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Original Article

Safety performance: Effectiveness of preventive strategies in construction projects

Rendimiento en materia de seguridad: eficacia de las estrategias preventivas en proyectos de construcción

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Spanish version

Abstract

Introduction: construction is one of the industries with the highest rate of accidents. Preventive strategies often lead to ineffective results as they are applied generically without considering the worker´s performance or on-site hazards.
Objetive: this research aims to evaluate the effectiveness of preventive strategies for safety by modelling how employees interact with the construction project environment.
Method: this paper puts forward an agent-based model that integrates factors such as the impact of social influence on safety behaviour, hazards varying during the construction process, work experience and safety awareness. We evaluate three preventive actions that take into consideration human monitoring, drone monitoring, and co-workers' care.
Results: indicated that social influence among the employees had a positive impact on safety awareness. Safety performance is not a direct result of a higher investment in safety. Therefore, better decision-making impacts positively on costs and project duration, as well as on the welfare of the workforce.
Conclusions: the construction sector continues to exhibit high accident rates despite considerable efforts by companies to mitigate them. Investments in prevention strategies do not always yield proportional improvements in safety outcomes.

Keywords: agent-based modelling; safety performance; building construction; construction safety; accident prevention; safety investment

Resumen

Introducción: la construcción es uno de los sectores con mayor índice de accidentes. Las estrategias preventivas suelen dar resultados ineficaces, ya que se aplican de forma genérica sin tener en cuenta el rendimiento de los trabajadores ni los riesgos in situ.
Objetivo: esta investigación tiene como objetivo evaluar la eficacia de las estrategias preventivas para la seguridad mediante la modelización de la forma en que los empleados interactúan con el entorno del proyecto de construcción.
Método: este artículo propone un modelo basado en agentes que integra factores como el impacto de la influencia social en el comportamiento en materia de seguridad, los riesgos que varían durante el proceso de construcción, la experiencia laboral y la concienciación sobre la seguridad. Evaluamos tres medidas preventivas que tienen en cuenta la supervisión humana, la supervisión con drones y la atención de los compañeros de trabajo.
Resultados: los resultados indicaron que la influencia social entre los empleados tenía un impacto positivo en la concienciación sobre la seguridad. El rendimiento en materia de seguridad no es el resultado directo de una mayor inversión en seguridad. Por lo tanto, una mejor toma de decisiones tiene un impacto positivo en los costes y la duración del proyecto, así como en el bienestar de la mano de obra.
Conclusiones: el sector de la construcción sigue presentando altas tasas de accidentes a pesar de los considerables esfuerzos de las empresas por mitigarlos. Las inversiones en estrategias de prevención no siempre se traducen en mejoras proporcionales en los resultados de seguridad.

Palabras clave: modelación basada en agentes; rendimiento en materia de seguridad; construcción de edificios; seguridad en la construcción; prevención de accidentes; inversión en seguridad.

Why was this study conducted?

Labor accidents in the construction industry, and specifically in residential building construction, are a major concern in terms of occupational safety that affect not only companies' productivity rates but also employees' quality of life. This research shows how the use of technologies such as drones can provide support and improve safety conditions, as well as generate positive impacts on management indicators and productivity in this type of project.

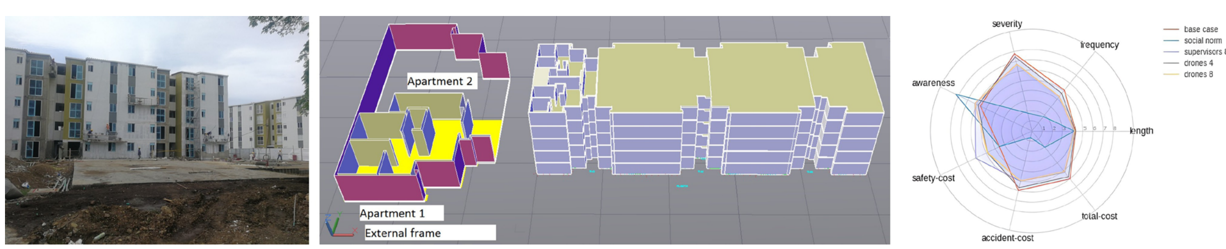
What were the most relevant results?

The study found that social influence among workers significantly boosted safety awareness. This increase in awareness correlated with reductions in observed accidents and improvements in key project metrics, including cost efficiency and shorter projected durations for residential-building tasks. The use of technology will not generate the desired effects if the psychological factors that impact upon the behaviour of workers are not taken into consideration in the analysis. The most cost-effective strategies, in order, are: social initiative, drones and supervisors.

What do these results contribute?

Results demonstrate that leveraging social dynamics and proactive safety culture can yield substantial safety and productivity benefits, potentially more cost-effective than simply increasing safety spending. Additionally, integrating dynamic hazard modeling and technology support with consideration of human factors enhances decision-making, leading to safer workplaces and more efficient housing construction projects.

