5th International/11th Construction Specialty Conference
5e International/11e Conférence spécialisée sur la construction

Vancouver, British Columbia
June 8 to June 10, 2015 / *8 juin au 10 juin 2015*

A SIMULATION FRAMEWORK FOR EX-ANTE ANALYSIS OF SAFETY AND PRODUCTIVITY IN CONSTRUCTION PROJECTS

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Abstract: Safety hazards are one of the major challenges facing construction industry across the globe. Despite a growing literature on assessment of construction safety, the majority of the existing studies are descriptive in nature, do not capture the specific conditions of construction operations and provide one-size-fits-all strategies for enhancing the safety of construction projects. On the other hand, productivity improvement is also a main concern in construction projects. However, the research effort addressing both safety and productivity improvement concerns is still missed in the construction industry. Among different tools used for construction project planning and productivity improvement, discrete event simulation is a well-known tool which has been widely used for analyzing and improving complex construction operations. In this research, for the first time, we are proposing a simulation based framework which concurrently follows safety and productivity improvement in construction projects.

1 INTRODUCTION

Job safety and productivity improvement are main interests in many construction projects. There is a growing literature in construction industry for enhancing safety in projects (e.g., Jannadi and Almishari 2003, Seo and Choi 2008, Zhou et al. 2011, Hinze et al. 2013, Votano and Sunindijo 2014). Improving productivity of construction projects has also been a big concern for many scholars (e.g., Maloney 1983, Arditi 1985, Roseefeld et al. 1992, Han et al. 2008, Zhai et al. 2009, Gouett et al. 2011, Borg and Song 2014). Despite the large number of research efforts done for enhancing safety and productivity in construction projects, construction industry is still missing the research efforts addressing simultaneous improvement of the both aspects. The need for this type of research efforts is more felt when we see mutual impacts that safety and productivity can have on each other in construction jobsites. For example the chance of job hazard is increased when improvement in work productivity amplifies jobsite congestion. Cumbersome safety systems, on the other hand, restrain work productivity and increase the costs of construction jobs. As a matter of fact, there is a big resistance from many construction managers to acquiesce to the safety regulation and enforce safety codes in the construction sites as they see it a non-productive and expensive part of the job and assume it a break on the work progress; this is especially the case in developing countries where construction jobsites are not frequently inspected by safety officers. Increased number of hazards and decreased productivity in construction jobsites are outcomes of this single-dimensional view to the work safety and productivity.

Among the different tools used for improving construction projects productivity, as a result of its capabilities to capture operation details, discrete event simulation (DES) has been widely used in the construction industry. DES capability for modeling complex construction operations has been proven by applying it in a variety of construction operations such as earthmoving (e.g., Farid and Koning 1994), lifting (e.g., Nam et al. 2002), piling (e.g., Zayed and Halpin 2004), pipeline construction (e.g., Lou and Najafi 2007), excavation (e.g., Marzouk et al. 2010) and road construction operations (e.g., Mostafavi et al. 2012). In this research we have introduced a new framework which uses capabilities of DES for modeling construction operations and has exploited it to concurrently model and evaluates safety and productivity levels of different operation scenarios. The framework enables construction project managers to select a scenario which fulfills safety and productivity concerns in the best way. Proposed framework has been tested by modeling a fabricated example of roof tile installation operation; safety and productivity levels of six different operation scenarios have been evaluated and compared in this example and the most suitable scenario has been identified.

2 SAFETY EVALUATION OF CONSTRUCTION OPERATIONS

Safety enhancement is not possible without obtaining a robust safety evaluation method which points the improvable parts of the job. Though, depending on the time and the scope of evaluation, safety evaluation itself can be done in different directions. After a review of safety evaluation research efforts done for construction projects, we identified four main directions for them.

1. Safety performance evaluation: These research efforts are focused on defining safety performance indicators using different project safety outcomes such as the number of accidents, the number of first aids and medical aids, the number of injuries and the time lost. Project safety improvement in this type of research efforts is sought by trending and analyzing values of safety performance indicators.

