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Discrete-event simulation of construction safety inspections

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Abstract

Construction safety inspections are primarily intended to manage the risks of incidents and safeguard the health and safety of crews at sites. However, understanding how often safety officers can conduct safety inspections requires the quantification of their utilization rate and understanding how the frequency of inspections affects project duration is yet unknown. In this study, a simulation model is illustrated to capture the weekly routine of a safety officer and how that routine is incorporated into tunnel boring operations. Discrete-event simulation is used to model the events and interactions between the construction processes and resources in *Simphony*. The utilization rate of the safety officer is quantified by varying the frequency of planned (programmed) inspections to understand the relationship between the frequency of programmed inspections conducted by the safety officer and the incident rates and overall project duration. Results show that the frequency of programmed inspections dramatically affects the utilization rate of the safety officer and the project duration. The simulation strategy and the key findings demonstrated in this study serve as a foundation for decision support in the context of assessing safety resource allocation and its impact on incident rates and project duration.

Keywords: Safety officer utilization; safety incident simulation; discrete-event simulation; tunnel boring operation

1. Introduction

1.1. Background

It is vital for everyone in a construction project organization to share the responsibilities for safety performance in a construction project. Established construction companies have Health, Safety, and Environment (HSE) manuals in which their policies, standards, and procedures are explicitly documented to influence safety behavior (Choudhry & Fang, 2008). Though the safety culture of a company typically cascades from the top management to the field crew (Lingard et al., 2012), the safety officer (as a first-level supervisor) has a relatively higher degree of influence on safety performance at the site (Lingard et al., 2012; Sawacha et al., 1999). This is encapsulated in the notion that *proximal* factors have a greater impact than *distal* factors (Christian et al., 2009; Suraji et al., 2001).

The construction safety officer oversees the monitoring and evaluation of health and safety hazards to control the risks at the construction site. The role of the safety officer in terms of site safety inspections can include work that can be classified as workplace inspections, task observations, and safety audits (Zhang et al., 2016). The safety officer is primarily concerned with executing the activities in the safety management system (SMS), i.e., safety planning, control measures in implementation, safety performance measurement and evaluation, and review and improvement (Robson et al., 2007). The safety officer is conventionally assigned to oversee the safety of a certain number of construction workers, often irrespective of the tasks required as per the company's guidelines in the SMS. As per the Occupational Safety and Health Administration (OSHA) definitions, inspections are classified into two categories: (1) *programmed,* which are proactive in identifying and reducing workplace hazards; and (2) *unprogrammed,* which are inspections that are the result of safety incidents and reports from employees (Li & Singleton, 2019). An explicit understanding of the relationship between the workload of the safety officer (which limits the capacity for conducting site inspections) and safety incident rates is not available in the literature. This knowledge gap opens an area of research to explore strategies and provide management teams with an objective basis for assigning a specific number of safety officers to a specific construction operation. Furthermore, a supposition can be formed based on the study conducted by Li and Singleton (2019) such that failure to assign a sufficient number of safety site inspections has a dramatic effect on the occurrence of safety incidents.

Computer simulation tools play an important role in construction in terms of understanding the intricacies of construction processes (AbouRizk, 2010; AbouRizk & Hajjar, 1998). One of the prevalent simulation tools is a discrete-event simulation (DES) which can predict the future state of a real construction system (Lu, 2003). In most cases, DES is a more suitable simulation model for capturing real-world scenarios when there are no time-series factors involved in the process simulation (Kuncova & Janitor, 2020). For example, Lamas-Rodríguez et al. (2016) used DES to develop models to reduce flow time, identify bottlenecks, update lead time, and reduce quality issues of jacket offshore structures. Moreover, DES can be used as an effective general-purpose tool to quantitatively examine the characteristics of the processes and resources (Martinez & Ioannou, 1999; Martinez, 2010). DES is oftentimes combined with continuous-event simulation. For example, Awad et al. (2019) integrated discrete and continuous event simulation models to analyze carbon emissions in panelized construction in cold regions. This comes in very handy in the context of representing the interactive behavior between the construction operation and the duties of the safety officer as the resource of interest in this study. Furthermore, Ead et al. (2019) extended the application of DES with combined continuous modeling to capture the risk impact of safety incidents on project schedules.

