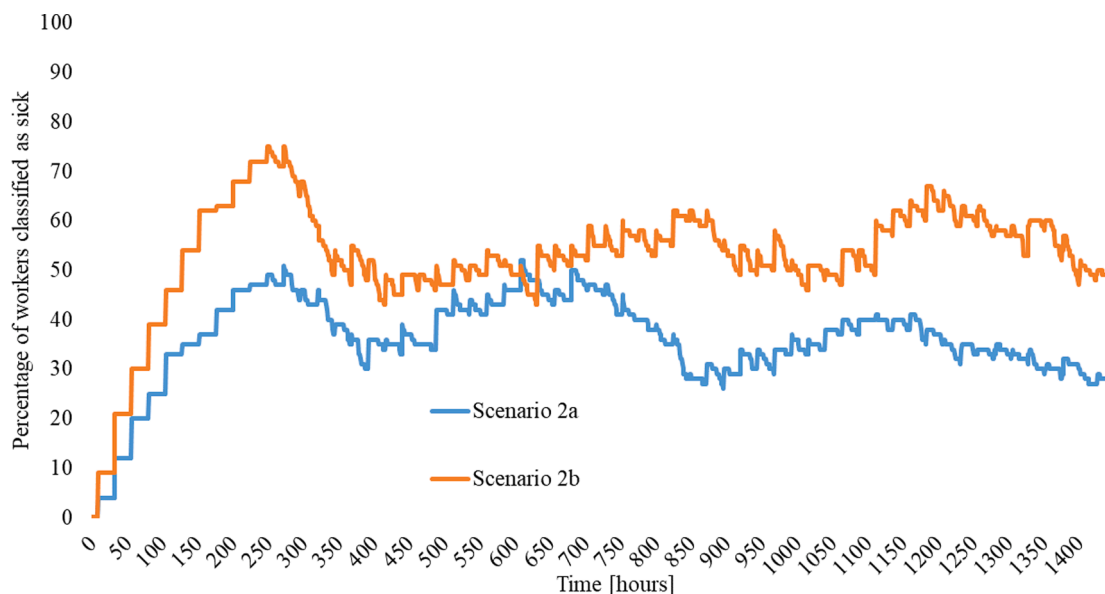**Fig. 4.** Models' results for scenarios 1a and 1b.

Fig. 5. Models' results for scenarios 2a and 2b.

to include to the construction workers while defining the level of risk associated to a construction task, as the workers are the ones that are going to perform the tasks, and thus, must feel safe while working during a construction project (Azeez et al., 2019). Otherwise, the construction workers willing to work during or right after a pandemic context may decrease (ENR, 2020c).

The results of this study quantify what represents a big challenge for construction engineering and management professionals in charge of projects during the pandemic. When looking at the percentages of workers that may get sick during a construction project—approximately between 30% and 90% depending on the level of risk of project's activities (Figs. 2 and 3)—managers in charge of planning the workforce may need to plan ahead, so the construction project can be completed as planned. From the results of this study, the main recommendation for construction and project managers should be to maximize the involvement of construction workers on low-risk construction activities regarding the spread of COVID-19. This may be the main way to ensure that the percentage of workforce is not reduced significantly during a

construction project. Otherwise, project managers may have to plan ahead and hire more workers than previously needed, so to have a stock of available healthy workers and healthy workers can replace the sick workers during the two weeks of quarantine, and as such, the construction project can be completed as planned. However, while aiming to reduce the risks related to the spread of COVID-19 among construction workers with measures that reduce the number of workers and their interaction, it is natural to expect a reduction in workers' productivity. This context will represent a challenge to construction and project managers, as the intuitive decision to improve the productivity of a construction project may be to involve more workers to the projects; nonetheless, in the current context, that decision might only make things worst by contributing to accelerate the interaction and spread of COVID-19 among workers.

