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# A Simulation-Based Framework for Concurrent Safety and Productivity Improvement in Construction Projects

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## ABSTRACT

**Purpose:** Safety and productivity are key concerns in the construction projects. While safety looks to the construction workers need to work in a safe environment, productivity affects the project’s profitability and is of a paramount importance from the project owner’s view. The different perspective to the safety and productivity from these two major players in construction projects poses a potential for the conflict between the two. This problem can be fundamentally addressed by methods concurrently improving project safety and productivity. **Methodology:** To this aim, a discrete event simulation (DES) based framework applicable was proposed for complex and hazardous operations. The utility of the framework was tested using a case study of an eight-story residential building in the northeast part of Tehran, Iran. The excavation and stabilization operation was identified as the most hazardous and critical operation in this case. The framework could improve safety and productivity of this operation, respectively, by 38% and 4%. **Findings:** This framework is a complement to the conventional construction project safety and productivity planning methods. Its main application is in complex and hazardous construction operations. **Originality:** For the first time, a comprehensive framework for concurrently improving safety and productivity of an entire project was proposed in this research. DES was used as the main modeling tool in the framework to provide an ex-ante evaluation foundation applicable to a wide range of construction projects.

**Keywords**: Construction safety; Safety improvement; Productivity improvement; Simulation

## 1 Introduction

One of the most hazardous industries in the world is the construction industry (Fang et al. 2015). Even though construction contributes to 7% of the world's workforce, 30-40% of work-related fatalities are linked to this industry (Sunindijo and Zou, 2011). Since the introduction of the *Occupational Safety and Health Act* in 1970, the American construction industry has faced a noticeable decline in the fatality rate (NSC 2006). The fatality and injury rates in construction are five times higher than the overall average, which implies high attention on the construction safety (BLS 2016).

Many research efforts focus on various aspects of safety improvement to respond to this essential need in the construction industry in different parts of the world. For example, Kines et al. (2010) conducted survey-based research and showed that daily verbal communication of safety concerns by construction site supervisors considerably improves the level of safety in the construction projects in Denmark. Zhou et al. (2011) found safety regulations, safety training, and safety promotions as the most effective factors stimulating safety improvement in the construction industry of China. Sunindijo (2015) identified different external factors detrimental to safety performance in small construction companies in New South Wales, Australia. They suggested the government, clients, and large organizations supports for safety performance improvement in these companies. Chan et al. (2016) identified 14 strategies for improving the safety performance of migrant workers working in Asian countries. Chen et al. (2017) found that organizational safety performance is improved by promoting positive safety climate and developing training programs on the employees' psychological health in Ontario, Canada. Construction safety improvement is the main incentive of the annual campaign organized across the United States to increase workers awareness of fall hazards and reduce the number of fall incidents (Bunting et al. 2017).

Another concern in the construction industry is project productivity. The term "productivity" is generally used to express comparisons between a system’s output and input (Yi and Chan 2014). Improving productivity and reducing costs in construction projects can significantly increase the projects’ profitability for owners, and contribute to a better economic condition overall (Vogl and Abdel-Wahab 2014). Due to the critical importance of productivity, it is frequently addressed in construction research (Yi and PC Chan 2014). Previous studies showed that construction operations contribute to 30-50% of a project's total costs (Hanna 2001; Harmon and Cole 2006; Kazaz et al. 2008). Many construction professionals (e.g., Kellogg et al. 1981; Rojas and Aramvareekul 2003; Thomas 2015) believe that improving productivity can reduce more than 15% of the construction costs.

Meanwhile, the link between construction safety and productivity, as two central concerns, is the topic of many research efforts. The core finding of most these research efforts is that job safety creates the better work environment, reduces cost-increasing and productivity-killing project hazards, and increases workers' satisfaction. Nevertheless, an argument is that job health and safety advocates have conducted most of these research efforts in favor of workers safety (Lamm et al. 2007). High productive business activity under shadows of serious occupational health and safety issues in China (Zhang et al. 2010) and early days of industrial development in Europe and North America (Walker 2015) are examples in favor of this argument. These achievements might explain why in the highly competitive construction industry cutting indirect and overhead costs and compressing activity timelines are a trend followed by many owners. Removing safety equipment from a project's purchase list, crossing out safety activities on a project's schedule, overlapping activities, and increasing the job-site congestion are among approaches pursued. In such cases, the productivity concerns of construction project owners and managers contradict the workers' desire for safety. Developing construction project planning methods which observe both sides' concerns and concurrently improve safety and productivity of construction projects can alleviate this contradiction.