1.2. Problem Identification

With the traditional means of assigning the safety officer (i.e., the sole consideration is the number of construction workers that a safety officer should oversee), some issues can be anticipated. It can be argued that this belief that the allocation of the required number of safety officers is dependent on the size of the crew is not an accurate representation of site safety management. If there is an under allocation of these site safety officers, this normally leads to overutilization of the site safety officers, which leads to higher priority tasks being overlooked or to missing some scheduled site inspections. It is then necessary for the HSE management team to employ effective tools to measure the safety officer utilization rate.

Additionally, programmed inspections play a significant role in reducing incidents (Li & Singleton, 2019); however, it is not yet well understood how the frequency of programmed inspections can impact the need for unprogrammed inspections. Since the capacity of a safety officer to conduct programmed inspections can be determined based on their utilization rate, there is a need to explore how an overworked safety officer can affect the safety incident rates.

Lastly, Ead et al. (2019) reported, based on a simulation study, that safety incidents dramatically affect production rates. If there is a link between programmed inspections and incidents, it is also of interest in the present study to explore how the frequency of programmed inspections affects the overall schedule of a construction project.

1.3. Purpose of the Study

Quantification of the utilization rate of the safety officer as a response to the frequency of the weekly programmed inspections is the main subject of interest in the present study. Moreover, this study attempts to explore the effect of programmed inspection frequency on the overall construction project duration. Field testing of either the utilization rate or the number of safety inspectors allocated to a project has ethical implications. Therefore, the relationship between the allocation of safety inspectors and the frequency of safety incidents can be first explored through computer simulation. DES modeling is the chosen means to conduct this analysis to capture the discrete events when safety incidents occur.

The academic contributions of the present study are twofold: (1) an embellishment model to accommodate the process interaction of the safety officer in the context of a tunnel boring operation, thus creating a quantification tool for resource allocation decisions; and (2) understanding the underlying impact of the frequency of programmed inspections on the utilization rate of the safety officer and the project schedule. Due to the immense level of effort required to build a simulation of a construction operation including all its incorporated resources, the proposed model is designed for reusability where the safety officers are incorporated into any construction operation as a resource to analyze their impact on the safety incidents and project schedule. Assumed features such as the severity of incidents and their corresponding priori probabilities are parameterized for flexibility of use at the activity level.

The following sections of the paper provide detailed descriptions as to how the identified problems are addressed in the present study. Section 2 provides a review of the literature to present the foundational concepts in the domain of construction safety management and the existing simulation strategies in modeling construction safety incidents. Modeling concepts of the tunnel boring operations using DES and important assumptions are discussed in Section 3. Section 4 presents the discussion of the simulation results where the effects of frequency of programmed inspections on the utilization rate of the safety officer and project duration are established. And lastly, the conclusion and future research steps are discussed in Section 5."

2. Literature Review

2.1. Construction Safety Inspection Management

The site safety inspection is a component of the SMS that is necessary to ensure the safe implementation of construction operations (Zhang et al., 2016). Various companies have their strategies for deploying safety inspectors depending on the relevant legislative regulations, the company's directives included in their safety work method statement (SWMS), and the project needs. From a pragmatic perspective, site inspections are required regularly. Moreover, Choudhry & Fang (2008) found that management's involvement and toolbox meetings are the most effective approaches for encouraging and facilitating site safety. However, in the field, it has been found that inefficiencies and ineffectiveness concerning inspection procedures have led to results that are less than satisfactory (Kang et al., 2011). Zhang et al. (2016) provided a more detailed account of the main procedures involved in safety inspections, which include preparation; on-site checking and documenting of the identified problems; action on the identified problems; dissemination of inspection results; and follow-up inspection. Construction operations typically start with a pre-job site inspection (PSI) where the safety officer works through a company-defined checklist to identify safety hazards and communicate precautionary measures with the crew. Moreover, the PSI also serves as a communication means to communicate safety incidents and near-misses (Choudhry & Fang, 2008). Hence, a safety officer plays a significant role in terms of ensuring that the site crews follow the safety protocols.