Graphical Abstract



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Introduction

The construction industry is a critical driver of economic growth and national development (1). Beyond its fundamental role in job creation, the sector's interconnectedness with other industries significantly contributes to GDP and overall economic advancement (2). Nevertheless, construction remains one of the most hazardous industries worldwide, affecting both developed and developing countries alike (3). Although the industry employs approximately 7% of the global workforce, it accounts for 30-40% of fatal occupational accidents (4), surpassing accident rates observed in countries such as China, Germany, the United States, and the United Kingdom. In developed countries, although absolute rates have declined thanks to strict regulations and prevention technologies, the complexity of projects and subcontracting have generated new emerging risks. In emerging countries, on the other hand, indicators continue to rise. For example, the Colombian Safety Council reported a 145% increase in occupational diseases between 2019 and 2020, especially in residential construction (5). Countries such as Brazil and Mexico also have high accident rates, where informal employment and lack of oversight are key factors that exacerbate accidents in the region (6). Given the substantial economic and human costs associated with these incidents (7), improving safety performance in construction has become a priority for both governments and industry stakeholders (8).

Multiple factors influence safety performance during construction projects. Hoła et al. (9) categorize these factors into three primary groups: 1- construction type and technologies employed (10)(11); 2- worker-related attributes, including experience, culture, beliefs, and social environment (12)(13); and 3- unconventional factors such as work pace, learning rate, risk awareness, and ergonomics (14)(15).

Construction firms mitigate project risks through diverse safety investments, ranging from traditional measures like personnel training and accident investigations to innovative technologies such as virtual reality and unmanned aerial systems (11). While most studies assess the effectiveness of these interventions via statistical analyses or empirical observations, they often overlook individual differences and interpersonal dynamics—elements especially relevant to unconventional factors and commonly excluded from safety evaluations (16). Agent-based modeling (ABM) provides a powerful computational approach to capture these non-linear interactions between individuals and their environment (17), enabling a more nuanced understanding of their impact on safety outcomes.

Safety performance in the construction industry has traditionally been assessed using reactive indicators such as accident rates and lost workdays using regulations such as Decree 1072 of 2015, which regulates the Occupational Health and Safety Management System (SG-SST) in Colombia and is mandatory for all companies, and Resolution 4272 of 2021, which establishes regulations for working at heights, a specific and frequent risk in construction. However, these metrics provide limited insight into accident prevention, as they are recorded only after incidents have occurred, thus reflecting a reactive rather than proactive approach. Consequently, recent research has emphasized the importance of proactive variables, including safety investments (14), safety climate, and safety awareness (13). Notably, safety awareness encompasses construction workers' perception of hazards and risk comprehension, which can be enhanced through improved

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situational awareness (18). Ensuring adequate situational awareness is critical for construction workers to navigate complex and dynamic environments safely (19). Experimental studies in simulated settings have demonstrated that situational awareness can decline under cognitively demanding tasks, such as forklift operation during loading or unloading (20). These proactive measures serve as early indicators of the effectiveness of company safety efforts. This study underscores the importance of integrating both reactive and proactive safety measures within the developed model.

Palaniappan et al. (21) proposed a conceptual framework to evaluate workers' responses to safety culture, employing a single agent type representing workers. In contrast, our model expands upon this by incorporating multiple agent types and additional input variables. Lu et al. (14) examined the influence of safety investments on accident rates, incorporating factors such as workload and agent-environment interactions. However, their model did not account for hazard variability throughout the construction lifecycle, nor did it consider employee age and experience. Zhang et al. (22) utilized agent-based modeling (ABM) to investigate the impact of safety management practices on worker safety by analyzing a specific unsafe behavior. Nevertheless, technological safety interventions and cost implications were not addressed in their study.

Building upon these limitations, our agent-based simulation analyzes the interactions among employees, projects, and sites to evaluate the efficacy of preventive safety strategies. Our model innovates by integrating variables such as hazard level differentiation based on building design and project progress, employee age, and social influences related to seniority (years of experience). Despite evidence from Feng et al. (12) and Meng & Chan (23) highlighting the significant influence of these factors on accident occurrence, their incorporation within ABM frameworks remains unexplored. Furthermore, Lu et al. (14) emphasized the necessity of including these variables to advance understanding of safety performance. Additionally, leveraging emerging technologies, this study evaluates the cost-effectiveness of various accident prevention strategies.

This study presents an agent-based model designed to evaluate the effectiveness of safety strategies in preventing accidents during apartment building construction, incorporating both conventional and unconventional factors typically omitted in prior analyses. Three strategies are examined: 1- fostering a social norm wherein each worker assumes responsibility for colleagues' safety; 2- employing supervisors to enforce compliance with safety standards on-site; and 3- deploying unmanned aerial systems (UAS), a novel intervention not previously analyzed within this modeling framework. The model integrates dynamic hazard conditions shaped by the evolving spatial layout of the construction site, as well as worker-specific phenomena such as learning processes and heterogeneity in risk awareness. These features represent significant advancements compared to existing studies. Model validation was conducted through comparison with data from an actual construction project in Colombia.

Method

To evaluate the impact of accident prevention actions on the safety and performance productivity, an agent-based simulation model was developed and calibrated employing real case data. The real data were collected on: 1- characteristics of the construction project (such as type of project,

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architectural design and dimensions); 2- investments in security (such as frequency of activities and personnel wages paid); and, 3- statistics on performance safety (such as fatal and non-fatal accidents and short term or permanent sick leave or disabilities). The data collected correspond to the construction of a residential building in the city of Cali, Colombia. These data allowed for the parameterization of some input variables as well as the calibration of those variables which had no available information. The model was developed using the Netlogo® platform (24).