To this end, in this study a planning framework which uses discrete event simulation (DES) to capture the operational details of construction projects and concurrently improve their safety and productivity was proposed. In this framework, construction project managers can assess the outputs of alternative construction operation scenarios before starting a project. They can choose scenarios that best address safety and productivity concerns. Following, first, the concurrent safety and productivity improvement concern in construction projects is discussed. Then, different aspects of the proposed framework are explained. The steps taken to evaluate the framework in a real construction project case of a multi-storey residential building in north-east of Tehran, Iran, is then presented. Finally, the research results and outcomes are discussed and concluded.

## 2 Concurrent Safety and Productivity Improvement

The idea of concurrently improving safety and productivity in construction projects was first proposed and discussed by Mitropoulos and Namboodiri (2009 and 2010), with a focus on safety and productivity measurement in construction activities. In their proposed model, they presented a new method, called task demand assessment (TDA). TDA is a cognitive method, inspired by cube model calculation method for ergonomic demands (Kadefors 1997). It is based on the fact that a task's specification and its environment have direct impacts on the potential hazards (Mitropoulos and Namboodiri 2010). It is used for evaluating the safety level of different construction activity scenarios by tracing its operational aspects, e.g., workers' distance from hazardous equipment or unprotected sides and edges. Mitropoulos and Namboodiri (2009 and 2010) used the TDA method for safety risk calculation through analysis of direct observation and videotape of the construction activities. In their approach productivity rate is estimated by the operation contractor and/or operation experts in a separate manner. Use of observation and videotape in this approach, however, cannot provide safety measures of different work scenarios in advance and before the construction activity begins.

In another study, Marzouk and Ali (2013) used the agent-based simulation (ABS) technique for improving the productivity of piling operations while addressing safety issues on the job. Interestingly, this study's concept for safety evaluation shares common ground with the TDA method developed by Mitropoulos and Namboodiri (2010). Again here, the operational situations with high risk of safety issues are recognized and accounted for evaluating safety level of different work scenarios. Marzouk and Ali (2013) used ABS for estimating the productivity of different work scenarios with adding safety concerns in their piling construction case. In this approach, the ABS model outputs productivity rates of available scenarios while safety requirements are fulfilled in each of them. Concurrent safety and productivity improvement can benefit construction project owners the most if it is applicable in advance and before a construction project begins. Use of ABS by Marzouk and Ali (2013), as a simulation-based technique, provides this capability. However, since the method applied by Mitropoulos and Namboodiri (2010) uses direct observation and videotape of construction operations, it does not allow in advance development of safety and productivity improvement plans. Mitropoulos and Namboodiri (2010) also claimed that their proposed method enables simulation for modeling construction activities, analyzing productivity and safety risks. However, they did not indicate the type of simulation technique to be used, and the method simulation model could be applied for evaluating safety and productivity.

Most previously developed simulation-based models in the construction industry capture operational details for productivity improvement and do not deal with safety improvement (Goh and Ali 2016). The most safety evaluation methods in the construction industry are based on project expert judgment rather than operational details. Some example are behavioural based safety method (Cooper 2009; Li et al. 2015), field level risk assessment (Hudson and Smith

1998; Becker 2015; Newby and Madley 2015), analytic hierarchy process (Wang et al. 2012; Taylana et al. 2014), fuzzy logic (Zhongguang and Ruijun 2012; Tang et al. 2014), and TOPSIS (Basahel and Taylan 2016). In this perspective TDA method, which uses operational details for evaluating the safety level, is a proper choice for being integrated with the simulation-based productivity improvement methods.

Applicability of concurrent safety and productivity improvement method to a wide range of construction operations is also an important capacity for construction managers and owners. Although Marzouk and Ali (2013) used agent-based simulation in their piling operation case, they did not discuss the expandability of their proposed approach to other construction operations. A disadvantage of using ABS for modeling construction operations is its limited applications in the construction industry. Many practitioners in the construction industry are not familiar with ABS. Compared to the ABS technique, DES is widely used and known in the construction industry with producing equally valid model outputs being more simply validated (Majid et al. 2009). Some of the DES application examples are earthmoving (e.g., Farid and Koning 1994), pipeline construction (e.g., Luo and Najafi 2007), steel construction (e.g., Alvanchi et al. 2011), excavation operation (e.g., Marzouk et al. 2010), tunneling (e.g., Al-Bataineh et al. 2012) and road construction operations (e.g., Mostafavi et al. 2012). From this perspective, DES models are more easily applicable to a variety of construction projects.

It should also be considered that safety and productivity are not necessarily measured in the same manner. For example, while the safety of an earthmoving operation can be measured as a chance of worker's collision with an excavator, productivity can be measured as volume of soil excavated in cubic meters. However, a single value which represents overall safety and productivity level for each scenario is required to compare different work scenarios.

Furthermore, it is important that safety and productivity of an entire project, not separated activities, are improved in a construction project. Nevertheless, past research efforts have focused on improving safety and productivity of a limited number of activities rather an entire project. The proposed framework in this research aims to address the above-mentioned concerns regarding the concurrent safety and productivity improvement.