On a different note, the supervisors embody organizational safety values that are critical to safe operations at the site. A research study by Lingard et al. (2012) highlighted the influence of first-level supervisors in exercising the organizational safety values upon their subordinates. In terms of the influence of supervisors' responses to safety, safety climate has been empirically associated with group safety performance (Lingard et al., 2012). In addition to that, workers are more comfortable when their supervisors care for their safety (Choudhry & Fang, 2008). When people are working in groups, their perceived value towards safety is heavily influenced by their immediate supervisors (Christian et al., 2009; Lingard et al., 2012; Suraji et al., 2001). More importantly, Li and Singleton (2019) explored the effect of OSHA inspections on worker safety for manufacturing establishments using fuzzy regression discontinuity design and local linear regression. They found that inspections resulted in a reduction of approximately 20% relative to the mean in the rate of cases that involved days away from work, job restrictions, and job transfers. The above-mentioned arguments strengthen the justification for the need for proper allocation of safety site officers to be present for site safety supervision and to properly translate and communicate the organizational safety values to the construction crew.

2.2. Safety Incident Simulations

The traditional computer-based tool used to understand the underlying behavior of construction systems through scientific development and experimentation is DES (AbouRizk, 2010). Moreover, computer simulation models can capture the dynamic resource interactions of the process events (Shi & AbouRizk, 1997).

DES is a simulation tool that is concerned with the changes in a system of discrete events by advancing the scheduled time (or time intervals) of each event. Such intervals may be described as deterministic or stochastic (Fishman, 2001). Pseudorandom number generators such as Multiplicative Linear Congruential Scheme (MLGC) are used to generate random numbers for stochastic time intervals of the events. AbouRizk (1990) conducted a comprehensive study on how the modeling input distributions affect the simulation output.

Simulation modeling has been used to successfully model construction safety incidents, and DES has proven useful in this regard. For example, Ead et al. (2019) used a combined discrete-event continuous simulation model to predict safety incident-related schedule delays. Their study simulates daily risk occurrence using a discrete-event process to model reduced project productivity. Another example of a study that employed a multi-pronged approach to simulation is by Goh and Ali (2015) who proposed a hybrid framework to incorporate the complex dynamics of safety culture and construction activities. Their framework incorporates DES, agent-based simulation (ABS), and system dynamics (SD) to mimic the natural behavior of an earthmoving operation while considering the truck driver's safety behavior. They employed DES as the core of their framework in which the entities and resources act as agents and can interact with other agents.

2.3. Research Gaps

Notable gaps in safety resource management research limit decision-making support due to oversimplification of the assignment of a safety officer to oversee the construction site. These limitations include the following:

1. Lack of objective quantification tools of the utilization rate of the safety officer while considering interactions with construction processes. This is important since the utilization rate of the safety officer is an indicator of the officer's capacity to be present in the field and manage the safety behavior of the crew at the site.
2. Lack of understanding of how the frequency of programmed inspections affects the utilization rate of a safety officer. The trade-off between the workload due to conducting programmed inspections and unprogrammed inspections is not well understood to date.
3. Consideration of how the frequency of programmed inspections affects the overall project duration as an extension to the delay analysis from safety incident-induced delays conducted by Ead et al. (2019) is not yet explored. This is a subject of interest since it is still unknown how slight changes in resource allocation for site inspection can affect the overall schedule of a construction project.

