A FRAMEWORK TO MODEL THE SPREAD OF INFECTIOUS DISEASES ON CONSTRUCTION SITES USING HYBRID AGENT-BASED MODELLING AND MONTE CARLO SIMULATION

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The construction industry has been severely affected by COVID-19 restrictions resulting in several challenges in form of supply chain disruptions, performance loss, and limited workforce interactions. The construction industry initially needs to understand and quantify the impacts of COVID-19 on each aspect of the industry. Simulation techniques are powerful tools for this purpose, which enable modellers to run construction projects virtually and assess their performance under different circumstances, scenarios or settings. In this paper, a hybrid simulation framework is developed using agent-based modelling (ABM) and Monte Carlo simulation techniques (MCS) to evaluate the impact of the spread of COVID-19 on the performance of construction projects. The proposed simulation framework enables the construction modellers to capture the interactions between construction workers effectively and to determine the impact of restrictions on the overall project performance. It also helps practitioners in the post-COVID-19 era by testing multiple virus spread scenarios on construction sites and minimize the adverse impacts of restrictions on the project performance.

Keywords: agent-based modelling; automation; productivity; risk; simulation

INTRODUCTION

The outbreak of COVID-19 pandemic forced many countries to place restrictions and take various risk mitigation measures including mobility restrictions, socio-economic restrictions, physical distancing, hygiene measures, communication and international support mechanism (Bruinen de Bruin *et al.,* 2020). It is evident that recovery from disruptive impacts of COVID-19 requires both strategic and detailed planning to address various aspects of COVID-19 impacts on businesses and people. World Bank (2020) emphasised that the labour productivity could be reduced for years following COVID-19 pandemic unless urgent policy actions are taken. The construction industry is one of the major industries that was significantly affected by the pandemic because majority of construction activities are physical and require human resources. Since the construction industry has significant contribution to the global economy, its success in addressing the consequences of the pandemic is crucial for faster economic

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recovery. Therefore, a comprehensive playbook to recover from COVID-19 adverse impacts and address each affected aspect of the industry is needed. The response of the construction industry to the COVID-19 pandemic is likely related to many factors including the features of the social system, government and policy frameworks, and the state of the economy that the industry operates in (Lingard *et al.,* 2021). Considering variation of these influencing factors, decision-making is challenging due to the inherent uncertainties and dynamics of construction projects. Simulation techniques are powerful tools for this purpose, which enable modellers to run construction projects virtually and assess their performance under different circumstances and settings.

This paper focuses on the impacts of the spread of COVID-19 on construction workers on jobsites. As the human interaction is a primary reason for the virus spread, this study aims to model workers' behaviour on construction sites using agent-based modelling (ABM). In addition, Monte Carlo simulation (MCS) is used to stochastically assess the influence of different strategies on controlling the spread of COVID-19 infections on the sites and minimizing its adverse impacts on the project staff performance.

In the next sections of this paper, first, research background on the COVID-19 impacts on construction and the different approaches for modelling and predicting various impacts of COVID-19 are discussed. After that, the research methodology and a framework for modelling human interactions on construction sites are explained. Then, the applicability of the developed framework is demonstrated in a hypothetical case study. Finally, the conclusions, limitations and directions for future research are discussed.

RESEARCH BACKGROUND

Developing an effective industry playbook to mitigate the COVID-19 risks requires a clear understanding about the impacts imposed to the industry and accurate predictive models for assessing the potential recovery plans from those impacts. Kamal (2020) recognized two types of COVID-19 disruptions:

1) Transformational disruptions, which were a planned disruption for adopting digital technologies in response to the imposed restrictions.

2) Hostile disruptions (e.g., economic disruptions), which were unexpected from external sources. Some industries could manage this type of disruptions by the bailout packages offered in some countries.

For the construction industry, COVID-19 imposed some threats such as disruptions in material supply chain and lower productivity due to absenteeism, which could lead to potential claims from contractors to compensate the cost and schedule impacts of these disruptions. At the same time, COVID-19 provided the construction industry with some opportunities. Jones *et al.,* (2020) identified some problems as well as the potential positive impacts of COVID-19 on the construction sector including:

- Changes to the site layouts and working practices.
- Increased worker productivity and effectiveness by deploying workers in smaller groups than usual.
- Improved housekeeping and tidiness, which can lead to better productivity, material planning and motivation, and less risks of incidents.

