ICCEPM 2022
The 9th International Conference on Construction Engineering and Project Management
Jun. 20-23, 2022, Las Vegas, NV, USA

An Agent-Based Framework for Investigating Safety-Productivity Tradeoff of Construction Laborers Considering Risk-taking Behavioral Heterogeneity

Ali Khodabandelu[1]*, JeeWoong Park[2], Seyedmohsen Kheyrandish[3]

[1] *Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Pkwy. Las Vegas, NV 89154, USA*, E-mail address: khodaban@unlv.nevada.edu
[2] *Department of Civil and Environmental Engineering and Construction, University of Nevada, Las Vegas, 4505 S. Maryland Pkwy. Las Vegas, NV 89154, USA*, E-mail address: jee.park@unlv.edu
[3] *Department of Civil and Environmental Engineering, Amirkabir University of Technology, 424 Hafez Ave., P.O. Box: 15875-4413. Tehran, Iran,* E-mail address: kheyrandish@aut.ac.ir

Abstract: Construction laborers and crews play a critical role in achieving a safe and productive construction site. Many past research studies used top-down approaches/perspectives for studying the impact of laborers' performance on overall construction site outputs with limited flexibility in accounting for laborers' various characteristics. However, the recent reap in computational advances allowed applications of bottom-up architectures, which can potentially incorporate heterogeneous characteristics of laborers' individual behavioral and decision-making features effectively. Accordingly, agent-based modeling (ABM), as a tool to leverage a bottom-up methodological approach, has been widely adopted by recent research. Existing literature investigated the influence of changes in laborers' behaviors and interactions on either construction sites' safety performance or productivity performance individually, leaving the tradeoff between safety and productivity in this context relatively unexplored. Accordingly, this study aims to develop an agent-based framework to study the tradeoff between project safety and productivity performances resulting from changes in laborers' behaviors after attending safety trainings. Our findings via simulations indicate that proper safety trainings can improve safety performance without negatively impacting productivity performance.

Key words: agent-based modeling, simulation, safety, productivity, construction worker

1. INTRODUCTION

The construction industry has long been suffering from a poor safety record [1], [2]. Based on the revealed statistics by the Occupational Safety and Health Administration (OSHA), 21.1% of the fatalities in the private sector are associated with the construction industry. At the same time, the construction industry has been widely recognized for its low productivity rate compared to other industries [3], [4]. While the productivity of the manufacturing industry has doubled over the course of the last fifty years, the productivity of the construction industry has remained the same at best [5]. Such poor safety and productivity records necessitate further investigation of practical solutions for improvement of both safety and productivity on construction sites [6].

Because the construction industry is one of the most labor-intensive industries, laborers and crews are regarded as the most significant contributors to productivity and safety outputs on construction sites [3], [7], [8]. Various factors can affect the safety and productivity performance outcomes resulting from laborers and crews' activities, as well as the interactions among activities and personnel, individually and as a whole. Such factors can be categorized into two groups: 1) laborers' individual characteristics such as their knowledge, skill levels, attitudes towards safety, learning abilities, and environment perceptions [9]; and 2) laborers' interactional features such as imitating foremen's safety behaviors, being influenced by senior managers' involvement in safety activities, supervisors' respect to safety procedures, and attending safety trainings [7]. Among all the mentioned parameters, safety training has been unanimously recognized by past studies as a critical factor affecting safety and productivity of construction projects. Past research has demonstrated the importance of safety trainings on raising the construction laborers' safety awareness, which in turn impacts their individual behaviors as well as their interactional relationships with other personnel [10].

Even though the necessity of safety trainings and meetings for laborers has been emphasized by past studies, the optimum cycle of safety trainings is a matter of dispute [11]. An increase in the frequency of safety trainings may reduce the number of potential on-site accidents; however, some contractors or construction managers argue that there should be a rational time period between safety trainings, because frequent trainings may be ineffective and adversely impact other aspects of metrics that are important to contractors, such as profit and time [11]. Besides, pressure put on construction laborers by their foremen or managers for productivity has a causal effect on compromised safety due to the conflict between productivity goals and safety procedures [12]. Such arguments arise the problem of tradeoff between safety, cost, and productivity on construction projects in the context of worker safety-related behaviors, which has not been sufficiently investigated by past research.