3. Simulation Modeling

3.1. General Simulation Concept

Following the definition of a model as described by Martinez (2010), the simulation model developed in the present study is a representation of the work routine of a safety officer. This routine primarily includes site inspections, administrative office tasks, and attending coordination meetings. Since the work of a safety officer is not stand-alone work, it is required to incorporate the work into a construction operation. In this case, a baseline model is adapted to include tunneling operations with dirt removal activities as illustrated by AbouRizk (2010). Interested readers are encouraged to refer to the study by AbouRizk (2010) for a detailed discussion on this operation.

The noteworthy feature of the present study is the embellishment model of tunnel boring operation created using DES in the Simphony (Hajjar & AbouRizk, 1999). The embellishment includes how the duties of the safety officer are represented in a specific construction operation and how the link between the varying frequency of programmed inspections and utilization rate is established. The model is further extended to model the effect of programmed inspections on the overall duration of the tunnel boring operation.

To properly manage the allocation of the safety officer, specifically in terms of managing the time required to conduct the unprogrammed inspections, quantifying the utilization rate is essential. This is possible if a simulation model can closely mimic the actual behavior of construction operations while incorporating the probabilistic nature of safety incidents. Once the utilization rate can be quantified, explorative experimentation models the relationship between the frequency of site inspections and the utilization rate of the safety officer.

3.2. Simulation Assumptions

The following assumptions are documented to closely capture real construction activity and behavior of incident events. These assumptions are organized into the general scenario, programmed inspections, unprogrammed inspections, and other relevant routines of the safety officer.

3.2.1. General Scenario

The first group of assumptions enumerated below describes the general behavior of discrete events or the set of rules that trigger scheduling another event.

1. General work shift is 48 hours per week and distributed equally over 6 days.
2. The frequency of programmed inspections is defined to be the weekly count of planned on-site safety inspections conducted by the safety officer and assigned herein as the variable x.
3. Priority of work for a safety officer is sequenced from highest to lowest: major incidents, on-site programmed inspections, minor incidents, and crane breakdown.
4. The moment a major incident happens, all activities will stop. Everything resumes only after the safety manager has completed processing the incident reports and signals clearance to operate.
5. The priori probabilities of incidents classified as minor are listed in Table 1. These probabilities change with the frequency of programmed inspections. The corresponding priori probabilities of major incident occurrence are described as $P_{major} = 1 - P_{minor}$. Overall, it is assumed that the chances of a major incident event are reduced as the frequency of programmed inspection increases. This assumes that programmed inspections lessen the severity of any incident. The incremental change in the probability of occurrence of minor incidents decreases with more frequent inspections. For instance, if the regular programmed inspection conducted by the safety officer is once per week, it is assumed that 70% of the incidents which may happen are classified as minor while 30% are major. The assumed proportion between minor

and major becomes 95% and 5%, respectively, if the safety officer conducts programmed inspections six times a week. However, it is further assumed that it is impossible that all incidents are to be classified as minor thus making the graph to be asymptotic to 100 percent. Provided that the construction operates only six times per week, the frequency of programmed inspections is capped at six times or daily.

6. If minor incidents happen before a major incident, the safety officer will return to the minor incident(s) after they are done processing the major incident. After the safety officer has finished dealing with minor incidents, they will go back to weekly office work.
7. Probabilities of incident occurrence and frequency of programmed onsite inspections are parameters that need to be varied to see the effect on the safety officer's workload.
8. Modeling incidents may only happen during two main activities in the tunneling operation—during excavation works and lining activities. The probabilities of an incident happening during other construction activities are treated as negligible for the sake of simplicity.
9. Project ends when the chainage requirement of 1,227 meters is reached.

It is worth noting that the priori probabilities and categories of major and minor incidents are only descriptors of a probabilistic event. A programmer may use different categories of events depending on the purpose of the model and the availability of data.

Table 1. Priori probabilities for an incident to be classified as minor.

Frequency of programmed inspections	P_{minor}
1	0.70
2	0.80
3	0.86
4	0.90
5	0.93
6	0.95

3.2.2. *Programmed Inspections*

The frequency of programmed inspections is the parameter of interest which is varied within the range of once to seven times per week. It is assumed that the safety officer stays at the site for 4 hours (or one half-day) per programmed inspection.