Case study

According to Cámara Colombiana de la Construcción – CAMACOL in 2018, considering that 65% of employees in the construction industry work in buildings intended for residential use, a case study was selected as a common example of an apartment construction project which consisted of 60 apartments distributed over 5 floors; each floor housing 12 flats. Figure 1 shows the design for the building and the internal layout of a typically designed and constructed apartment.

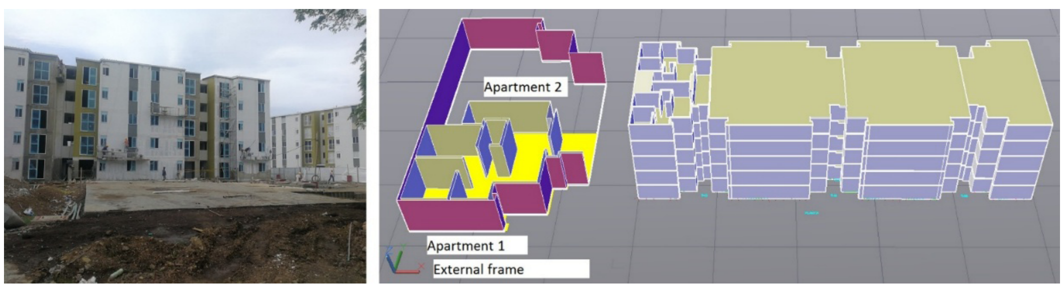

Figure 1. Building and flat design

The pouring of monolithic concrete slabs, simultaneously pouring foundation walls and flooring while using formwork, is the system which has become industrialized in the construction of apartment buildings. This phase in the construction is known as 'structure'. According to national statistics, 'structure' is the stage with the highest intensity use of labour per housing unit (2.3 workers).

Model

An agent-based model is based on three elements: 1- agent properties, behavior, and environment; 2- agent interactions with the environment; and 3, agent interactions with other agents. Therefore, the description of the model is based on the classification of these three elements.

Environment and agents

Environment: The environment in which the agents interact is representative of a building under construction. This space is made up of a 555-cell grid, each of which represents 1 m2. Space cells vary in terms of workloads and hazards; levels may vary from 1 (very low) to 10 (very high). Initially, the assumption was made that the entire area shared the same workloads, being given a value of 2 units; although, the hazard levels vary depending on the area of the building that is being constructed. In Figure 2, the blank cells are indicative of cells in which agents do not operate, no construction work is needed and therefore there is an absence of hazards. The cells in light blue represent the interior of the apartments, in which the hazard level is low. Likewise, the cells in

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black represent the divisions inside the apartments; these do not have an associated hazard level. However, the cells in dark blue represent the outside edges of the building; there, the hazard level is high due to the risks associated with falling from significant heights.

Agents: The agents of the developed model represent construction workers, specifically those working on the structure stage which has been selected for the study. Each worker has the following attributes:

Age: a factor which determines the worker's ability to influence the safety behaviour of his colleagues.

Social influence: defined as the worker's ability to modify the behaviour of his workmates.

Speed: understood as the number of workloads per day that the worker can perform.

Awareness: understood as the level of danger consciousness.

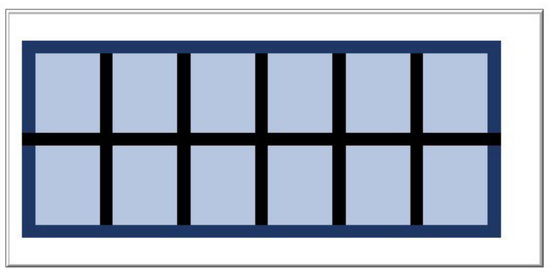

Figure 2. Environment

Interactions between the environment and agents

The interaction between agents and the environment involves two routines: job search and security check. Each routine is explained below.

Job Search: each worker moves throughout the building under construction, seeking to complete the cell workload he is responsible for; then moving on to a new task, a new cell. In this way and taking into consideration both the speed of the worker and the workload of the cell, it is possible for some workers to finish their work before others; thus, on the same day, these workers can move on to the next cell, ahead of the other agents. At the beginning of the simulation, the workers are in the centre of flat #1 on the first floor. As it has been indicated, given the authentic conditions of the case study, the agents complete one apartment at a time.

Security check: This security check consists in comparing the hazards associated with that cell to the worker's safety awareness. If the worker's awareness overcomes the hazards of the cell, the worker will implement the safety procedural and will not be predisposed to injury.

At the start of the simulation, all agents are aware of the hazard of even the most hazardous cells involved; this is because the initial awareness is equal to the maximum hazard. If the worker were to have an accident that should prove to be fatal (with some probability), the worker is replaced. If,

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on the other hand, the accident turns out to be non-fatal, the worker remains inactive for the time accorded by his disability insurance; and is not replaced. Additionally, during the days accorded by the insurance, the worker will not be able to carry out any activity nor contribute to the work in progress.

Both the probability of having a fatal accident and the severity of non-fatal accident increases in a manner which is directly related to the number of floors being constructed. The higher the building, the greater the number of fatal accidents. However, in previous research models (14) (22), the progress of the work does not alter the exposure to danger, it is assumed to be constant; nevertheless, different studies recognize its dynamic nature (25). Therefore, this effect has been included in our model.

Our simulated model calculates the total costs involved due to accidents that are incurred during the structural phase of the project. In Figure 3 we present the flow chart for worker's decision-making process, which includes the two main routines explained above: blue colour for the task search routine, and yellow colour for the security check routine.