- Increased advance planning, which demands more time from management but can improve productivity by providing more detailed planning for some tasks, and more detail liaison between trades.
- Social distancing, which could cause issues for communication between workers on the site while it could improve productivity by reducing chatting time.
- Distraction and less focus on ordinary health and safety.
- Improved safety by having fewer people on site and tidier sites.
- Increased working from home and remote meeting, which could increase productivity for some staff (e.g., management and admin staff), and decrease productivity for some staff due to reduced wellbeing and working in isolation.

Alsharef *et al.,* (2021) studied early impacts of COVID-19 on the construction industry in the United States and reported significant delays on projects, inability to secure materials on time, reduction in productivity rates, and material price escalations as the main adverse impacts. They also identified the new opportunities for the construction industry including new projects for building medical facilities and residential buildings, transportation-related work, and opportunities to recruit skilled workers.

Overall, COVID-19 imposed some threats and provided some opportunities for the construction industry. Mitigating the threats and taking advantages of the opportunities are essential to keep business continuity for the construction industry, which needs substantial efforts and planning at both high level (strategic level) and low level (project level).

Modelling Approaches for Predicting the Impacts of Covid-19

A number of studies attempted to model and predict different aspects of COVID-19 impacts. Some researchers (e.g., Tuan *et al.,* (2020) and Samui *et al.,* (2020)) used mathematical methods for COVID-19 transmission modelling. Amaral *et al.,* (2021) used a Susceptible-Infectious-Recovered-Deceased model to predict infections, recoveries, deaths, and viral reproduction numbers. Truong and Truong (2021) used a statistical method, i.e., time series, to forecast the travel behaviour of United States citizens by distance at the national level and found the patterns of daily trips and the COVID-19 spread.

Simulation is a suitable method for modelling, forecasting, and making decisions under uncertain circumstances. Depending on the nature of the problems, different simulation techniques such as MCS, ABM, Discrete Event Simulation (DES), System Dynamics (SD) and hybrid simulation can be adopted for modelling. There are successful applications of simulation techniques for modelling the impacts of COVID-19 on human societies, including: to predict hospital capacity needs during pandemic, Weissman *et al.,* (2020) used MCS for developing a susceptible, infected, removed (SIR) model, and providing insights into the dynamics of the infection spread. MCS was also used to compare two testing strategies for different infection prevalence and pooled group sizes (Deckert *et al.,* 2020). A study by Ghaffarzadegan and Rahmandad (2020) used SD to estimate the magnitude of outbreak and early spread of COVID-19 based on the Susceptible, Exposed, Infectious, and Recovered (SEIR) framework.

ABM has been widely used for modelling COVID-19 outbreak and decision-making. Covasim (Kerr *et al.,* 2020) is an open-source stochastic agent-based simulator that was developed specifically for COVID-19 analyses and used by several researchers for modelling purposes. For instance, Li and Giabbanelli (2021) used Covasim for modelling two vaccination plans in the United States and experimented different non-pharmaceutical intervention scenarios to evaluate effectiveness of the plans. Cuevas (2020) developed an agent-based model to evaluate the COVID-19 transmission risks in facilities and simulated the spatiotemporal transmission process by modelling individuals as agents and their decisions based on their social characteristics and health conditions, spatial patterns and infection conditions. The model was used to experiment strategies for reducing the transmission risks of COVID-19 within the facilities.

Silva *et al.,* (2020) used ABM for simulating people, business and government, and experimented different scenarios of social distancing interventions to evaluate their health and economic effects. Similarly, Kano *et al.,* (2021) developed an agent-base model to simulate COVID-19 outbreak and find its interrelation between virus spread and economic losses. In another study, Mukherjee *et al.,* (2021) investigated reopening strategies for educational institutions during COVID-19 using ABM.