3.2.3. *Unprogrammed Inspections*

The assumptions described for unprogrammed inspections are in probabilistic terms. Unprogrammed inspections are discrete events that occur by chance. Crane breakdowns are expected to happen once every month or at an exponential distribution with a mean of 192 hours. The corresponding repair time is 3 hours. After the repair is done, a follow-up inspection is conducted for clearance to operate. In a tunnel boring operation, it is assumed that the project duration is relatively short, to the point of being negligible, in comparison to the lifespan of the crane. In this context, the equipment's aging process (which may be a potential factor in crane breakdown) is neglected. For cases where it is important to incorporate the age or condition of the equipment (a static means of modeling), the static probabilistic parameter used in this model can be fine-tuned upon the availability of data. Furthermore, a continuous simulation can be embedded to incorporate the dynamic feature of the aging process of equipment, which is outside the scope of the present study.

The assumed probabilities of incidents where the safety officer is required for unprogrammed inspections are provided in Figure 1. In this graph, it is assumed that there is a greater reduction in incidents if the frequency of inspection is doubled from 1 to 2. The probability of no incident given the frequency of programmed inspections can be analytically expressed as a second-degree polynomial in the form:

$$P(n|x) = ax^2 + bx + c \qquad (1)$$

where the parameters used in the present study are $a = -0.005$, $b = 0.058$, $c = 0.80$, and $1 \leq x \leq 6$. The expression can be established by fitting data points containing the frequency of programmed inspections as an independent variable and the incident rates as a dependent variable as illustrated in Figure 1. However, the analytical expression used in the present study is an approximation based on the findings by Li and Singleton (2019). This is a research gap found during the execution of this study and is discussed further in Section 5. Moreover, as the frequency of programmed inspection increases, the incremental reduction in the probability of no incidents decreases. This suggests that the probability graph could only approach and never reach 100 percent as the frequency increases. In other words, incidents may still happen even with a high frequency of programmed inspections.

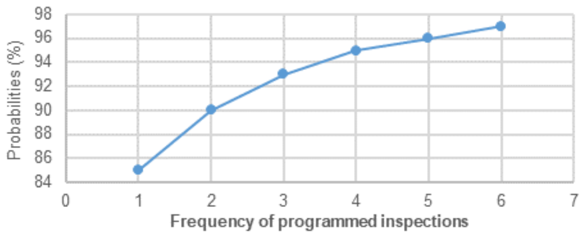

Figure 1. Assumed priori probabilities of no incidents as a function of weekly programmed inspections.

It is important to note that this probability chart may vary depending on the nature of the task and other influencing factors affecting the safety conditions at the site. However, it is assumed that excavation and lining tasks follow the same probabilities provided in Figure 1. Moreover, these probabilities are treated as parameters in the simulation to adjust when data is available.

3.2.4. *Routine Tasks of the Safety Officer*

The typical routine of safety officers must be included to precisely capture their utilization rate. These activities are covered in a plan-do-check-act (PDCA) strategy for managing the risks of incidents.

1. Weekly office tasks include reporting, meeting, training, and planning, each with consistent durations from week to week.
2. Regular meetings are scheduled once every week for one hour.
3. Safety planning tasks are allocated for two hours per week.
4. For reporting, three documents are expected to be completed in one hour daily.
5. Two hours per week are dedicated to the safety training of employees.

3.3. Simphony Modeling

To quantify the utilization rate of the safety officer as a resource, first, a construction operation that requires the presence of a safety officer is necessary. In the present study, the entire construction simulation model is composed of four parts: (1) the baseline construction operation, which is a tunnel boring operation with hauling of dirt; (2) incident events, which incorporate all incident events that may happen during a construction activity; (3) the tasks of the safety officer; and (4) modeling of an equipment breakdown. This construction operation has been modeled in *Simphony* using the DES logic. Details on these components are discussed in subsequent sections.