## 3 Proposed Framework

Figure 1 presents six main parts of the proposed framework including, 1) identifying critical, i.e., complex and hazardous, operations within the project, 2) recognizing operational details of alternative scenarios for the critical operations, 3) preparing safety evaluation method, 4) preparing productivity evaluation method, 5) developing the DES model with capability of concurrent safety and productivity evaluation, and 6) concurrently evaluating and comparing the safety and productivity of different work scenarios. Following, each part is discussed in more details.

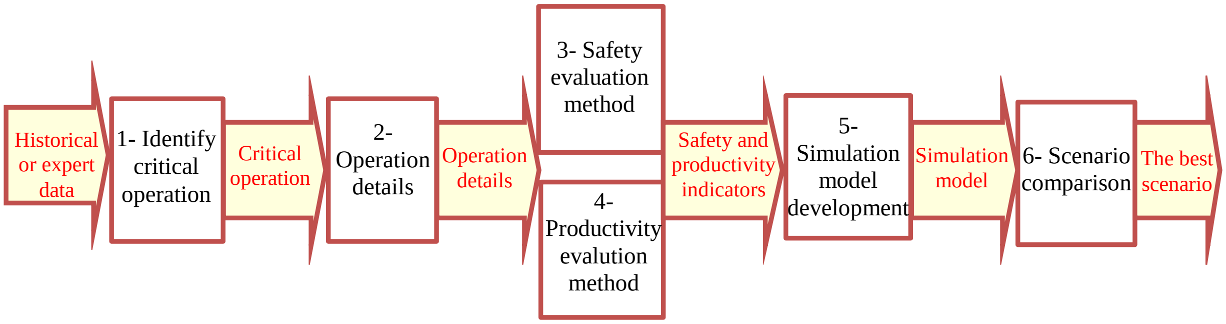


Figure 1. Different parts of the framework

### 3.1 Identifying Critical Operations

In the first part of the proposed framework, complex and hazardous or critical operations, e.g., operations with interconnected activities and high risks of hazards involved, require to be identified among a variety of operations performed in the construction project. A team consists of the project manager, HSE team members, project planners, and other key project participants familiar with safety and productivity aspects of the project forms for identifying critical operations. Identified critical operations are the main focus of applying concurrent safety and productivity evaluation and improvement method. Safety and productivity improvement of other project operations is followed through regular procedures set by the project managers and owners.

### 3.2 Operation Details

Developing a DES model of operation requires a good understanding of the base operation and available alternative scenarios. Activity sequences, required and available resources, operation rates of resources, activity durations, job-site layout, work volume, working hours, project constraints, and safety policy are typical data collected. Identifying important operation hazards is also essential. It should be considered that operation hazards are dependent on both operation specifications and the specific conditions of the work environment. For example, falling hazard is a main concern during steel installation operations in windy regions while workers' dehydration causes more concern in hot regions. Project specifications usually are collected from current or past similar project documents, project managers and experts, or even by direct project observation and field survey.

### 3.3 Safety Evaluation Method

In the proposed framework, modified TDA calculation formulas are used for safety evaluation. A detailed explanation of the original TDA method is set out in Mitropoulos and Namboodiri (2010). Here, a brief explanation of the modified TDA method is provided. In the TDA method, a three-level task demand rating of 1, 3 and 9 represent low, moderate and high chance of hazards in different conditions of influential factors, respectively. At every given time, the task demand level (TDL) of a hazard is calculable as the product of the task demand rate (TDR) of the effective hazard’s influential factors at the time (Equation 1). For example, with a TDR of 3 for the first effective influential factor, and a TDR of 6 for the second effective influential factor at a given time, the hazard’s TDL becomes 3 x 6 = 18 for that time. To calculate the overall hazard’s TDL in the modified TDA method, the area under TDL curve over time is calculated during the operation’s duration (Equation 2). For instance, if for 30 hours of an operation’s duration the TDL of a hazard is 2, for 60 hours it is 3, and for 10 hours it is 18, the overall relative task demand value (TDV) of the operation is $30 \times 2 + 60 \times 3 + 10 \times 18 = 420$ hours. The TDV here is represented by the equivalent duration of operation’s exposure to the hazard.