Past studies in this area explored the impact of trainings related to safety and other worker safety-related behaviors in relation to safety and/or productivity performance [7], [13], [14]. Despite this, research still lacks an understanding of the combinational aspect of safety and productivity upon safety trainings. Accordingly, this study aims to investigate a training strategy with respect to effective training cycles while accounting for both safety performance and productivity performance. To do so, the present study takes advantage of agent-based modeling (ABM) to simulate the laborers' activities on construction sites over a certain period of time and explore an effective safety training strategy considering the safety-productivity tradeoff.

2. ABM IN THE CONTEXT OF CONSTRUCTION WORKERS

Agent-based modeling is a relatively new simulation method that has recently gained significant popularity across various areas [15]. In the construction domain, ABM has been applied to solve different problems, such as contract and bids [16], supply change management [17], managing construction equipment [18], construction planning [19], design [20], emergency management [21], and facility operation management [22]. ABM is an effective modeling and simulation technique that regards each entity in a system as an agent with its own unique attributes. ABM is suitable for analyzing complex and dynamic environments, such as construction sites, and for predicting collective outcomes of these environments. The following unique features distinguish ABM from other simulation techniques:

1) ABM follows a micro-level bottom-up approach in studying systems, thus generating system outcomes, i.e., safety and productivity performances in the case of this study, as emergent outcomes

of the construction site. Therefore, unlike macro-level approaches, it has a striking advantage in not heading the model towards a biased and pre-arranged direction [15].

2) ABM follows a heterogeneous perspective towards agents/entities of the system; i.e., instead of oversimplifying the model by attributing identical average features to all the agents of the same type, it differentiates agents by attributing different features to them [15]. In the case of the present study, each laborer possesses a varying rate of risk-taking level, as an example of a laborer's feature, which results in achieving more accurate and realistic safety and productivity outcomes compared to other simulation approaches.

3) ABM can follow any specific convention over time progression. Unlike other simulation methods that only follow a discrete approach, ABM is able to offer a continuous time framework, which means agents and their attributes can change anytime over the course of the simulation [23]. In the case of construction workers, e.g., the rate of risk-taking level associated with each laborer can change at any time such as after participating in safety training or a meeting.

4) ABM is an effective simulation method for prediction of an effective strategy. Since ABM can assign varying features to agents of the same type, it effectively allows the generation of as many scenarios as possible, and thus find the best one based on the executed cases [15]. The present study leverages this feature of ABM in scenario generations because: 1) various rates of risk-taking behavior are attributed to construction workers; 2) such rates vary over the simulation run by attending safety trainings; and 3) different safety training cycles are explored.

3. METHODOLOGY

In this study, an agent-based model is developed to study the tradeoff between safety and productivity performances on construction sites resulting from laborers' activities and to explore an effective safety training strategy that best fits both safety and productivity outcomes. Figure 1 depicts the developed model along with the to-be-tested strategies and expected outcomes. In the model, laborers, trainers, and tasks are the main agents with their own attributes with varying rates. The risk-taking rate is the main attribute associated with laborers, which can be impacted by attending trainings, as the interactional relationship between trainers and laborers. The next two subsections explain the details of the developed model, and the training strategies along with their safety and productivity outputs, respectively.