3.3.1. *Baseline Construction Operation*

A tunnel boring operation was used as a baseline process for this model. The concept behind this model is illustrated in detail in the paper authored by AbouRizk (2010) in Figure 8 entitled "Events simulated in tunnel federate and dirt removal federate". In the model, the tunneling operation starts by excavating a load of dirt from the ground while capturing the tunnel boring machine (TBM). This load of dirt is transported for hauling using the crane while the surveying crew checks for lining for the extension of the tracks. This loop cycles every section of about 1 meter and stops when 1,227 meters of chainage is reached. The time to finish each loop is treated as the cycle time.

There are four entities in the tunnel boring operation, namely: trucks, trains, the extension of tracks, and surveyors. Heavy equipment such as the crane, spreader, and the TBM are all considered resources.

3.3.2. *Incidents During a Construction Activity*

The random occurrence of incidents is modeled within each major construction activity. In this simulation model, the incidents that may happen during the *Excavation* task and *Lining* task are modeled as shown in Figure 2.

Since the events in this model are treated as discrete, modeling the incident at any time during the construction activity could be challenging. It is then that the activity is subdivided into four segments by which an incident may happen randomly during any time an entity passes to these activity segments. The model is designed to check whether an incident already occurred based on priori probabilities, as shown in Figure 1. Any incident is categorized as either major or minor. For major incidents, a stoppage is triggered for the entire construction operation until the safety officer conducts unprogrammed inspections and clears it to resume operation. On the other hand, minor incidents only require the presence of the safety officer for an unprogrammed inspection. The entities will cycle through all the activity segments until completion before the entities can exit the activity.

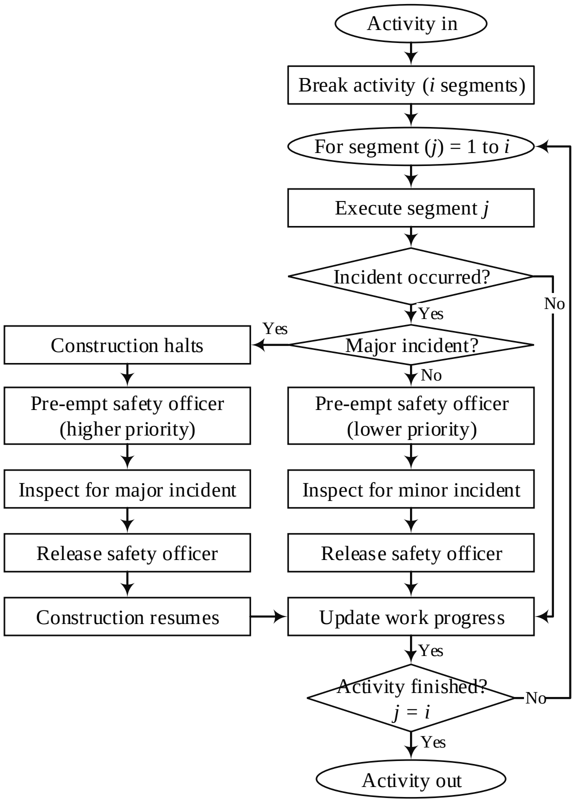

Figure 2. Conceptual model of occurrence of incidents under each activity (excavation and lining works).

The priori probabilities of an incident with its corresponding severities are assumed to change with the number of programmed inspections that the safety officer conducts onsite. If the officer can do more inspections, the number and severity of incidents are expected to decrease. Thus, in this model, the number of inspections that a safety officer can perform in a week is varied to keep track of the frequencies of site inspections and their relation to the safety officer utilization rate and overall project duration.