*A hazard's TDL at time t =*

$$\prod_{k=1}^{Number\ of\ \ influential\ factors} TDR\ of\ influential\ factor\ k\ at\ time\ t \tag{1}$$

*TDV of an operation scenario=*

$$\int_0^{Operation\ scenario's\ duration} Hazard's\ TDL\ at\ time\ t \times dt \tag{2}$$

In the original TDA method, the TDVs are calculated separately for each hazard identified for an operation. The TDV comparison is conducted between different operation scenarios with several possible hazards identified in each, however, not between every operation hazards. This comparison is simply made by calculating a single value of TDV representative for each operation scenario which requires TDV of different hazards to be combined. To combine TDVs, construction managers require to estimate the relational severity weight of each hazard and calculate the overall *initial safety value* of each operation scenario by using those weights (Equations 3). Based on construction manager's discretion, relational severity weights can be determined from past hazard records or through variety of methods such as analytic hierarchy process, Delphi, weighted least squares methods (Meng et al. 2008), multiple objective programming (Lotfi and Fallahnejad 2010) and data envelopment analysis (Farrell 1957).

$$Initial\ safety\ value = \frac{\sum_{j=1}^{Total\ number\ of\ hazards} TDV_j \times Hazard\ weight_j}{\sum_{j=1}^{Total\ number\ of\ hazards} Hazard\ weight_j} \tag{3}$$

During the scenario comparison process (Section 3.6), the scenario with the best-combined safety and productivity value is selected. It means safety value for each operation scenario needs to be comparable to its productivity value. Furthermore, since initial safety values represent relative risks assigned to each operation scenario, higher values represent higher risks and lower safety. The direction of values needs to change to the normal form where higher values represent more desirable safety conditions. A normalization method for the initial safety value calculated for each scenario is proposed to respond to these needs. To normalize the safety value of each operation scenario, first, a major safety improvement percentage is determined based on construction managers' past experiences and priorities (e.g., 40% or 50% safety improvement). Then, major safety improvement value is calculated by multiplying the major safety improvement percentage to the *average* of the initial safety values of different operation scenarios (Equation 4). Finally, in the Equation 5, *normalized safety value* of a scenario is calculated based on its *initial safety value*, the average of initial safety values of all scenarios and the major safety improvement value. The average of *initial safety values* is transferred to 50 on the normalized safety axis and the major safety improvement percentage is scaled to 50 normalized safety units. For example, if the calculated *initial safety values* for different scenarios of a steel construction operation are 12, 15 and 21; the average value becomes 16 representing 50 on the normalized safety axis. In case the major safety improvement percentage is 40%, the major hazard safety improvement value becomes 6.4. The normalized safety values of these scenarios, respectively, become 81.2, 53.8 and 10.9.

$$\textit{Major safety improvement value} = \textit{Major safety improvement\%} \times \textit{Average of initial safety values} \quad (4)$$

$$\textit{Normalized safety value of Scenario i} = 50 + 50 \times \frac{Average\ of\ initial\ safety\ values - Initial\ safety\ value\ of\ scenario\ i}{Major\ safety\ improvement\ value} \quad (5)$$

### 3.4 Productivity Evaluation Method

Depending on the construction project managers priorities different productivity measures, such as production rate, operation duration, operation cost, resource utilization, hours spent, and waiting time, are used for measuring construction operation productivity. For example, Chui et al. (2012) consider labour-hours for measuring the productivity of two building construction projects. Marzouk et al. (2010) consider time and cost for measuring the productivity micro-tunneling projects. It is important before the DES model development to decide about the productivity factors, so that the model can be adapted to calculate them.

A productivity normalization method is proposed here to prepare a comparison between different operation scenarios. In this normalization method, a desirable value, not simply achievable, is set to 100 for each productivity factor. A major productivity difference, e.g., a critical or non-easily reachable difference, is also set equal to 100 units on the normalized productivity measure. For example, project duration is the main productivity factor with the desired value of 10 weeks and the critical delay of 3 weeks. When the expected duration of available scenarios are estimated as 10.5, 11 and 12, the normalized duration of each scenario is, respectively, calculated as follows:

Normalized value of duration of 10.5 weeks = 100 + (10-10.5) / 3 *100 = 83.3

Normalized value of duration of 11 weeks = 100 + (10-11) / 3 *100 = 66.7

Normalized value of duration of 12 weeks = 100 + (10-12) / 3 *100 = 33.3

Since here shorter durations are more desirable, duration values participate in the normalization equation with the minus sign. When there are multiple productivity factors, relative weights of importance are set by construction project managers to combine different normalized productivity values and represent the productivity of each scenario by a single normalized productivity value.

### 3.5 Simulation Model Development

A DES model needs to be developed for the base, and alternative scenarios of all critical operations identified based on the operation details recognized. Detailed steps of DES model development are explained in DES textbooks (e.g., Banks et al. 2005; Choi and kang 2013). However, improvements made to the information technology in recent years have brought an emergence of user-friendly commercial DES programs such as AnyLogic, Arena, FlexSim and Promodel. Nowadays, practitioners with minimum knowledge about DES can use them to develop simulation models. Furthermore, there are many DES model examples developed for productivity evaluation of different types of construction operations and can help practitioners in their DES model development. For example DES models are developed for earthmoving (e.g., Farid and Koning 1994), pipeline construction (e.g., Luo and Najafi 2007), steel construction (e.g., Alvanchi et al. 2011), excavation operation (e.g., Marzouk et al. 2010), tunneling (e.g., Al-Bataineh et al. 2012) and road construction operations (e.g., Mostafavi et al. 2012). Safety equations also need to be embedded in each DES model; therefore, safety and productivity can be calculated in parallel to DES model runs.