2. Safety system evaluation: This type of safety evaluation follows a holistic view to the safety, similar approach safety standards such as OHSAS18001, ILO-OSH 2001 and Z1000 pursue. Safety system evaluations or audits ,in this point of view to safety evolution ,is done by direct inspection of different parts of the company to check the compliance of different parts of the organization to the safety procedures, codes and regulations. (e.g., Griffith 2011, Alvanchi and Kanerva 2012).

3. Safety evaluation of job site condition: In these research efforts the safety condition of the job site and its relation to specific job hazards are evaluated. (e.g. Huang and Hinze 2003. Sacks et al. 2012)

4. Project safety risk assessment: Project safety risk assessment is a widely used safety planning method in construction projects. In this method likelihood and severity of possible hazards (or hazard potentials) are estimated based on the project condition. Proper responses are suggested to prevent, control, or transfer risk of hazards during the course of the project. (e.g., Jannadi and Almishari 2003, Mitropoulos and Namboodiri 2010, Lee et al. 2012)

Among these four directions, in the first two directions researchers have based their evaluation methods on the implementation or construction phase of the project and use implementation records for safety evaluation; these approaches pursue a passive perspective to the safety improvement, i.e., improve wherever deficiency has occurred. In the third direction researchers follow a general view to the jobsite safety condition rather than evaluating and improving a specific safety project. Direction four refers to the safety evaluation methods done for a project during the planning phase. Therefore, in terms of safety evaluation method, our ex-ante approach to the safety hazards follows this direction of safety evaluation.

Accuracy in estimation of hazard potentials is a major concern in the research efforts done for safety planning. For example, Jannadi and Almishari in 2003 developed a computerized safety assessment program which bases its estimation on the historical data collected for injuries occurred in different construction activities. This research, however, disregards dynamic nature of construction jobsites, i.e., result of historical data collected from different construction sites, with their specific work conditions, are not necessarily applied to another construction project with its unique work condition; the safety level estimated in this research contains a level of bias depending on the variation of the work condition. In their proposed model, Mitropoulos and Namboodiri (2010), have introduced a new model called task demand assessment (TDA) for safety evaluation of construction operations. In this model they trace construction operation work steps using videotaping, measure the changes happening in safety influential factors over time, and finally calculate the safety hazard potentials. They have proposed a three level rating of 1, 3 and 9 to respectively represent low, moderate and high impact of influential factors on the chance of a hazard occurrence. Multiplication of values of influential factors at each step of the job proportionally represents the chance of the hazard. In this research we have adopted TDA approach for safety evaluation; the way which has been incorporated in the proposed framework is discussed in 4.

3 PRODUCTIVITY EVALUATION OF CONSTRUCTION OPERATIONS

When it comes to improvement, using a proper productivity evaluation method is quite essential. It is impossible to identify a project's improvement without a suitable evaluation method. During recent decade many research efforts done in construction industry for improving productivity evaluation methods (e.g., Chao and Skibniewski 1994, Fayek and Oduba 2005, Gong and Caldas 2010, Ranaweera et al. 2013). Most prevalent evaluation methods, however, are critical path methods (CPM) and earn value management (EVM) (e.g., Tavakoli and Riachi 1990, McConnell 1985). Both methods base their measurement on a project's direct time and cost outcome. For evaluating productivity of construction operation, however, in this research we only use cost as the main productivity measurement factor. Here again, our proposed productivity evaluation and improvement method is used at the planning phase.

4 SAFETY – PRODUCTIVITY EVALUATION FRAMEWORK

The proposed framework in this research helps decision makers to concurrently evaluate safety and productivity levels of a construction project and base their decisions on the both aspects of the planning stage of a project. DES is the main modeling tool used in the framework. The framework consists of four main parts as demonstrated in figure 1. More explanations on each part of the framework come at the rest of the section.