For the construction industry, Araya (2021) adopted the ABM technique for modelling COVID-19 spread on construction workers and found that construction workforce may be reduced by 30% to 90% due to COVID-19 infections. In the developed model, workers were modelled as agents, and possibility of the virus spread in a construction project was modelled by classifying construction activities into low, medium, and high risks for the virus spread.

The Proposed ABM-MCS Framework to Model Covid-19 Impacts

The proposed framework utilizes hybrid ABM-MCS to model the impacts of COVID-19 on construction industry. The ABM component is used: (1) to model the performance of the construction labourers and to determine the project performance as the aggregated performance of the team; and (2) to model the spread of COVID-19 on the project site based on the specifications of jobsite, agents, and the disease. The spread of COVID-19 is extremely random, since it is be initiated by a random set of agents who enter to the construction site with infections every day and the virus is spread due to the proximity of agents that occurs by the random movements of the agents on the jobsite. Accordingly, the results for each simulation run can be significantly affected by the initial set of random numbers selected and the random seeds (Hadzibeganovic *et al.,* 2015). To address this challenge, the proposed framework integrates the MCS technique with the ABM component and runs the simulation model for several times (e.g., 100 or 1000 runs) and determines the simulation results as a stochastic variable rather than a deterministic one. For more flexibility and easier accessibility of the final research products, the proposed framework is developed in Python® programming language using Mesa library for ABM and upon the finalization of the framework, the open-source code for the framework will be released on GitHub®. Fig 1 presents the flowchart of the proposed framework and the flow of information between its different components.

ABM component's settings

The settings of the ABM component are specified by the modeller as follows. First, the specifications of the jobsite are entered, consisting of the dimensions of the jobsite assuming it is in a rectangle shape; and the location of material/equipment warehouse. Secondly, the characteristics of agents are specified by entering the size of project team (i.e., number of agents), the infection rate (i.e., the percentage of the agents who are infected at the start of each day), and the length of each simulation time-step. Thirdly, the details of the infectious disease are specified by determining the minimum distance required for the transmission of the virus (i.e., two meters for COVID-19 in this research).

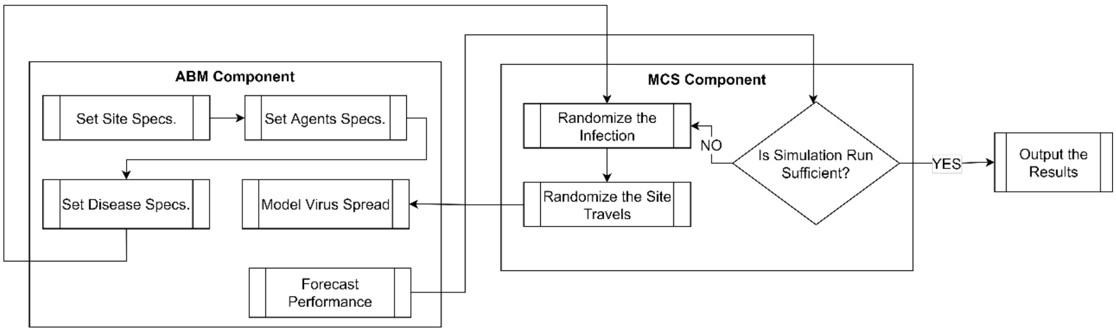

Fig 1. The Proposed ABM-MCS Framework

ABM Simulation process

The process of simulation starts with a drawing of the jobsite in a rectangle shape with the pre-specified dimensions locating the material/tool warehouse. Then, the jobsite drawing is further detailed by gridlines, where each grid is a square of two-by-two meters (i.e., the spacing of the gridlines is equal to the minimum distance required for the transmission of the virus). Next, a pre-specified number of agents are generated and randomly located at the project site, whilst it is assumed that an unlimited number of agents can be located at each grid simultaneously. Then, the ABM component simulates the behaviour of the agents within the project site in discrete time steps. For this purpose, each agent is randomly assigned to one of the three following states, which were extracted from the previous research by Tsehayae and Fayek (2016): (1) tool time/direct work with 60% probability, where the agent stays stationary at the same location for the length of the time-step; (2) tools/material handling with 15% probability, where the agent moves to the tools/material warehouse to pick-up or drop some tools and material; and (3) random walk with 25% probability, where the agent randomly walks within the project site. For the random walk state, each agent can only move to one of the six grids that surrounds its current position, meaning it can move up to three meters at each time-step. Then, the ABM component simulates the infectious behaviour of the virus by transmitting the infection from the infected agents to all the healthy agents within two meters of distance. Finally, the ABM model determines the number of infected agents at the end of each time step.