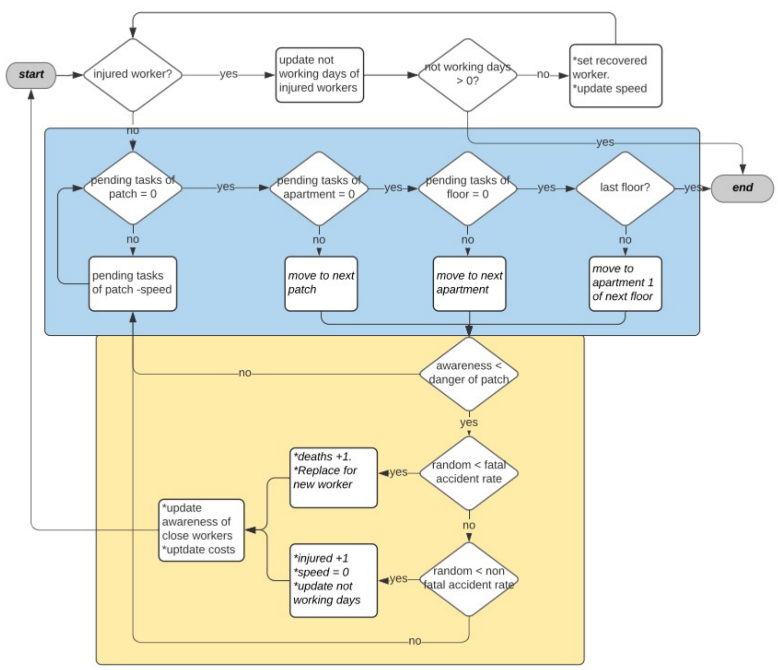

Figure 3. Workers' decision rules.

Notice that in both inside the routines and outside of them we update worker's properties and global project security performance variables, such as costs, deaths and injured workers. We explain these mechanisms further in the following sections.

Evolution of the agent's properties

Workers' awareness increases with some events. Non-fatal accidents have an effect, not only on the level of consciousness of the injured worker, but also on the level of consciousness of colleagues who work in the vicinity of the place where the accident occurred. This then determines how, after the non-fatal accident, the awareness of the injured worker´s companions increase by 10 units

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(same value that the initial level of awareness). Thus, the level of awareness of the workers who witnessed the accident is that of 10 units added on to the level of awareness that the worker had at that time. As a result, those who witnessed the accident become much more attentive to safety recommendations in the future. Additionally, when the injured worker returns to work, his level of awareness will have increased by 20 units (twice the initial level of awareness).

HSI Likewise, when a fatal accident occurs, the increase in awareness of those companions of the deceased who continue to work near the site in question is four times greater than the initial state; evidence of susceptibility to a much greater impact than a non-fatal accident, an impact of 40 units. In any case, the agents´ awareness of the dangers naturally decreases as time passes. This emphasizes the fact that at the beginning of the project, the workers followed the safety recommendations to a far greater extent than at the end of the project. This then reflects a decreasing awareness or a decreasing concern when faced with danger. The assumption is made that day by day, the awareness of the worker decreases naturally by as much as 2 units; that at the end of 5 days of work, the worker will not follow any of the safety standards. To counteract this phenomenon, it is common practice for construction companies to give short talks on safety measures several times a week. The modelling of this strategy, already immersed in the data of the real case, increases worker awareness by 2 units per talk (coinciding with the awareness that is lost daily; thus, these talks provide for the daily awareness needed).

nput variables (table 1)

Based on the information collected, and grounded on the case study, the following statistics were obtained:

- The duration of the structure building phase was 75 days of active work.
- Workers were able to complete 1 apartment per Shift
- A total of 9 non-fatal accidents were registered, and 0 fatal accidents.
- The total number of disability days based on the 9 accidents was 127.

According to this, the non-fatal accident rate of the work is 47.4%. This is equivalent to a daily accident rate of 0.63%. However, using this ratio in a simulation model whose time step is given in days, it would seem that all cells moving in the space are at risk. Therefore, the accident rate used for the model must reflect the fact that not all cells in the space operate at high risk, the ones at high risk would only be those working on the edges of the building (98 of 555 cells, corresponding to 18% of the space); In this sense, the accident rate used in the model is 3.6% (0.63% / 18%). Although this construction site did not experience any fatal accidents, the model took into consideration the fatality rate for the Colombian construction sector.

Real case ratios regarding days of disability-related absences due to on-the-job accidents are 14.1. Nevertheless, this data does not classify absences according to the floor upon which the accident took place. To correct this lack of information, the number of days which are calculated within the model according to the severity of the accident use a factor which is multiplied by the number of the floor, e.g. assuming the factor is 5, a fall from the fourth floor will provide for 20 days of

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disability-related absence. Likewise, a fall from the first floor will provide for a 5-day disability-related absence. With this modification, the average number of days of disability-related absences is 15, a value which is reasonably close to reality (the exact value would be achieved by means of a factor of 4.7 days instead of 5 days; nevertheless, this does not make sense for a model whose advance of the time step is calculated in full days).