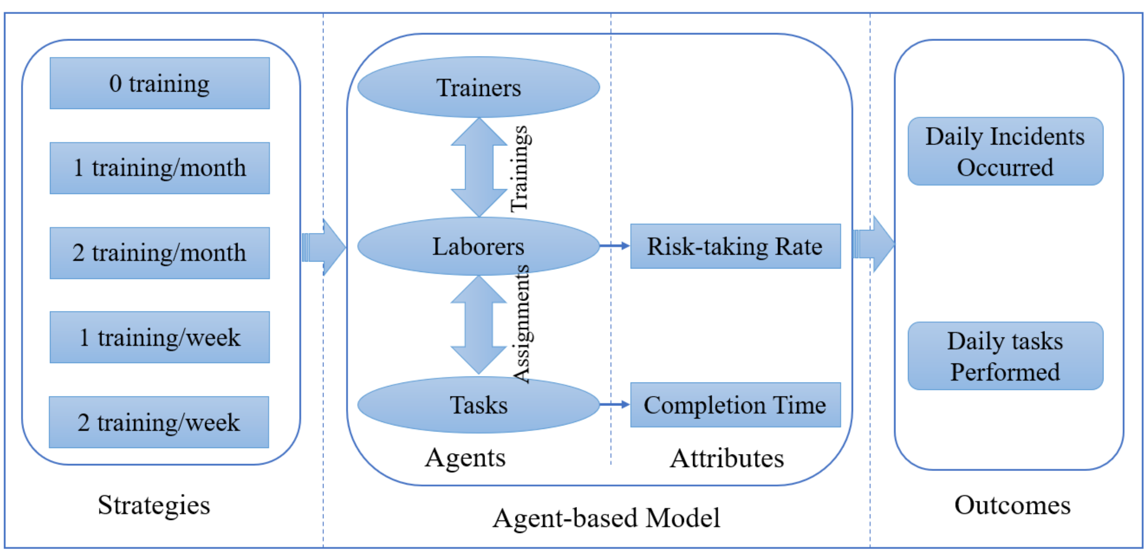

Figure 1. Model environment, strategies, and expected outcomes

3.1. Modeling of safety and training details with ABM

The model simulates a fixed number of laborers performing certain daily tasks on a construction site over a one-month/four-week period. Since the model is developed based on the agents' heterogeneity, the laborers are assumed to demonstrate varied safety behaviors. The model reflects it by assigning laborers different rates of risk-taking level, as an attribute that represents a laborer's safety behavior. The rates represent a diverse environment with an average risk-taking level of 13.5%, ranging from 1% to 25% for different workers. The risk-taking level is a number that indicates the probability of taking the risk of performing a hazardous action, which may lead to an accident. Some examples include ignoring safety inspections before task initiation, lack of attention to site alarms, taking shorter paths, and not allowing sufficient space for other laborers in order to speed up task completion. The risk-taking rates associated with each laborer vary, according to the learning curve concepts, after attending safety trainings [24]. To reflect the above factors, the research makes the following assumptions and rules to model/govern the agents, their behaviors, and interactional relationships:

1) Each of the ten laborers works eight hours a day and five days a week, thus the working days span a one-month/four-week period (of 20 days). 2) Laborers possess different rates of risk-taking behaviors, which are: 1, 5,7, 10, 12, 15, 17, 20, 22, and 25 percent. These numbers can be obtained by distributing surveys among project managers and employers of construction projects and asking them about past safety records of their current laborers; however, the numbers have been generated on a random basis in this research 3) Risk-taking level rates decrease by 25% after the first safety training, and reduce further according to the learning curve concepts after the next trainings [24]. For instance, risk-taking rates associated with a laborer with an initial risk-taking rate of X, change to 0.75X, 0.66X, 0.61X, and 0.59X after attending the first, second, third, and fourth training, respectively. 4) If a laborer takes the risk of a hazardous action, the probability of accident occurrence in this construction site is 0.1 percent [25]. 5) Task completion takes ten minutes on average when performed safely, while it takes nine minutes when a laborer takes the risk of conducting a hazardous action. 6) Each laborer is assigned a new task immediately after completing the current task.