### 3.6 Scenario Comparison

The ultimate outputs of an operation simulation model are normalized safety and productivity values. A scenario with the highest normalized safety and productivity values is selected as the best available scenario. However, it is not guaranteed to find a scenario with the highest safety and productivity values. The best operation scenario must be selected in a trade-off between the safety and productivity values achieved for different scenarios. Construction managers might have specific considerations about some safety or productivity factors. For example, they might be only interested in scenarios with a normalized safety value above average or scenarios with lower costs than a specific limit. It is suggested that the results achieved for safety and productivity are presented in a two-dimensional diagram. Here, the x-axis is normalized productivity values, and the y-axis is normalized safety values. It presents a visual view to the construction managers. Therefore, they can judge better between different alternatives based on their priorities.

# 4 Case Study

The framework was applied to a real case of an eight-story residential building project in northeast part of Tehran, Iran, to verify its utility. Main operations involved in the project were excavation and stabilization, foundation and structure installation, roof and wall construction, various finishing operations, and façade installation.

## 4.1.Excavation and Stabilization: A Critical Operation

Among different operations carried out in this project, excavation and stabilization operation was identified as the critical operation. In this operation, heavy construction equipment was working in a constricted space shared with construction workers. There was an elevated risk of laborers colliding with equipment during the operation.

## 4.2 Operation Details

The entire project is scheduled for 14 months, while the duration of excavation and stabilization operation is estimated for 3 weeks. The excavation area has 33.6 meters long and 13.8 meters wide with an existing noticeable slope at the ground level. The excavation operation was done for 7 meters below the ground level in three phases (Figure 2). The total excavation volume was estimated 2535 cubic meters. Due to the traffic constraints in the area; the excavated soil was hauled out of the job-site during the night time. As soon as the excavation of pit walls was complete in each phase, stabilization activities began. Stabilization activities included the installation of 86 stabilizing nails, using mesh and shotcrete on the excavated pit walls, and installing 10-meter piles at each corner of the excavated pit. Figure 3 shows basic activities followed in each phase of the excavation and stabilization operation. All durations were characterized by minimum, maximum and most likely parameters by project experts and estimated by triangular distribution. Table 1 presents the estimated durations of different activities.

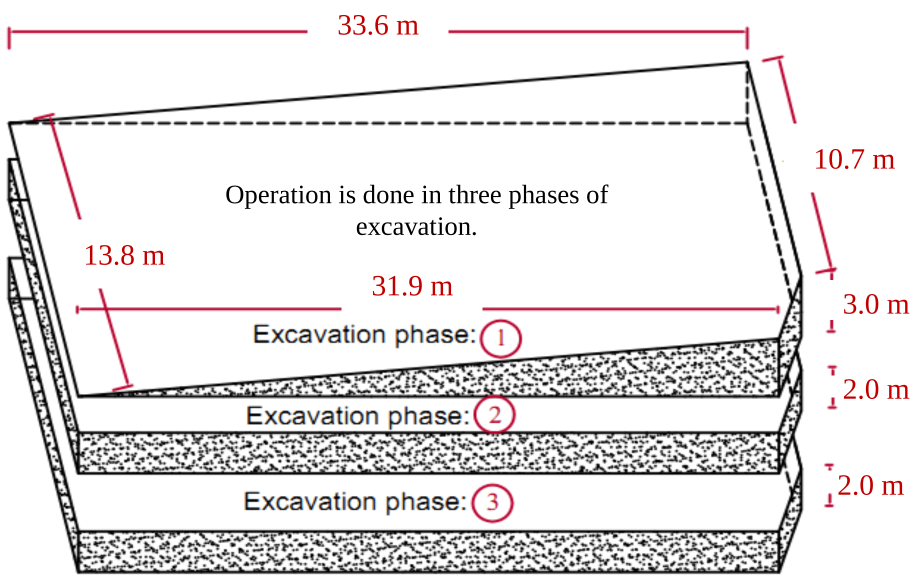


Figure 2. Schematic view of the job-site


Figure 3. Different activities done in each round of excavation and stabilization operation