Project security performance variables

The model constantly monitors six project performance variables:

- Length: time required to complete all the work during the structure phase.
- Frequency index: standardized for a job of 100 workers who work a total of 240000 hours per year.
- Severity index: standardized for a job of 100 workers who work for a total of 240000 hours per year.
- Safety costs: daily costs of the safety measures implemented on the site, per worker.
- Accident costs: daily costs of on-site accidents, including both fatal and non-fatal accidents, per worker.
- Total costs: total daily costs of the job safety measures include safety strategy costs as well as the cost of accidents per worker.

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Table 1. Set of variables considered in the model.

Variable	Description	Value	Source
W#	Number of construction workers	19	Case study
Age	Age of the workers	Distribution of power between 20 and 40 years. 70% of the workers are under the age of 30.	Case study
Daily-non-fatal-accidents	Probability of a non-fatal accident per day	3.6%	Case study
Daily-fatal-accidents	Probabilities of a fatal accident per day	0.06%	Case study
Severity rate due to nonfatal-accidents	Days missed due to disabilities assigned to each non-fatal accident	5 days x floor height	Case study
Severity rate due to fatal-accidents	Days assigned per year due to each fatal accident	6000 days	ICONTEC NTC3701
Cost /non-f accident	Cost per non-fatal accident	$222 (USD)	(26,27)
Cost / f accident	Cost per fatal accident	$125000 (USD)	Colombian Ministry of Labor. Minimum wage for 2020.
Training talks costs	Cost per training talk	$12 (USD)	Indeed. Construction Supervisor Salaries in Colombia
Talks per week	Number of training talks per week	3	Case study

Results and discussion

This section presents the findings of the baseline case simulation, based on 5,000 iterations to ensure low variance and statistical significance.

Baseline case results

Table 2 summarizes the baseline simulation results. The model estimates an average project duration of 74 days, with a frequency index of 167 accidents and a severity index of 2,400 lost workdays. These values deviate less than 1.5% from actual project data, supporting the model's validity.

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Table 2. Base case results

Variable	Real	Average	CI 95% - lower limit	CI 95%- upper limit
Length	75	74.1	74.0	74.3
Frequency	168	167.0	165.4	168.6
Severity	2377	2400.1	2374.8	2425.4
Awareness	NR	279.3	271.9	286.7
Safety-cost	NR	0.31	0.31	0.31
Accident-cost	NR	21.14	20.77	21.52
Total-cost	NR	21.45	21.08	21.83

Daily costs per worker are approximately USD 21.45, composed of USD 21.14 related to accident costs and USD 0.31 attributed to prevention strategies (e.g., bi-daily safety training sessions). The average worker safety awareness is quantified as 279.3 awareness units.

The 5,000 simulations reveal variability in outcomes due to inherent stochasticity. Figure 3 depicts the distributions of key safety performance metrics. Project duration fluctuates between 62 and 96 days (Figure 4a), with 95% of simulations not exceeding 74 days, consistent with typical structural phase durations in Colombian construction projects.

The frequency index ranges from 75 to 250 accidents (Figure 4b), with lower frequencies correlating with shorter project durations. Severity was analysed separately for cases with no fatal accidents (97%, Figure 4c) and those with fatal accidents (3%, Figure 4d). For the former, severity averaged 2,281 lost workdays; for the latter, severity ranged from 6,000 to 9,000 days.

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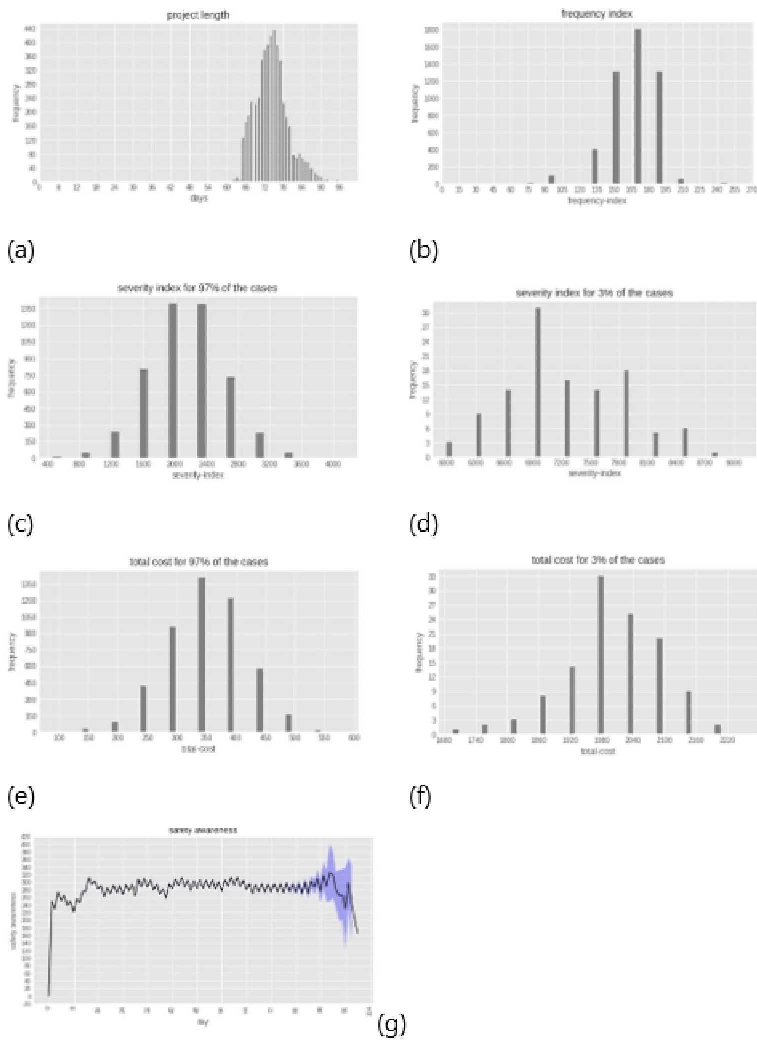

Figure 4. (a) Project length; (b) Frequency index; (c) Severity index for 97% of the cases; (d) Severity index for 3% of the cases; (e) Total cost for 97% of the cases; (f) Total cost for 3% of the cases; (g) Safety awareness.