3.2. Training strategies and impacts on safety and productivity

Five strategies for holding safety trainings are examined in this study: S0 (no training), S1 (one training per month), S2 (two trainings per month), S3 (one training per week), and S4 (two trainings per week). We run the simulation 100,000 times per strategy per day to study safety and productivity outcomes over a one-month period. Safety performance is measured by the average number of potential daily accidents while productivity performance is measured by the average number of daily tasks completed by each laborer. Figures 2 and 3 show the simulation outcomes with respect to safety and productivity over a one-month period. The interpretation of the diagrams is presented in the next section.

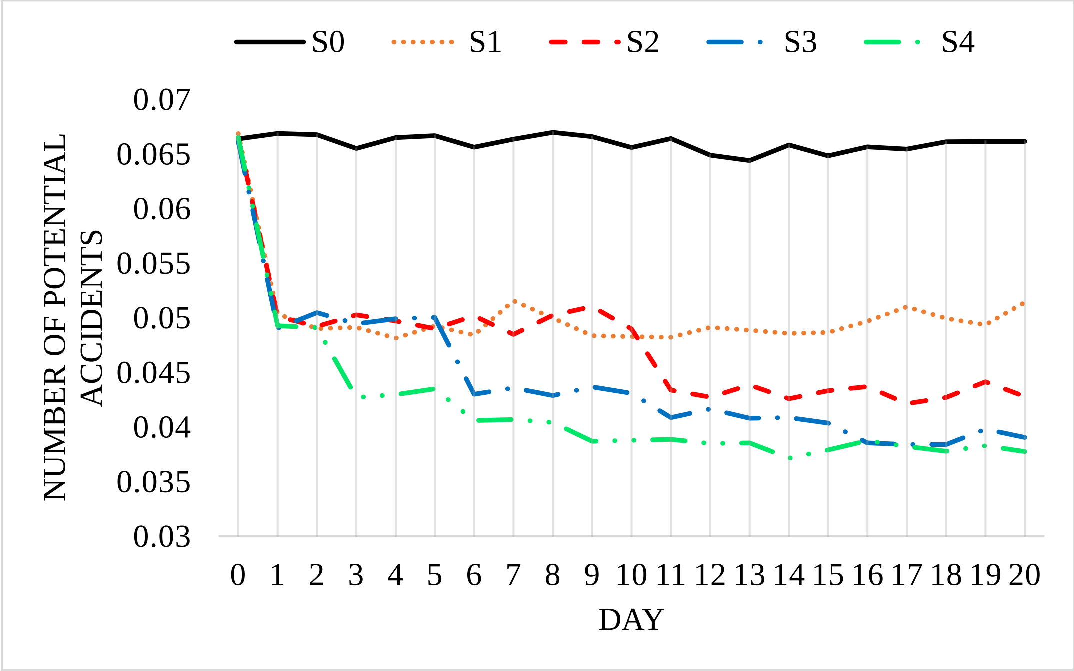

Figure 2. Safety performance outcome over a one-month period

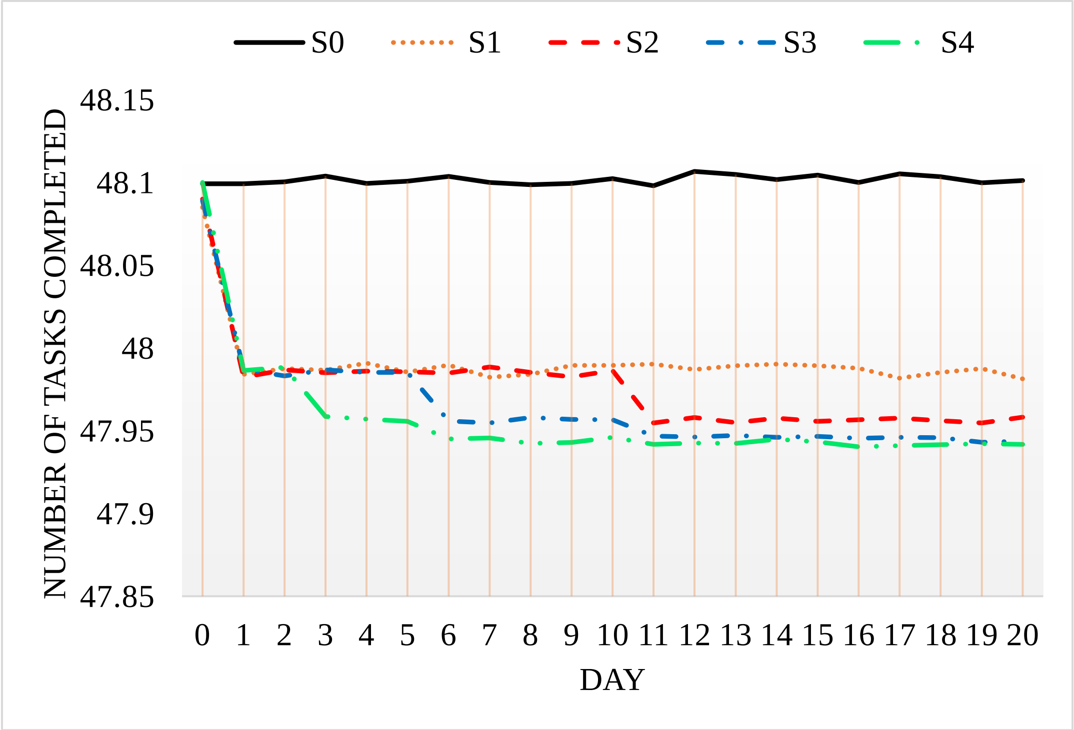

Figure 3. Productivity performance outcome over a one-month period

4. DISCUSSION

This section presents the following noticeable findings of the research based on the simulation outcomes:

1) In general, holding safety trainings results in significant safety performance improvement while maintaining productivity performance on almost the same level. As seen in Figure 2, the number of average daily accidents has fallen by almost half in S3 and S4 compared to S0. On the other hand, as shown in Figure 3, the number of daily tasks has reduced by a negligible amount of only 0.3 percent. This can be adjusted by the increased level of laborers' cautiousness after attending safety trainings. 