6. Conclusions

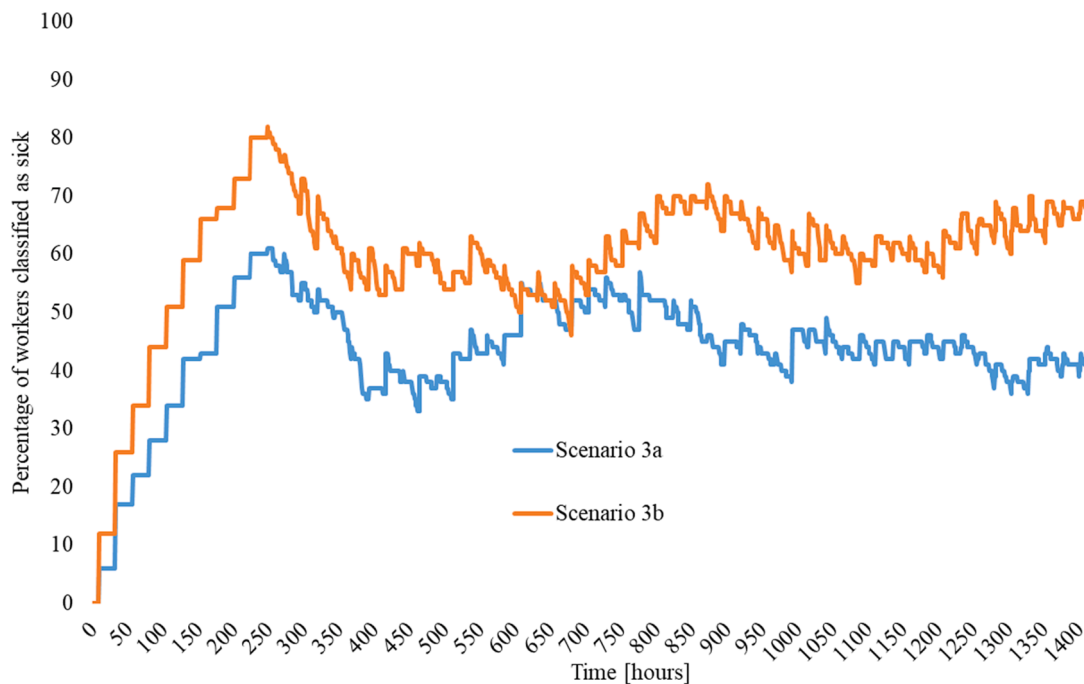This study proposes an agent-based modeling (ABM) framework to

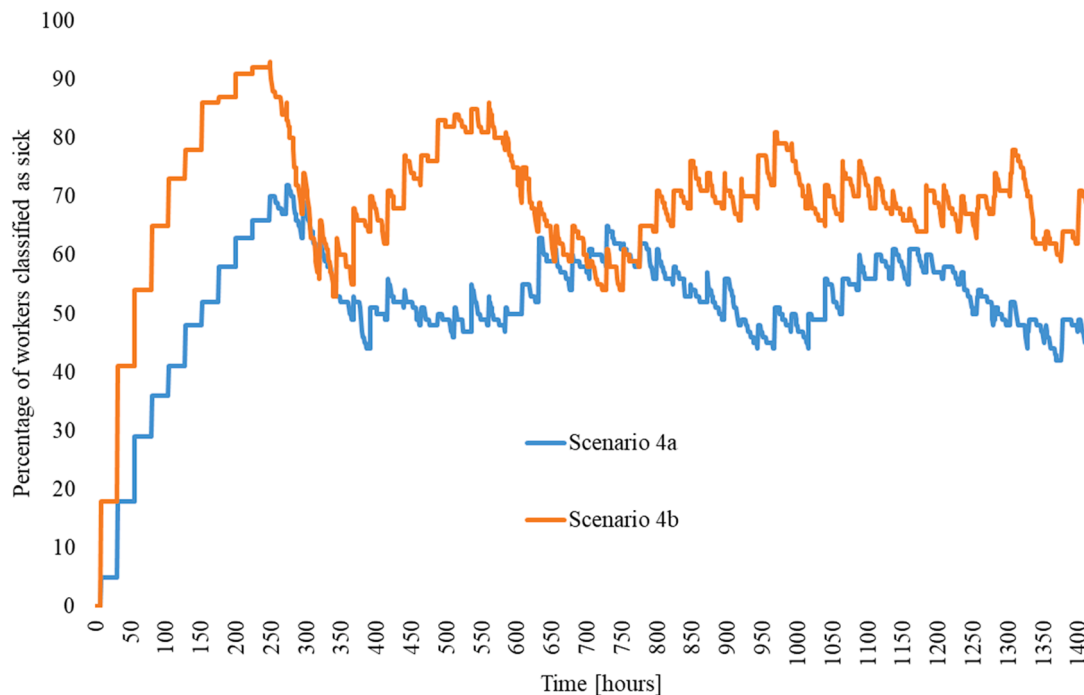**Fig. 6.** Models' results for scenarios 3a and 3b.

Fig. 7. Models' results for scenarios 4a and 4b.

simulate the spread of COVID-19 among construction workers. This study found that the spread of COVID-19 among construction workers may reduce the workforce of a project approximately between 30% and 90%, which represents a challenge for construction and project managers regarding the planning of the workforce for a project. The main way that managers may have to reduce the spread of COVID-19 among construction workers is to maximize construction activities classified as low-risk regarding the spread of COVID-19.

Future studies should investigate to classify the activities involved in construction projects as low, medium, and high risk regarding the

spread of COVID-19. By doing that, construction managers will know specifically which activities need to be re-design to minimize the spread of the virus. However, that type of studies will require to visit construction sites to collect actual data regarding which activities are more/less risky for construction workers.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

the work reported in this paper.

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