Table 1. Duration estimated for different activities of excavation and stabilization operation

| | Task name | Time (min) | | |
|---|---|---|---|---|
| | | **Min** | **Max** | **Most Likely** |
| 1 | Drilling one cubic meter of well | 60 | 150 | 110 |
| 2 | 2-1-Destruction of one square meter of center region of excavation pit | 0.5 | 2 | 1 |
| | 2-2-Moving one nail to the side of excavation pit | 1 | 2 | 1.5 |
| 3 | 3-1-Loading bucket of excavation machine | 0.08 | 1 | 0.17 |
| | 3-2-Turning bucket of excavation machine | 0.07 | 0.25 | 0.10 |
| | 3-3-Dumping bucket of excavation machine | 0.08 | 0.12 | 0.1 |
| 4 | Smoothing and plummeting down 6 square meters around the excavation pit | 20 | 80 | 40 |
| 5 | Drilling the location of nails and install them | 48 | 60 | 53 |
| 6 | 6-1-Installing one base of one square meter | 2 | 10 | 4 |
| | 6-2-Installing one mesh(6 square meters) | 10 | 19 | 13 |
| 7 | 7-1-Shotcrete one square meters of walls | 2.5 | 3.5 | 3.0 |
| | 7-2-Injection cement slurry into hole of one nail | 0.05 | 0.10 | 0.07 |
| 8 | Installing the plate of each nail | 4 | 25 | 8 |
| 9 | Welding one pile | 40 | 100 | 50 |
| 10 | Installing one pile | 10 | 20 | 12 |
| 11 | Concreting piles | 45 | 55 | 50 |

In total, 7 alternative scenarios were assessed for the operation. Table 2 presents main specifications for each scenario.

Table 2. Alternative scenarios

| Scenario | New specification | Base specification | Comment |
|---|---|---|---|
| 1 | - | - | Base scenario |
| 2 | Using one excavator 210LC-7H (HYUNDAI) | Using one excavator 120LC-7H | Excavator capacity was not compatible with the project specification |
| 3 | Using two drill wagons | Using one drill wagon | The drill wagon needs approximately one hour for each nail. In fact, this activity is the bottleneck of operation and leads to increase labor idle time. |
| | Using one compressor with two outlets | Using one compressor with one outlet | |
| 4 | At the time of displacement nails, the excavator is turned off | At the time of displacement nails, the excavator is on | Implement rigorous safety management: In this scenario, the safety management is implemented with high attention. |
| | At the time of nail-plate installation, the excavator is turned off | At the time of nail-plate installation, the excavator is on | |
| 5 | Cumulative changes of scenario 2 and 4 | | |
| 6 | Cumulative changes of scenario 3 and 4 | | |
| 7 | Cumulative changes of scenario 2 and 3 | | |

### 4.3 Safety Evaluation Preparation

Three collision hazards between excavator and workers were identified during different parts of the operation by the project management team:

1. Collisions during moving the nails and excavating activities.
2. Collisions during smoothing the walls around the excavation pit and excavating the edge of the land.
3. Collisions during plate installation at the end of nails and excavating activities.

Since all hazards were collision incidents, they were equally weighted. Influential factors on the risk of each collision hazard and their rates (or TDRs) were determined in consultation with the project management team as presented in Table 3.

Table 3. Hazard influential factor assessment for excavation and stabilization operation

| **Hazard** | **Influential factors** | **Task demand rate** | | |
|---|---|---|---|---|
| | | **Low(1)** | **Moderate(3)** | **High(6)** |
| Hazard 1 | Distance between bucket and labor | Greater than 8m | Between 4 to 8m | Less than 4m |
| | Excavator condition | In digging | Turn less 60 degree | Turn greater 60 degree |
| | Workers movement | No movement | Forward movement | Backward movement |
| Hazard 2 | Distance between bucket and labor | Greater than 10m | Between 6 to 10m | Less than 6m |
| | Excavator condition | In digging | Turn less 60 degree | Turn greater 60 degree |
| Hazard 3 | Distance between bucket and labor | Greater than 10m | Between 6 to 10m | Less than 6m |
| | Excavator condition | In digging | Turn less 60 degree | Turn greater 60 degree |

## 4.4 Productivity Evaluation Preparation

The labor and equipment cost was the main factor used for the productivity evaluation. The daily rates of different laborers and equipment types were received from the project management team as presented in Table 4.

Table 4. Daily rates of different labors and equipment types

| | **Name** | **Daily cost($)** |
|---|---|---|
| 1 | Excavator, model 210LC-7H (Hyundai) with operator | 170 |
| 2 | Excavator, model 120LC-7H (Hyundai) with operator | 130 |
| 3 | Shotcrete machine T260 | 17 |
| 4 | Air Compressor Ingersoll-Rand 825 with two outputs | 115 |
| 5 | Air Compressor Ingersoll-Rand 825 with one output | 170 |
| 6 | Wagon drills | 115 |
| 7 | Grout injection equipment to nails (mixers pump, mixer plant, slurry creator) | 45 |
| 8 | Labour well digger | 30 |
| 9 | Labour | 15 |
| 10 | Wagon drills operator | 25 |
| 11 | Supervisor | 17 |