The infected agents are assumed to have a pre-symptomatic period of three days (Slifka and Gao, 2020) prior to developing any symptoms and hospitalization. During this period, agents are present at the jobsite and can transmit their disease to the other agents. In the proposed framework, once the infected agents develop symptoms, they are hospitalized (i.e., are not present on the jobsite anymore) for 10 days (Slifka and Gao, 2020) and then, will return to work once the hospitalization period is completed. In this framework, no mortality rate is considered for the virus, since in the context of construction projects, the construction labours are often healthy young individuals who have the lowest mortality rate for COVID-19.

ABM simulation outputs

The ABM component outputs a heatmap for the jobsite at the end of each timestep or at the end of simulation run, showing the number of agents located on each grid on the site. Fig 2(a) presents an example for the heatmaps generated by the ABM component for one timestep and Fig 2(b) shows the heatmap generated for the whole simulation run of 10 timesteps. It should be noted that the yellow rectangle in Fig 2(b) with more than 70 occupants throughout the simulation run represents the tools/material warehouse location on the jobsite.

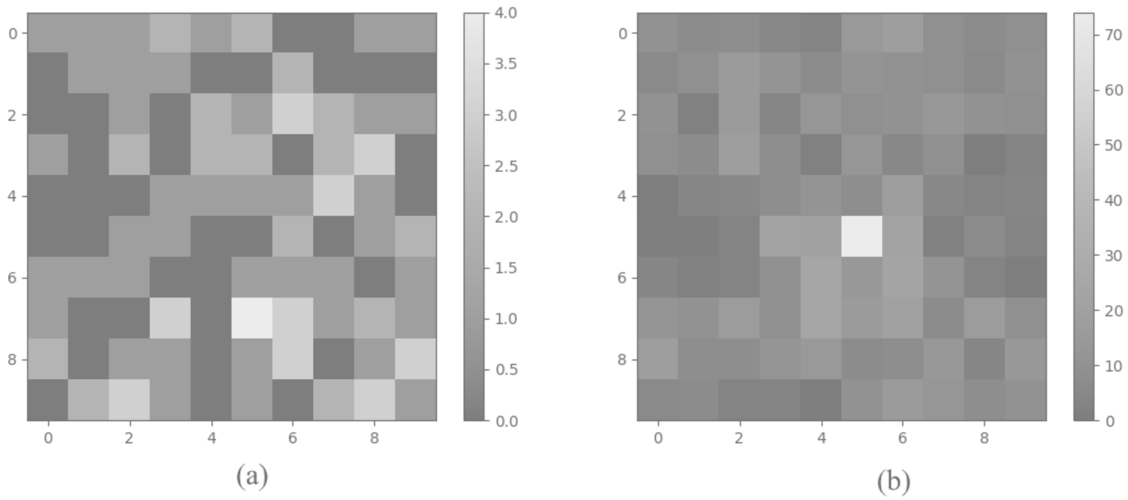

Fig 2. Heatmap output of the ABM component

In addition to the heatmap, the ABM component provides the following outputs: the total number of agents who are present on the jobsite; the state of each agent at each time step (i.e., direct work, material/tool handling, or random walk); the number of agents who are infected at each time step; and the number of agents who are hospitalized at each time step.

The MCS component

The MCS component of the proposed framework generates random numbers at each time step for the three following functions: (1) to randomly select a number of agents who are infected outside of the project site at the start of each workday; (2) to randomly select the state of each agent on the project site at the start of the workday; and (3) to determine the destination of those agents, who are in random walk state. Then, the MCS component runs the simulation for a pre-specified number of times and collects the selected outputs from the ABM component at the end of each simulation run. Finally, the MCS component develops the histograms of the results, implements the statistical analysis on the results and reports the mean value, standard deviation, the three percentiles (i.e., 25%, 50%, 75%), and the minimum and maximum value of the ABM outputs.