3.3.3. Tasks of a Safety Officer

The next step is to model the safety officer's tasks and duties during this construction operation. To achieve this, the safety officer's tasks were categorized into two sub-models. First is the modeling of the routine tasks, which include the in-office tasks as described in Section 3.2.4. Second is the modeling of situations that require the presence of the safety officer, including incidents that happened during the project (see Figure 2) and equipment breakdowns (see Figure 3). If an incident happens, based on its severity, the safety officer must go to the site and complete the inspection, reporting, corrective actions, and so on, and then they can go back to their normal routine.

3.3.4. Equipment Breakdown

Equipment may fail or may require preventative maintenance during the construction operation. This happens in a random pattern on a time-dependent probability. In this simulation, the crane is the crucial piece of equipment given that crane downtime can cause significant delays in the entire operation. This will also require the presence of a safety officer to inspect and provide clearance for its safe utilization during construction works. The flow of logic as illustrated in Figure 3 categorically entails that the equipment cannot operate until the safety officer clears it for operation.

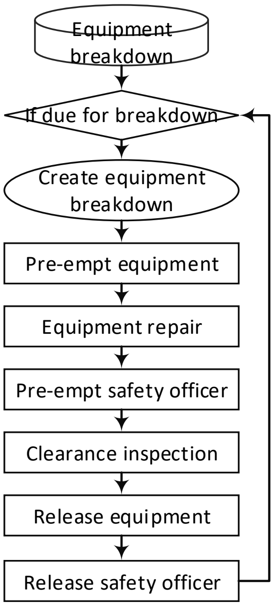

Figure 3. Conceptual model of an equipment breakdown.

3.4. Modeling Inputs and Outputs

The normal routine and the corresponding durations vary and depend on the nature of the construction project and the company to which the safety officer is assigned. In the present study, the assumptions made are listed in Table 2. This table contains the task durations in hours and their frequency per week.

The relevant outputs of the simulation are: (1) the total project duration when 1,227 meters of chainage is reached; (2) the utilization rate of the safety officer; and (3) the utilization rates of all the heavy equipment. All these outputs are stochastic since incidents are events that are modeled probabilistically.

Table 2. Model inputs for the duties of a safety officer.

Task	Duration (hours)	Frequency (weekly)
Safety Meeting	1	1
Safety Planning	2	1
Reporting	1	6
Safety Training	2	1
Programmed Inspections	4	*Varied*
Inspecting After Minor Incidents	1	*Probabilistic**
Inspecting After Major Incidents	6	*Probabilistic**
Checking Breakdown Equipment	0.25	Exponential (mean=192 hrs)

*The corresponding priori probabilities of minor incidents are listed in Table 1.

4. Discussion of Results

4.1. Effect of Programmed Inspections Frequency on Utilization Rate

Figure 4 illustrates the response plot of the frequency of programmed inspections versus the utilization rate of the safety officer. As the number of inspections increases, the utilization rate of the officer decreases up to a certain point. In this case, the lowest utilization rate was reached when the safety officer was assigned to conduct four programmed inspections per week, and when the inspection frequency is greater than four per week, the utilization rate increases.

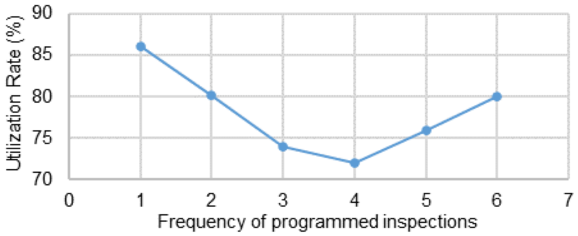

Figure 4. Impact of weekly programmed inspection frequency on the utilization rate of the safety officer.

The main reason for the decreasing utilization rate at the start is due to the assumed relationship of the frequency to the probability of occurrence of unprogrammed incidents. On the downward trend of the chart, increasing the number of site inspections means that the officer is going to spend more time doing programmed site inspections. However, this decreasing trend indicates that increasing the programmed site inspection would result in a reduction in the time spent on unprogrammed inspections. From the point of reversal, further increasing the frequency of programmed inspections does not prevent incidents from happening. Therefore, the safety officer utilization rate increase is a result of the time spent on both programmed and unprogrammed inspections on top of their fixed routine tasks.