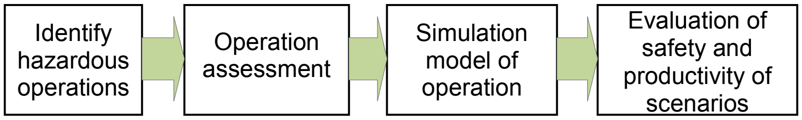


Figure 1. Different parts of the framework

4.1 Identify hazardous operations

Although in recent years simulation software packages have been improved a lot and development of simulation models has become much more easier for model developers, but still development of simulation models requires more efforts compared to traditional planning tools such as CPM or EVM; we need to make sure that we are going to do the simulation modeling for the operations that are in our priorities for safety improvement. In fact, there might be operations which are not considered as hazardous operations, based on the organization past experiences. So, the first part of the framework is to identify most hazardous operations within the project. This can be done by a team of project manager, HSE team members, project planners and any other key project participant at the project manager's discretion (namely project team) via review of past records, jobsite condition and the project's priorities.

4.2 Operation assessment

Every operation which is going to be simulated needs to be analyzed in two main aspects including 1) alternative scenarios and 2) possible hazards and influential factors.

4.2.1 Alternative operation scenarios

Alternative operation scenarios are formed by deviations in activities and/ or resources. These deviations can cause change in the operation's safety and productivity levels for different scenarios. In fact, in many cases (e.g., Lamptey 2010, Namboodiri 2010, Dikmen, 2012, Liu, 2005) one of the main concerns construction managers are dealing with during the planning phase is to find scenarios with the most suitable combination of safety and productivity levels. So, simulation of construction operations, which is the main approach for evaluating safety and productivity levels of hazardous operations in this research, is basically the case if there is more than one alternative scenario for an operation. To be able to develop simulation models of construction operation scenarios, orders and durations of activities done in an operation as well as the number and types of resources required should be estimated. These estimations are usually based on past records and project expert judgement.

4.2.2 Possible hazards and influential factors assessment

Possible operation hazards as well as influential factors affecting those hazards should be recognized and quantified to be able to incorporate them in the simulation model. First, we need to assign relative weights to different hazards; this relative should be assigned by project team considering past hazard experiences. Then, we need to measure the impact of changes in values of influential factors on hazard potential. The quantification process itself can be a challenging process; moving from one company to the other or even from one project to the other within a company can change the extent of influential factor impact on hazards. It should be considered that organizational and environmental factors, such as workers skill, climate condition, geographical condition, safety equipment used and past experiences, play significant roles in hazards and influential factors quantification (Mitropoulos et al. 2009). For example working in a windy region might cause more concern for the height falling hazard during steel installation operation while working in a hot region might create more concern for workers dewatering threat during the job. In fact, many safety quantification data collected for a project operation are only valid for that specific project; a mechanism through which safety measurement data is collected and validated for a project is required.

At the first step of influential factor assessment it is suggested that a list of possible influential factors be prepared. As proposed by Mitropoulos et al. (2009), to be able to better recognize a variety of influential factors better, we divide influential factors into three main categories including: task factors, environmental factors and work behavior factors. Activity factors are influential factors affecting activity condition and can increase/ decrease hazard potentials during activity. Activity height, distance to the edge, equipment specifications, and material movement distance are some examples for activity influential factors. Environment factors return to the environmental condition in which work is done such as wind, light, temperature, humidity and topography. Operation factors refer to the work congestion and concurrency of different operations. Shared workspace, shared equipment and equipment speed in an adjacent operation are some examples for operation factors. It is recommended for every operation a table, presenting different hazards and related influential factors, is drawn as the output of the first step. The table is going to be completed in next two steps.

The Second step of influential factor assessment is to set thresholds and range of values of influential factors. For example working within 1.8 meter distance to the edge can create a more hazardous condition than beyond 1.8 meter. Safety codes and standards, past hazard reports and team members' past experiences are the main assets for this step. The output table at step one is more completed by writing down different ranges next to each influential factor. At the third step , the extent of the impacts of different values of influential factors on hazard potential is determined by the project team. The use of a three level rating method proposed by Mitropoulos and Namboodiri (2010) in TDA method, as discussed in section 2, is recommended here. At this step team members evaluate impact of every value range of each influential factor by assigning 1 (low impact), 3 (moderate impact) or 9 (high impact) ratings. Team members are encouraged to use output table from the second step to assign proper rates to the value ranges of influential factors. Table 1 presents a sample output from implementation of three steps of hazard and influential factor assessment.