Safety awareness tends to decline over time due to increased worker confidence and reduced self-protective behaviours but is periodically reinforced through training, warnings, or accident occurrences, resulting in oscillatory awareness patterns (Figure 4g). Awareness fluctuates within a stable range of approximately 220 to 320 units.

Total costs per worker vary significantly depending on accident severity. In simulations without fatalities (97%), costs range from USD 7.9 to USD 28.9 per day, whereas simulations including fatalities (3%) report costs between USD 88.4 and USD 116.8 per day.

Figure 5 illustrates the interrelations among frequency, severity, and project duration. Projects with higher frequency and severity indices exhibit prolonged durations (Figures 4a and 4b). A direct linear relationship was observed: doubling the frequency index extends project duration by 25%,

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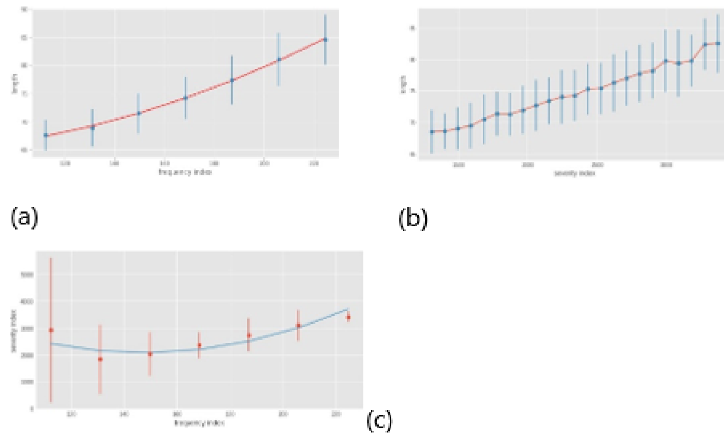
while doubling severity increases duration by 17%, aligning with existing literature on safety impacts on construction delays (28).



(a) (b) (c)

Figure 5. Interactions among frequency, severity and length.

Note: (a) Length time vs Frequency index; (b) Length time Vs Severity index; (c) Severity index vs Frequency index. The length of the vertical bars indicates the variability in the results obtained indicating an average of all the simulations.

It is observed that those projects which present higher indexes, both in severity and frequency, last longer (See Figure 5a and 5b). The relationship between these variables is direct and linear. Thus, when the frequency index is doubled, the length of the project increases by 25%, and when the severity index is doubled, the length of the project increases by 17%. This finding is consistent with what other authors indicate regarding the incidence of safety performance in construction delays (28)(29).

Interestingly, the frequency-severity relationship displays a U-shaped curve (Figure 5c), with minimum severity near average frequency values. This pattern suggests that while higher accident frequency generally increases severity due to more lost workdays, some projects with low frequency still experience high severity, often due to fatal accidents, which subsequently raise worker awareness and reduce accident frequency.

Model Validation

It is no trivial task to validate an individual model which would represent a social system. No standard procedure exists which could accomplish this; however, there is a collection of fragmented techniques aimed at increasing confidence in the model. A general exploration of the model makes evident the adequate behaviour regarding the evolution of the main variables of state (animation techniques and operational graphs). Figure 6 shows the graphs of one of the many simulations which were done.

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We can observe that the frequency index, the severity index and the number of accidents increase with time while the work pending in the construction project diminishes as the days go by, until zero is reached on day 74. Average conscience among workers oscillates as days go by (negative factor), as chats are carried out (positive effect) and as on the job accidents occur (positive effect). Thus, one can note that the number of workers involved in the project remains constant in time (in other words, there are no new workers, nor do initial workers leave). It should be noted that those workers who are incapacitated continue to be recognized as company workers. It should also be noted that the number of workers who are incapacitated, as well as those who are not, make up the total number of company workers. Maintaining the mass contributes to the validation of the model.

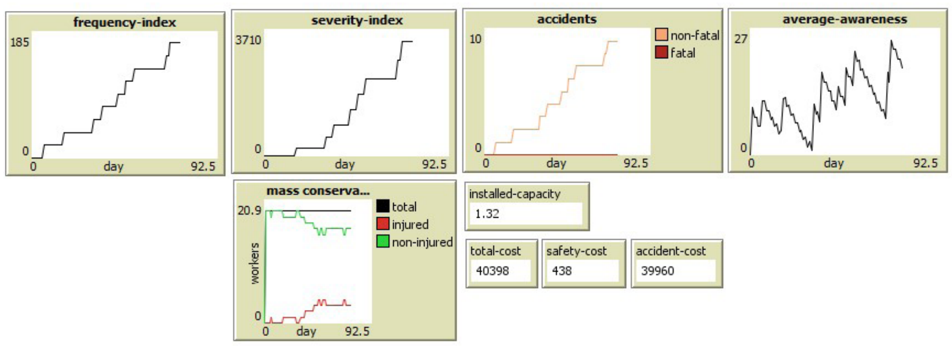

Figure 6. Animation, operational graphs and mass conservation validation tests

A degenerate test was undertaken. In this test the dynamic risk effect was annulled while being replaced by a fixed risk in which, ignoring the height of the floor being constructed; the severity rate of each accident was that of 15 days (the average value of the dynamic risk). To understand in greater detail, the effects of this dynamic risk, the tables were analysed using time simulation. Figure 7 presents the results of this analysis regarding the variables of frequency and severity.