## 4.5 DES Model Development

Anylogic software was used for developing simulation models of different operation scenarios. Simulation models traced the distance between the excavator and workers throughout the job-site to calculate the operation's safety value. Operation productivity was calculated for each scenario by capturing the daily rates of construction workers and equipment. Visual features were added to the models to allow satisfactory verification. Face validity tests were done by involving the project manager and the site superintendent in the model development and model calibration processes. Figure 4 presents a view of the base simulation model developed for original operation or Scenario 1 in Anylogic. The model follows a similar activity sequence to the one previously explained for the operation. Pile, piling soil, excavation soil, side wall sections and nail were defined in the model as entity elements. Welders, labourers, drill wagon station, compressor, excavator and cement injection machine are the main resources in the model. DES models of other operation scenarios, i.e., Scenario 2 to Scenario 7, were developed by adjusting the base model to the specific conditions of each scenario.

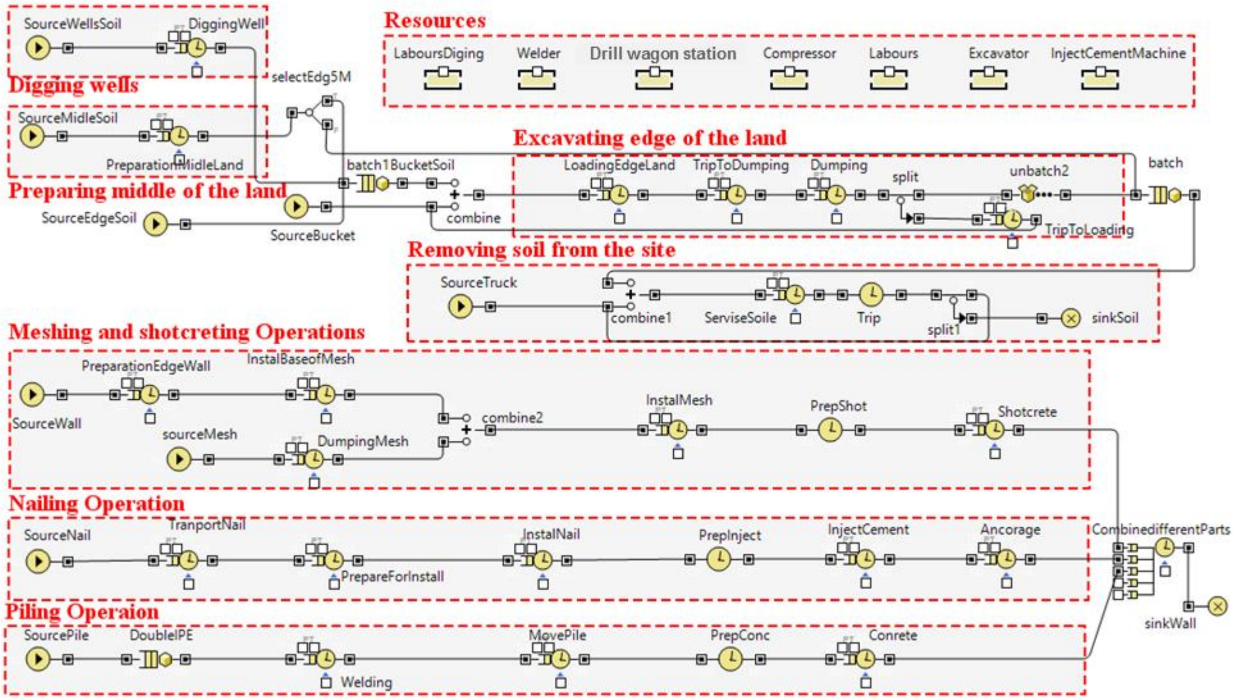


Figure 4. A view of the base model developed in Anylogic

### 4.6 Simulation Results

With the standard deviation of 4.5 hours achieved for the operation duration of the base scenario, the confidence level of 95% and accepted error level of 2 hours, the minimum required number of replications became 20 using Banks et al. (2005, pp. 348-349) equation. Aggregated results of 20 simulation runs were used for the safety and productivity comparison between different alternative scenarios. The major safety improvement was 30% and the major productivity difference was 15% by the project management team as discussed in Sections 3.3 and 3.4. Table 5 presents the summary of initial and normalized safety and productivity values calculated for each operating scenario. In this case study, construction project managers opted equal relational weights for safety and productivity. Therefore, combined safety and productivity values were simply calculated by averaging normalized values achieved for safety and productivity. Scenario 6 was identified as the scenario with the highest combined value.