2) This study does not account for the influence of accidents, which might result in working with fewer laborers, on the number of tasks being completed after accident occurrence. Therefore, if the research accounts for this impact, it is highly probable that holding safety trainings improves the productivity performance as well. 3) Accident rates reduce significantly after the first training, but the slope of reduction becomes milder and milder after the next trainings. This emphasizes the importance of the first few trainings on safety performance. As seen in Figure 2, S3 and S4 offer almost identical safety performance in the last week, while showing considerable differences in the first. The learning curve concepts can adjust this outcome. 4) Based on the findings, an effective training strategy is to hold a maximum number of safety trainings, e.g., daily over the first week, and gradually lengthen the time period between trainings thereafter.

5. CONCLUSION

This study explored an effective cycle of safety trainings that results in an effective tradeoff between project safety and productivity performances through developing an agent-based model. The study accounted for the heterogeneity in laborers' behaviors by assigning them varied risk-taking rates, which changes after holding each safety training, according to the learning curve concepts. The findings indicated that holding safety trainings can significantly improve the project safety performance by lowering the average number of daily accidents, while maintaining the project productivity performance without showing any substantial reduction in the average number of tasks performed each day. Also, the findings suggested that an effective training strategy could be holding a maximum number of safety trainings over the first week, and gradually reduce the number of trainings thereafter.