Table 1: A sample hazard and influential factor assessment for steel erection operation

Hazard	Influential factors	Factor impact		
Height falling	Distance to the edge	0 m to 1 m *High*	1m to 3 m *Moderate*	Beyond 3 m *Low*
	Height	0 m to 1.6 m *High*	1.6 m to 4 m *Moderate*	Beyond 4 m *Low*
	Steel element weight	0 kg to 5 kg *Low*	5 kg to 20 kg *Moderate*	Beyond 20 kg *Moderate*

4.3 Simulation model of operation

Productivity evaluation of construction operations is a common output from DES models (Martinez 2010). But, the use of DES models for evaluation of safety level is a new approach we are proposing in this research. To be able to evaluate safety levels of different operation scenarios we need to make sure the model can trace changes in hazard influential factors, especially when they pass their thresholds. For calculating safety level of an operation scenario, Mitropoulos and Namboodiri (2010) were videotaping the operation and manually changing ratings of influential factors when their values cross thresholds. In our approach, however, DES model traces change in value of influential factors over time and automatically calculates the level of each hazard at a given time by multiplying rates of its different influential factors. Total safety level of an operation is then calculated by considering relative weights of different hazards. In addition, work productivity level of an operation is calculated simultaneously by calculating cost of workers and the equipment (and material, if is a source of deviation in scenarios) used in the operation. In our simulation based approach when the model of a base scenario is developed, development of other scenarios (usually) requires minimal efforts by simply deviating DES model elements from the base model. So, capacity of the proposed framework to easily evaluate outcomes of different work scenarios is an advantage of the framework compared to the TDA method proposed by Mitropoulos and Namboodiri (2010). For detailed explanation on DES model development and simulation processes please refer to Banks et al. (2005).

4.4 Evaluation of safety and productivity of scenarios

Dimensionless values of safety levels and dollar values of productivity levels measured are main outputs of an operation simulation model. In cases where a scenario scores the minimum cost and hazard potential, simply this scenario is considered the best scenario. However, it will not happen in most cases. So, to be able to compare results achieved in different scenarios properly and select the most suitable scenario we need a comparison method which works for all situations. Our suggestion is a normalization method in which safety and productivity values are transferred to the range of 0 to 100. More explanation for the proposed normalization method follows.

4.4.1 Normalization of safety

The safety results calculated for scenarios represent hazard potentials of scenarios, i.e., lower values are more favourable. The normalization method is in a way that can address our two main concerns. First, we aimed to be able to distinguish major and trivial safety value differences in different scenarios; it is very important to avoid giving extra credits to trivial safety improvements and degrading substantial safety improvements. Second, we were interested in setting higher values as higher priorities, as a prevalent approach used in grading. Our proposal for addressing the first point, again, is to refer to the project team and ask them to set a desirable value of safety or hazard potential improvement (namely SDV); it is going to be set in percent. For example, while 3% safety improvement, as a result of organizational culture and past experiences, can be assumed a desirable improvement for a project team, another project team might consider 10% safety improvement as a desirable improvement. It is important that improvements close to the desirable value can be easily seen by comparing different scenarios. We also do not expect to receive much higher improvements than desirable improvement, during comparing safety results.

Furthermore, as improvements get more distance from the desirable value (i.e., are reduced) their level of significance decreases and we need to see this reduction in improvement level.