Table 5. Concurrent safety and productivity results calculated for excavation and stabilization operation

| | **Safety** | | | **Productivity** | | | **Combined Safety and productivity Value** |
|---|---|---|---|---|---|---|---|
| | **TDA Value (hour)** | **Normalization Parameters** | **Normalized** | **Labor and Equipment Cost ($)** | **Normalization Parameters** | **Normalized** | |
| **Base** | 234 | Average =225 h<br>Major Difference%= 30%<br>Major Difference Value = 68 h | 43.9 | 9,573 | Average =9841 $<br>Major Difference%= 15%<br>Major Difference Value = 2952 $ | 53.2 | 48.5 |
| **Scenario 2** | 301 | | 6.7 | 10,929 | | 11.4 | 9.1 |
| **Scenario 3** | 232 | | 45.0 | 84,24 | | 88.6 | 66.8 |
| **Scenario 4** | 156 | | 87.2 | 9,573 | | 53.2 | 70.2 |
| **Scenario 5** | 209 | | 57.7 | 10,420 | | 27.1 | 42.4 |
| **Scenario 6** | 145 | | 93.3 | 9,168 | | 65.7 | 79.5 |
| **Scenario 7** | 298 | | 8.9 | 10,800 | | 15.4 | 12.1 |

## 4.7 Result Analysis

Different scenarios are presented on a two-dimensional diagram (Figure 5) to more easily analyze results achieved. Visual comparison of different scenarios presents that scenarios 1, 2, 4, 5 and 7 are inferior in both safety and productivity values when compared to scenario 6. Therefore, no matter what weights are set for safety and productivity, these scenarios result in lower combined safety and productivity values compared to Scenario 6 and were excluded from the final comparison. Scenario 6, with a normalized safety value of 93.3 and productivity value of 65.7, has the highest normalized safety value, and Scenario 3, with a normalized safety value of 45 and productivity value of 88.6, has the highest normalized productivity value. Interestingly, both these scenarios have higher safety and productivity values as compared to the base scenario (Scenario 1). In Scenario 3 safety is improved by 0.8% and productivity is improved by 12% and in Scenario 6 safety is improved by 38% and productivity is improved by 4%.

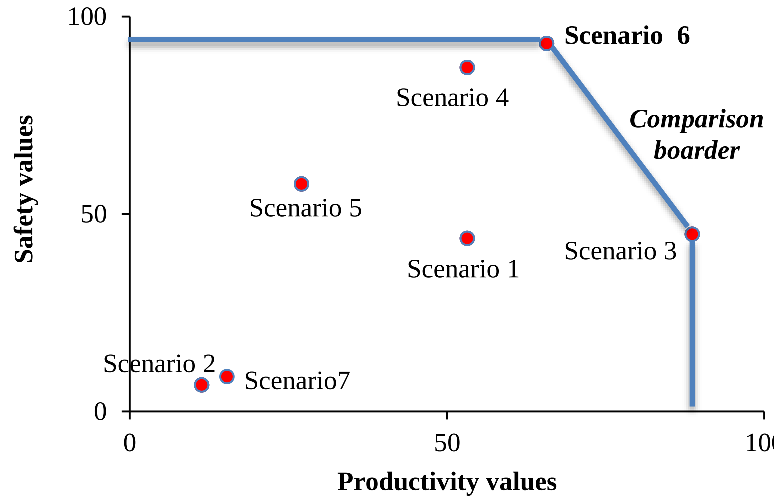


Figure 5. Normalized results of different scenarios from simulation models

In this project, the project manager considered equal weights for safety and productivity, the combined safety and productivity values of operation scenarios were calculated by averaging normalized safety and productivity values. The combined safety and productivity values became 66.8 for Scenario 3 and 79.5 for Scenario 6. Therefore, Scenario 6 was selected as the best scenario for the excavation and stabilization operation. However, if construction management team selects higher weights than 68% for the safety, Scenario 3 results in a higher combined safety and productivity value.

## 5 Summary and Conclusions

In this study, the existing contradiction between safety and productivity in construction projects was discussed. Concurrent safety and productivity improvement was identified as a viable solution to this contradiction. Few research efforts attempted to address this desire were reviewed and the shortfalls found were responded in the proposed DES-based framework. This framework complements the conventional construction project safety and productivity planning methods for improving critical operations with complexity and hazardous activities involved. The framework was successfully applied to a real construction project of an eight-story residential building project in the northeast of Tehran, Iran. The excavation and stabilization operation was identified as the critical operation in the case, and its safety and productivity were improved using the proposed framework.

The proposed framework contributes to the construction project improvement in multiple directions. It provides a step by step approach to be followed by construction project managers to improve safety and productivity of an entire project, rather than single or limited activities, considered in the past research efforts. The proposed DES-based framework is capable of developing ex-ante plans for safety and productivity improvement, applicable to a wide range of construction projects. The normalization method introduced in this framework suggests a calculation foundation for comparing safety and productivity and selecting the best construction operation scenarios based on their standings.

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