Despite the considerable effort made, the study is based on some assumptions that may play a substantial role in the simulations and results. For instance, assigning different risk-taking rates to different laborers, although helps in representing a heterogeneous and more realistic environment, still requires further verifications by empirical-based real-world cases to produce more authentic results. Due to the socio-cognitive nature of this topic, it demands numerous studies and investigations on real-world cases in future. In addition, there are many aspects in this research that can be further explored by the future studies. For example, the present study only accounts for the impact of holding safety trainings on safety and productivity performances, while other parameters, such as foremen's and other laborers' safety behaviors, senior managers' involvement in safety activities, supervisors' respect to safety procedures, and safety officer's inspections, can have influences on the collective laborers' safety behaviors over time. Moreover, future research can add cost to this equilibrium and explore time-cost-productivity tradeoff. Besides, even though the research takes into account the heterogeneity in laborers' risk-taking behavior, it does not differentiate workers in terms of their learning ability. Finally, the study does not consider the effect of laborers' memory and forgetfulness on determining the optimum training cycle, which is an interesting topic for future studies.

REFERENCES

[1] "NIOSH (National Institute for Occupational Safety and Health) 'Highway work zone

safety.’ Centers for Disease Control and Prevention, Atlanta, GA,” 2014.

[2] J. Park, Y. K. Cho, and A. Khodabandelu, “Sensor-based safety performance assessment of individual construction workers,” *Sensors (Switzerland)*, vol. 18, no. 11, 2018, doi: 10.3390/s18113897.

[3] M. Abdel-Hamid and H. Mohamed Abdelhaleem, “Impact of poor labor productivity on construction project cost,” *International Journal of Construction Management*, vol. 0, no. 0, pp. 1–8, 2020, doi: 10.1080/15623599.2020.1788757.

[4] A. Nekouvaght Tak, H. Taghaddos, A. Mousaei, and U. (Rick) Hermann, “Evaluating industrial modularization strategies: Local vs. overseas fabrication,” *Automation in Construction*, vol. 114, no. February, p. 103175, 2020, doi: 10.1016/j.autcon.2020.103175.

[5] P. J. Kruger, “Rheo-mechanics modelling of 3D concrete printing constructability.” Stellenbosch: Stellenbosch University, 2019.

[6] A. N. Tak, H. Taghaddos, A. Mousaei, A. Bolourani, and U. Hermann, “BIM-based 4D mobile crane simulation and onsite operation management,” *Automation in Construction*, vol. 128, no. May, p. 103766, 2021, doi: 10.1016/j.autcon.2021.103766.

[7] P. Zhang, N. Li, Z. Jiang, D. Fang, and C. J. Anumba, “An agent-based modeling approach for understanding the effect of worker-management interactions on construction workers’ safety-related behaviors,” *Automation in Construction*, vol. 97, pp. 29–43, 2019, doi: 10.1016/j.autcon.2018.10.015.

[8] A. Golabchi, S. U. Han, and S. AbouRizk, “A simulation and visualization-based framework of labor efficiency and safety analysis for prevention through design and planning,” *Automation in Construction*, vol. 96, no. February 2017, pp. 310–323, 2018, doi: 10.1016/j.autcon.2018.10.001.

[9] B. Mahjoubpour, F. Nasirzadeh, M. Mohammad Hosein Zadeh Golabchi, M. Ramezani Khajehghiasi, and M. Mir, “Modeling of workers’ learning behavior in construction projects using agent-based approach: The case study of a steel structure project,” *Engineering, Construction and Architectural Management*, vol. 25, no. 4, pp. 559–573, 2018, doi: 10.1108/ECAM-07-2016-0166.

[10] N. Z. Muhammad, A. Sani, A. Muhammad, S. Balubaid, E. E. Ituma, and J. H. Suleiman, “Evaluation of factors affecting labour productivity in construction industry: a case study,” *Jurnal Teknologi*, vol. 77, no. 12, 2015.

[11] N. Ghodrati, T. W. Yiu, and S. Wilkinson, “Unintended consequences of management strategies for improving labor productivity in construction industry,” *Journal of Safety Research*, vol. 67, pp. 107–116, 2018, doi: 10.1016/j.jsr.2018.09.001.