4.2. Effect of Programmed Inspection Frequency on Project Schedule

Regarding the assumed priori probabilities of incidents requiring unprogrammed inspections as described in Section 3.2.3, as the number of programmed inspections increases, the probability of incident occurrence will decrease, which results in fewer incidents. Since the occurrence of both major and minor incidents can cause delays during operations, the reduced incident rates further result in faster project completion. For instance, if any major incidents happen, all work onsite will be stopped for 6 hours until all reports have been submitted and permission is granted to resume the work. Moreover, if any minor incidents happen, the safety officer will handle them without stopping the work onsite. However, as the number of programmed inspections increases, the utilization rate of the safety officer may also increase, which may cause other entities to wait for the safety officer and pause production leading to an increase in the project time. For these reasons, the link between the frequency of programmed inspections and project duration is established.

By simulating the operation in *Simphony*, the trend of the project duration as a function of the frequency of programmed inspections is achieved as seen in Figure 5. This trend indicates that the project duration is inversely related to the frequency of programmed inspections. In other words, more frequent programmed inspections lead to shorter project duration based on the simulation report. Therefore, the prediction of project duration is affected by the number of delay-inducing incidents.

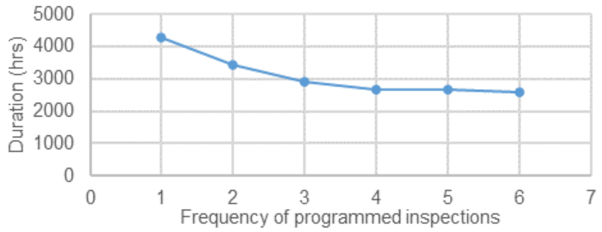

Figure 5. Impact of weekly programmed inspection frequency on the overall project duration.

In terms of quantification, the simulation model showcases the capability of quantifying the reduction in the number of days as a function of the frequency of weekly inspections. As illustrated in Figure 5, the project duration decreases by approximately 0.7 years by increasing the programmed inspections from 1 to 4 times per week. Moreover, the total project duration converges to 1 year regardless of the increase in programmed inspections beyond 4 times per week. Quantifying the total project duration in terms of the number of inspections and priori probabilities of incidents occurring can support decision-making by project managers when planning safety inspection work to optimize the production rate.

5. Conclusion

This study explored the relationship between the frequency of programmed inspections and the utilization rate of a safety officer and the overall duration of the construction operation. This finding is a crucial step in understanding the importance of site inspections in terms of schedule delay. Moreover, it also highlights the possibilities of quantifying the utilization rate of safety officers to schedule their time for programmed inspections. Therefore, by analyzing the utilization rate of the safety officer, it has been shown that the safety officer's workload can be better managed to reinforce the safety values among the site crew as prescribed by their organization. As expected, the utilization rate of the safety officer decreased to a certain point due to decreased incidents resulting from increased weekly safety inspections; however, beyond that certain point, the utilization rate increased, also as expected. Moreover, the programmed inspection frequency was found to impact the overall duration of the operation.

The primary limitation of the present study is the assumed relationship between the frequency of programmed inspections and priori probabilities for having no incidents as described in Section 3.2.3. The occurrence of an incident is not solely influenced by the frequency of programmed inspections (i.e., incident occurrence can be influenced by crew behavior, safety training, work experience, etc.) and the quantified probabilities require actual data that would support or update the documented assumptions. The limitation also extends to the model not being tested yet in an actual case study. Moreover, the routine of the safety officer and the breakdown of tasks can be detailed where the durations of such tasks can be in the form of a distribution rather than a deterministic form as illustrated in the present study.

The recommended steps for future study are (1) examining the influencing factors that may affect the priori probabilities of incidents and their severity; (2) incorporating actual historical data as inputs to the model; and (3) validation of the model through multiple case studies of a heavy construction operation where the safety officer is actively involved.

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