Construction Case Study

To assess the applicability of the proposed framework for simulating the spread of COVID-19 on construction project sites, the proposed framework is applied to a hypothetical construction case study, as its details are presented in Table 1.

To determine the impact of the spread of COVID-19 on the performance of the hypothetical project, the output of the ABM component is selected to be the number of agents who are directly working on the project tasks (i.e., tool time) at each time step. Moreover, the simulation model has been running by hourly time-steps for the total duration of 1040 time-steps, which denotes six months of project time with 5 days/week and 8 hours of work/day calculated as follows: $26(\text{weeks}) \times 5(\text{days}) \times 8(\text{hours}) = 1{,}040\ \text{hours}$. The MCS component then, runs the project for 100 times does the statistical analysis on the ABM component's outputs and the results are presented stochastically as presented in Fig 3.

Table 1. Construction case study specifications

Project Site Specification		Agents Specifications		Disease Specifications	
Description	Value	Description	Value	Description	Value
Size of project site in meters (m × m)	30 × 30	Number of agents	50	Contagiousness radius (m)	2
Material/equipment warehouse location	20 × 20	Infection rate	0, 5, 7, and 10%		
		Time steps	Hourly		

Referring to Table 1, there are four different scenarios for this case study to determine how the spread of the virus changes by changing the infection rate between 0% (i.e., no infection) 5%, 7%, and 10%. As the results indicate, the performance of the project drops significantly by the spread of the virus on the project site, where the mean value direct-working agents drops from 29.98 for the "No Infection" scenario to 11.76 for "5% Infection" scenario. According to the results presented in Fig 3, the performance of project does not significantly change by changing the infection rate, from 11.76 for "5% Infection" to 11.51 for "7% Infection" to 11.20 for "10% infection" scenarios.