[12] D. L. McLain and K. A. Jarrell, “The perceived compatibility of safety and production expectations in hazardous occupations,” *Journal of Safety Research*, vol. 38, no. 3, pp. 299–309, 2007, doi: 10.1016/j.jsr.2006.10.011.

[13] M. Watkins, A. Mukherjee, N. Onder, and K. Mattila, “Using Agent-Based Modeling to Study Construction Labor Productivity as an Emergent Property of Individual and Crew Interactions,” *Journal of Construction Engineering and Management*, vol. 135, no. 7, pp. 657–667, 2009, doi: 10.1061/(asce)co.1943-7862.0000022.

[14] P. Zhang, N. Li, D. Fang, and H. Wu, “Supervisor-Focused Behavior-Based Safety Method for the Construction Industry: Case Study in Hong Kong,” *Journal of Construction Engineering and Management*, vol. 143, no. 7, p. 05017009, 2017, doi: 10.1061/(asce)co.1943-7862.0001294.

[15] A. Khodabandelu and J. W. Park, “Agent-based modeling and simulation in construction,” *Automation in Construction*, vol. 131, no. August, p. 103882, 2021, doi: 10.1016/j.autcon.2021.103882.

[16] F. Kog and H. Yaman, “A multi-agent systems-based contractor pre-qualification model,” *Engineering, Construction and Architectural Management*, vol. 23, no. 6, pp. 709–726, 2016, doi: 10.1108/ECAM-01-2016-0013.

[17] X. Xue, X. Li, Q. Shen, and Y. Wang, “An agent-based framework for supply chain coordination in construction,” *Automation in Construction*, vol. 14, no. 3, pp. 413–430, 2005, doi: 10.1016/j.autcon.2004.08.010.

[18] A. Khodabandelu, J. W. Park, and C. Arteaga, “Crane operation planning in overlapping areas through dynamic supply selection,” *Automation in Construction*, vol. 117, no. May, p. 103253, 2020, doi: 10.1016/j.autcon.2020.103253.

[19] J. Du and M. El-Gafy, “Using agent-based modeling to investigate goal incongruence issues in proposal development: Case study of an EPC project,” *Journal of Management in Engineering*, vol. 31, no. 6, pp. 1–18, 2015, doi: 10.1061/(ASCE)ME.1943-5479.0000343.

[20] C. J. Andrews, D. Yi, U. Krogmann, J. A. Senick, and R. E. Wener, “Designing buildings for real occupants: An agent-based approach,” *IEEE Transactions on Systems, Man, and Cybernetics Part A:Systems and Humans*, vol. 41, no. 6, pp. 1077–1091, 2011, doi: 10.1109/TSMCA.2011.2116116.

[21] C. Arteaga and J. W. Park, “Building design and its effect on evacuation efficiency and casualty levels during an indoor active shooter incident,” *Safety Science*, vol. 127, no. January, p. 104692, 2020, doi: 10.1016/j.ssci.2020.104692.

[22] S. Norouziasl, A. Jafari, and C. Wang, “An agent-based simulation of occupancy schedule in office buildings,” *Building and Environment*, vol. 186, no. June, p. 107352, 2020, doi: 10.1016/j.buildenv.2020.107352.

[23] A. Jabri and T. Zayed, “Agent-based modeling and simulation of earthmoving operations,” *Automation in Construction*, vol. 81, pp. 210–223, 2017, doi: 10.1016/j.autcon.2017.06.017.

[24] S. Johari and K. N. Jha, “Learning Curve Models for Construction Workers,” *Journal of Management in Engineering*, vol. 37, no. 5, p. 04021042, 2021, doi: 10.1061/(asce)me.1943-5479.0000941.

[25] R. Sacks, O. Rozenfeld, and Y. Rosenfeld, “Spatial and Temporal Exposure to Safety Hazards in Construction,” *Journal of Construction Engineering and Management*, vol. 135, no. 8, pp. 726–736, 2009, doi: 10.1061/(asce)0733-9364(2009)135:8(726).