It should be noted that a hypothetical fixed risk has a negligible impact upon the frequency index of the construction. However, this hypothesis overestimates the severity index during the first half of the time of construction while underestimating it during the second half. In the result, the hypothetical fixed risk underestimates significantly the final severity index of the construction, going from 2400 to 2043 in accordance to the hypothetical fixed risk (a sub estimation of 14.9%).

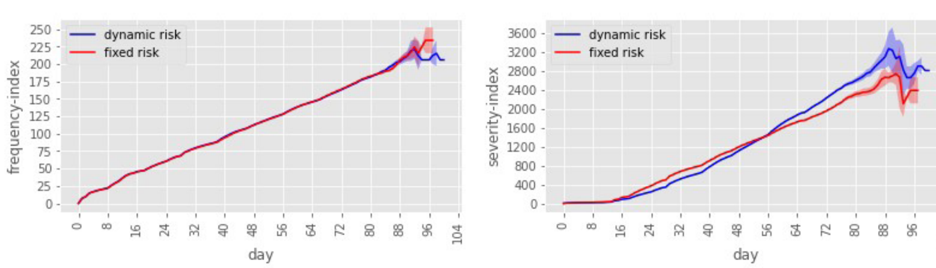

Figure 7. Effect of dynamic risk. Degenerate test for validation

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This same test was applied to annul the effect of social influence according to experience due to worker age. The results are graphed below in Figure 8. By the time the construction is completed, the average value of the frequency and severity indexes repudiating the effect of influence due to experience can be found to be within the confidence interval of the indexes when taking into consideration said effect. In other words, the inclusion of the effect of influence due to experience has a negative effect upon the frequency indexes as well as upon the discipline of the construction.

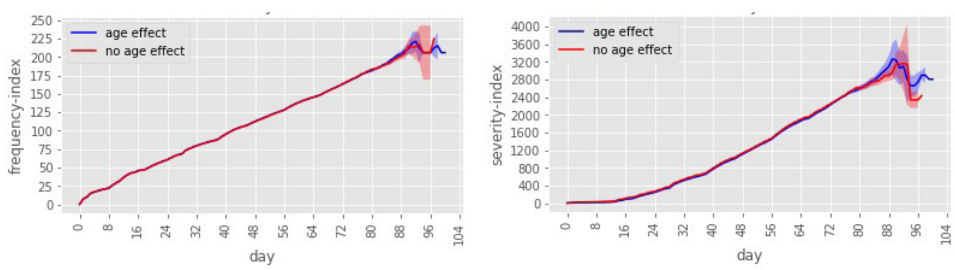

Figure 8. Effect of influence by experience. Degenerate test for validation

Because agent models require the development of a code, other techniques were developed for validation. Examples of these were traces and desk checking. These evidenced satisfactory results. Correspondingly, the model results were compared with the results yielded in studies made by of others (14)(16); these yielded satisfactory results. However, it was not possible to carry out code comparison because the model codes as reported by the literature were not available.

The comparison between historical values and simulations of output variables such as length, frequency and severity constituted proof regarding the historical validity of the model. According to the construction companies Bolivar and Normandia in Colombia, continued consultation with the experts regarding this problem, adds to its validity using the face validity technique. The numerous simulations run performed to capture the stochasticity of the results due to the randomness of the input variables, are part of the internal validity. Lastly, the prospect of including improvement policies in the model and of carrying out analyses considering the standardized indicators of the phenomenon contributes to generating confidence in the model.

Strategies of prevention

Three preventive interventions were modelled to assess their impacts on safety and productivity:

Social initiative

This strategy assigns responsibility to each worker for the safety of nearby colleagues within a 1 m² radius. When moving cells, a worker warns the nearest colleague with the greatest discrepancy between awareness and fall risk, increasing that colleague's safety awareness by 3 to 7 units depending on the social influence, which correlates with worker experience and age. Though cost-free, this strategy may be challenging to implement in practice.

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Construction supervisors charged with occupational health and safety

Two construction supervisors charged with occupational health and safety are hired to inspect the practice of safety standards in the field. In the model, supervisors are a new type of agent that does not work on construction but rather moves constantly among the workers. In each round, the supervisor selects the closest worker within his sphere of action (10 m^2 around) who exhibits the greatest difference between safety awareness and the risk of falling. Upon being warned about the safety rules to be followed, the awareness of said worker increases by 8 units, this value responds to the assessment of the experts consulted. It is important to note that the warnings given by the supervisors who have been invested with the authority to inspect safety standards are far more influential than the advice and warnings given by the most experienced workers. According to platforms such as Indeed Colombia, this action requires the costs of the salary which must now be paid to the supervisors; costs which must also include social benefits.