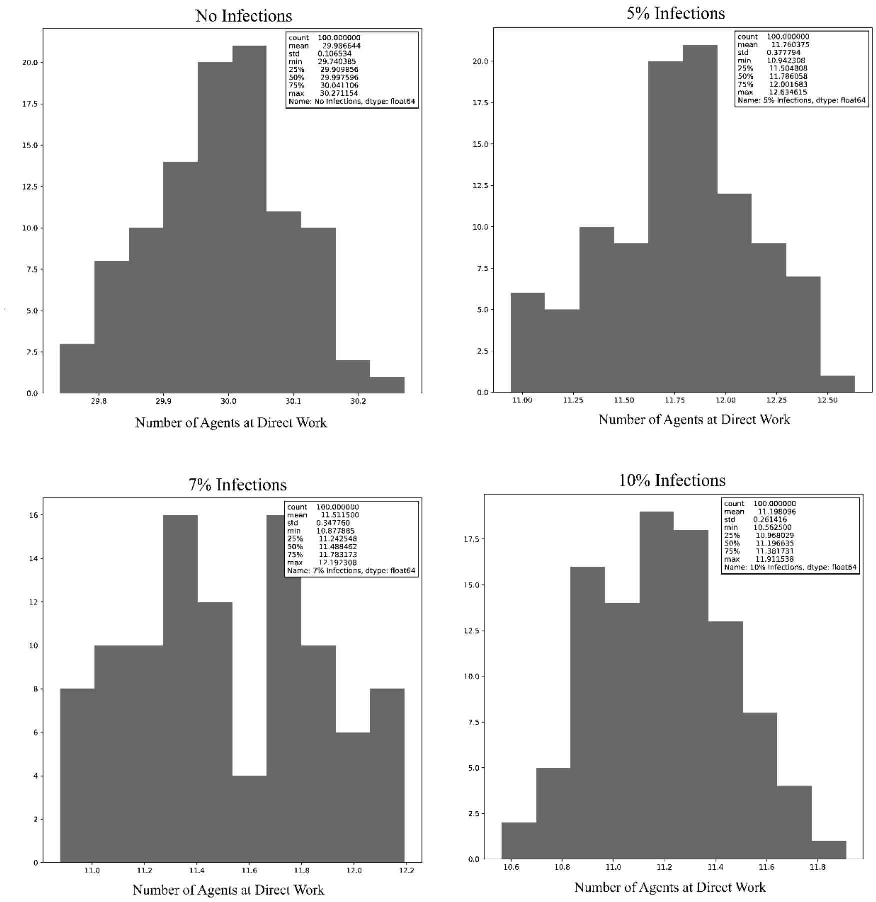

Fig 3: Histograms of the project performance for four different scenarios

This phenomenon indicates that the dominant cause of infection on the project site is the transmission of disease between the workers rather than being infected outside the jobsite.

CONCLUSIONS

In this paper, a novel ABM-MCS framework is developed for simulating the spread of COVID-19 disease in construction sites and forecast the impacts of this disease on the performance of construction projects. The framework consists of two main components: (1) the ABM component that simulates the behaviour of individual agents on the project site and the transmission of the disease between the different agents; and (2) the MCS component that implements the statistical analysis and captures the random behaviour of the agents and disease transmission.

The results of simulation presented in the case study reveals that the transmission of the disease on the jobsite is the dominant cause of infection; and the changes in the infection rate from outside the jobsite does not significantly affect the spread of the virus unless the transmission on the site is controlled by some means.

Moreover, the simulation results show that the introduction of a few infected agents to the jobsite can significantly decrease the project performance, up to 61% drop in the project performance by the entrance of only 2 infected agents (among 48 healthy agents) to the jobsite daily. Accordingly, the monitoring programs on the jobsites can significantly alleviate the negative impacts of COVID-19 on construction projects. This research was conducted based on some assumptions due to the limitation of the available data regarding virus spreads on construction sites. In future research, this limitation will be addressed by collecting more data from construction sites. In addition, this framework can be extended to simulate the impact of COVID-19 on workers' behaviours such as stress and other mental impacts, and simulate the use of personal protective equipment, COVID-19 monitoring protocols and hospitalization to determine an optimum strategy for executing construction projects in the post-COVID-19 era. Moreover, a generic ABM-MCS framework developed in the Python® programming language will be released to determine the impact of infectious diseases on construction industry and to improve the resiliency of construction projects.

REFERENCES

Alsharef, A, Banerjee, S, Uddin, S M J, Albert, A and Jaselskis, E (2021) Early impacts of the COVID-19 pandemic on the United States construction industry, *International Journal of Environmental Research and Public Healt*h, **18**(4), 1-21.

Amaral, F, Casaca, W, Oishi, C M and Cuminato, J A (2021) Towards providing effective data-driven responses to predict the COVID-19 in São Paulo and Brazil, *Sensors*, **21**(2), 540.

Araya, F (2021) Modeling the spread of COVID-19 on construction workers: An agent-based approach, *Safety Science*, **133**, 105022.

Bruinen de Bruin, Y, Lequarre, A S, McCourt, J, Clevestig, P, Pigazzani, F, Zare Jeddi, M, Colosio, C and Goulart, M (2020) Initial impacts of global risk mitigation measures taken during the combatting of the COVID-19 pandemic, *Safety Science*, **128**, 104773.

Cuevas, E (2020) An agent-based model to evaluate the COVID-19 transmission risks in facilities, *Computers in Biology and Medicine*, **121**, 103827,

Deckert, A, Bärnighausen, T and Kyei, N N A (2020) Simulation of pooled-sample analysis strategies for COVID-19 mass testing, *Bulletin of the World Health Organization*, **98**(9), 590-598.

Ghaffarzadegan, N and Rahmandad, H (2020) Simulation-based estimation of the early spread of COVID-19 in Iran: actual versus confirmed cases, *System Dynamics Review*, **36**(1), 101-129.

Hadzibeganovic, T, Stauffer, D and Han, X P (2015) Randomness in the evolution of cooperation, *Behavioural Processes*, 113, 86-93.

Jones, W, Chow, V and Gibb, A (2020) *COVID-19 and Construction: Early Lessons for a New Normal?* Balfour Beatty / Loughborough University, Available from: https://www.balfourbeatty.com/media/318555/covid19-and-construction-early-lessons-for-a-new-normal.pdf [Accessed 13 July].

Kamal, M M (2020) The triple-edged sword of COVID-19: understanding the use of digital technologies and the impact of productive, disruptive and destructive nature of the pandemic, *Information Systems Management*, **37**(4), 310-317.

Kano, T, Yasui, K, Mikami, T, Asally, M and Ishiguro, A (2021) An agent-based model of the interrelation between the COVID-19 outbreak and economic activities, *Proceedings of the Royal Society a: Mathematical, Physical and Engineering Sciences*, **477**(2245).

Kerr, C C, Stuart, R M, Mistry, D, Abeysuriya, R G, Hart, G, Rosenfeld, K, Selvaraj, P, Núñez, R C, Hagedorn, B, George, L, Izzo, A, Palmer, A, Delport, D, Bennette, C, Wagner, B, Chang, S, Cohen, J A, Panovska-Griffiths, J, Jastrzębski, M, … Klein, D J (2020) Covasim: An agent-based model of COVID-19 dynamics and interventions, *Plos Computers in Biology*, **26**(7), 1009149.

Li, J and Giabbanelli, P J (2021) Returning to a normal life via COVID-19 vaccines in the USA: A large-scale agent-based simulation study, *JMIR Medical Informatics,* **9**(4), e27419.

Lingard, H, Peihua Zhang, R, Räisänen, C, Miang Goh, Y, Bowen, P and Bhandari, S (2021) Special issue: what have we learnt from the COVID-19 global pandemic: improving the construction industry's abilities to foresee, respond to and recover from future endemic catastrophes, *Construction Management and Economics*, **39**(2), 192-197.

Mukherjee, U K, Bose, S, Ivanov, A, Souyris, S, Seshadri, S, Sridhar, P, Watkins, R and Xu, Y (2021) Evaluation of reopening strategies for educational institutions during COVID-19 through agent based simulation, Scientific Reports, **11**(1), 6264.

Samui, P, Mondal, J and Khajanchi, S (2020) A mathematical model for COVID-19 transmission dynamics with a case study of India, *Chaos, Solitons and Fractals*, **140**, 110173.

Silva, P C L, Batista, P V C, Lima, H S, Alves, M A, Guimarães, F G and Silva, R C P (2020) COVID-ABS: An agent-based model of COVID-19 epidemic to simulate health and economic effects of social distancing interventions, *Chaos, Solitons and Fractals*, **139**, 110088.

Slifka, M K and Gao, L (2020) Is presymptomatic spread a major contributor to COVID-19 transmission? *Nature Medicine*, **26**(10), 1531-1533.

Truong, D and Truong, M D (2021) Projecting daily travel behavior by distance during the pandemic and the spread of COVID-19 infections - Are we in a closed loop scenario? *Transportation Research Interdisciplinary Perspectives*, **9**, 100283.

Tsehayae, A A and Fayek, A R (2016) System model for analysing construction labour productivity, *Construction Innovation*, **16**(2), 203-228.

Tuan, N H, Mohammadi, H and Rezapour, S (2020) A mathematical model for COVID-19 transmission by using the Caputo fractional derivative, *Chaos, Solitons and Fractals*, **140**, 110107.

Weissman, G E, Crane-Droesch, A, Chivers, C, Luong, T B, Hanish, A, Levy, M Z, Lubken, J, Becker, M, Draugelis, M E, Anesi, G L, Brennan, P J, Christie, J D, Hanson, C W, Mikkelsen, M E and Halpern, S D (2020) Locally informed simulation to predict hospital capacity needs during the COVID-19 pandemic, *Annals of Internal Medicine*, **173**(1), 21-28.

World Bank (n.d.) *Productivity Growth, Key Driver of Poverty Reduction, Threatened by COVID-19 Disruptions*. Geneva: World Bank.