Drons

This action employs two drones to inspect the safety regulations which are being employed in the field. A choice is made in favour of multirotor drone. This type of drone was recommended in new studies made regarding the possible uses of drones according to their technical specifications (30). Similar to what happens with supervisors, in the model, drones are a new type of agent that does not work on the construction, rather it moves constantly among the workers, with each movement selecting the closest worker in its sphere of action (5m^2, half the supervisor's sphere of action), which marks the greatest difference between awareness and the risk of falling. By warning the worker regarding the safety rules that should be followed, his awareness increases by x units. Given the fact that this policy has not been implemented in construction jobs in Colombia, there is no knowledge regarding the social influence the drone might have; therefore, two analyses were performed: (a) drone influence is = to 8 units of awareness (as much as that of a supervisor); and (b) drone influence is = to 4 units of awareness (half the influence of a supervisor which corresponds to the average social influence leveraged by workers). This action carries with it the costs of the purchase of the drone, and the assumption that the useful life of said drone would be 36 months in accordance with its technical specifications and eventual technological obsolescence. Table 3 shows the basic parameters needed to model these actions.

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Table 3. Parameters of preventive strategies contained in the model

Variable	Description	Value
Social radius	Radius of worker influence	1 m^2
Min social influence	Minimum influence wielded by a worker	3 units of safety awareness
Max social influence	Maximum influence wielded by a worker	7 units of safety awareness
Radius-supervisor	Radius of supervisor influence	10 m^2
Supervisor´s impact	Supervisor's impact	8 units of safety awareness
Supervisor´s cost per month	Monthly cost of a supervisor	$ 200 (USD) / month
Drone radius	Drone's radius of influence	5 units of safety awareness
Drone impact	Drone's impact	4 and 8 units of safety awareness
Drone's monthly cost	Drone's monthly cost	$70 (USD)

Once again, 5000 simulations were obtained for each one of the three prevention strategies modelled. To facilitate their comparison, the results were graphed on a logarithmic scale and a radar-type graph was used to represent them. This can be observed in Figure 9.

Figure 9. Comparison of preventive actions

The four strategies analysed obtained better results than the base case regarding the following variables: length, severity, safety awareness, and frequency. Additionally, this led to better results in accident costs and total costs. The lowest total cost strategy is the social norm strategy; without incurring additional monetary investment, it decreases the frequency and severity indices, presenting the lowest total cost of the strategies ($0.42 (USD) per day per employee, a reduction of more than 95% of costs). This is consistent with the argument made by (12) and (13): the greater the workers' safety awareness because of a good safety culture, the lower the rate of accidents. Furthermore, this strategy reduces the average completion time of the work by 65 days; a gain of 10 days representing 12% of the time taken for the completion of the structure stage for this project. The strategic use of drones and supervisors requires additional investments made to the base case (3% and 268%

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respectively). Is evident that the greater the investment in security is not equal to the best safety performance. However, the positive impact on safety made by the supervisors diminishes the total cost of the project by 56% as compared to the cost of the base case.

The effectiveness of the drones will depend on the influence they have on the workers. As stated by (31), if the psychological factors that impact upon the behaviour of workers are not taken into consideration, the use of technology will not generate the desired effects. If the impact of the drones is the same as that of the supervisor, the total costs of the project would be reduced by 59%, making it the second most cost-effective strategy, above even that of the use of supervisors. If, on the other hand, the impact of the drones is only half the impact of the supervisors, the total costs of the project would be reduced by 23%, and its effectiveness would be less than that of the supervisors.

Conclusions

The construction sector continues to exhibit high accident rates despite considerable efforts by companies to mitigate them. Investments in prevention strategies do not always yield proportional improvements in safety outcomes. While numerous studies have examined the factors influencing accidents and assessed the impact of traditional prevention practices, few have leveraged the advantages of computational modelling—particularly in representing employee heterogeneity and the complex interactions among accident-influencing factors—while simultaneously evaluating emerging technologies in accident prevention.

In this study, we developed an agent-based simulation model to represent the accident dynamics during the structural phase of building construction. The objective was to identify strategies with the greatest potential to reduce the frequency, severity, duration, and associated costs of accidents during this phase. The model was calibrated using data from a real case study, establishing a baseline scenario for comprehensive analysis.

Our results demonstrate that all three evaluated strategies contributed to improved project safety indicators. These findings suggest that construction projects can enhance safety performance by implementing these interventions. Notably, the study confirms that higher investment levels in accident prevention do not necessarily guarantee superior safety outcomes. Key findings include: 1- the social norm strategy—where workers assume responsibility for the safety of their colleagues—requires the lowest investment while achieving the highest levels of safety awareness, productivity (measured as project duration), and overall safety performance; 2- the use of drones for site inspection during the structural phase positively impacts safety, outperforming supervisor-based oversight when the behavioral influence of drone-generated safety alerts is comparable to that of supervisors. However, empirical evidence regarding this social influence under real-world conditions remains limited; 3- incorporating dynamic hazard levels that evolve throughout the construction process is critical for accurately capturing accident phenomena; and 4- including worker age and seniority in the model did not significantly affect outcomes, as scenarios with and without these variables produced essentially equivalent results.

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Conflict of interest

The authors declare that they have no conflicts of interest related to this research. Ethical aspect: does not declare.

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