In our normalization method, we assume 0 to 100 represents a range equal to twice of the desirable safety improvement value (DSV). Suppose SSb represents the scenario with the best (or minimum) hazard potential score, SSw is the scenario with the worst (or maximum) hazard potential score. We set the middle value (SSm) as formula below:

[1] $SSm = (SSw + SSb) / 2$

In the normalization method SSm or middle value reflects value of 50 (at the range of 0 to 100). But depending on the improvement achieved SSw is normalized to a point between 0 and 50 (namely SNw) and SSb is normalized to a point between 50 and 100 (namely SNb). However, their transferred points are symmetric about 50. If SSi represents hazard potential score of its scenario, its normalized value or SNi is calculated as formula below:

[2] $SNi = 50 - (SSi - SSm) / SSw / DSV * 50$

To calculate normalized values for the best and the worst scenarios, simply replace SSi with them. For example if hazard potential values for an operation with 3 scenarios have been calculated as 25, 27 and 31 with desirable safety improvement of 10% set by the project team, normalization calculations, using formulas 1 and 2 are:

$SSm = (31 + 25) / 2 = 28$

$SN1 = SNb = 50 – (25 – 28) / 31 / 10\% * 50 = 98.4$

$SN2 = 50 – (27 – 28) / 31 / 10\% * 50 = 66.1$

$SN3 = SNw = 50 – (31 – 28) / 31 / 10\% * 50 = 1.6$

4.4.2 Normalization of Productivity

The Similar approach followed for normalization of safety is followed for productivity too. The only difference here is that the values scored for each scenario here have monetary unit. With similar approach and different notation for the desirable productivity improvement value of DPV, scenario with the best productivity value of PSb, scenario with the worst productivity value of PSw, middle value of PSm, productivity value for its scenario of Psi and its normalized value of PNi, related formulas are:

[3] $PSm = (PSw + PSb) / 2$

[4] $PNi = 50 - (PSi - PSm) / PSw / DPV * 50$

4.4.3 Scenario comparison

Combining normalized safety and productivity values achieved, for example, by assigning priority or weight to them, is possible but it is a challenging issue. At its simplest way, we can ask project team to set weights for safety and productivity and simply calculate final values of different scenarios to be able to select the best scenario. However, at this stage we propose a colour coded two dimensional X-Y diagram, with productivity values represented on the X axis and safety values represented on the Y axis (Figure 2). The diagram has been divided into four areas by intersection of middle values (i.e., 50):

- Area 1 or green area: Holds scenarios with high safety and productivity levels
- Area 2 or yellow area: Scenarios with high safety and low productivity levels fall into this area
- Area 3 or orange area: Scenarios with high productivity and low safety are seen in this area
- Area 4 or red area: Holds scenarios with low safety and productivity levels

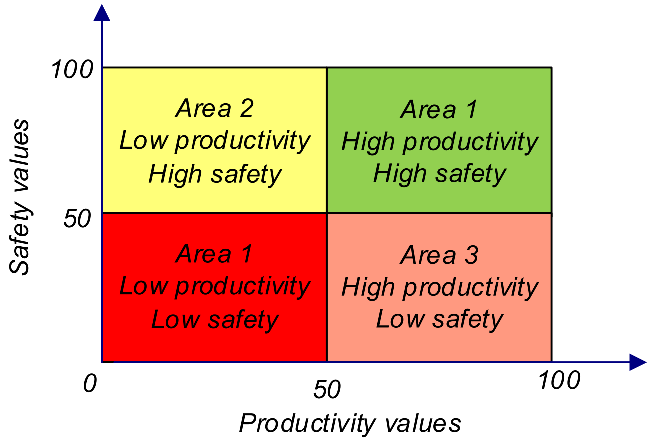


Figure 2. Colour coded diagram to be used for scenario comparison

In general, scenarios within area 1 are more desirable. However, depending on the project team's priority, scenarios within area 2 (with project team priority on safety) and area 3 (with project priority on productivity, might be selected as well. Distance to the middle values is also another effective factor. It is likely that a project team rejects scenarios within area 1, but very close to middle point and accept a scenario within area 2 with high standing in safety and minor distance to the middle value of productivity.

5 FRAEMWORK IMPLEMENTATION

To test different features of the proposed framework, different steps of the framework have been applied to a fabricated roof tile installation operation. Since this is a fabricated operation rather than an actual project, in this test we skip step one to "identify hazardous operations". Furthermore, a group of authors have played the role of project team with inputs from literature.

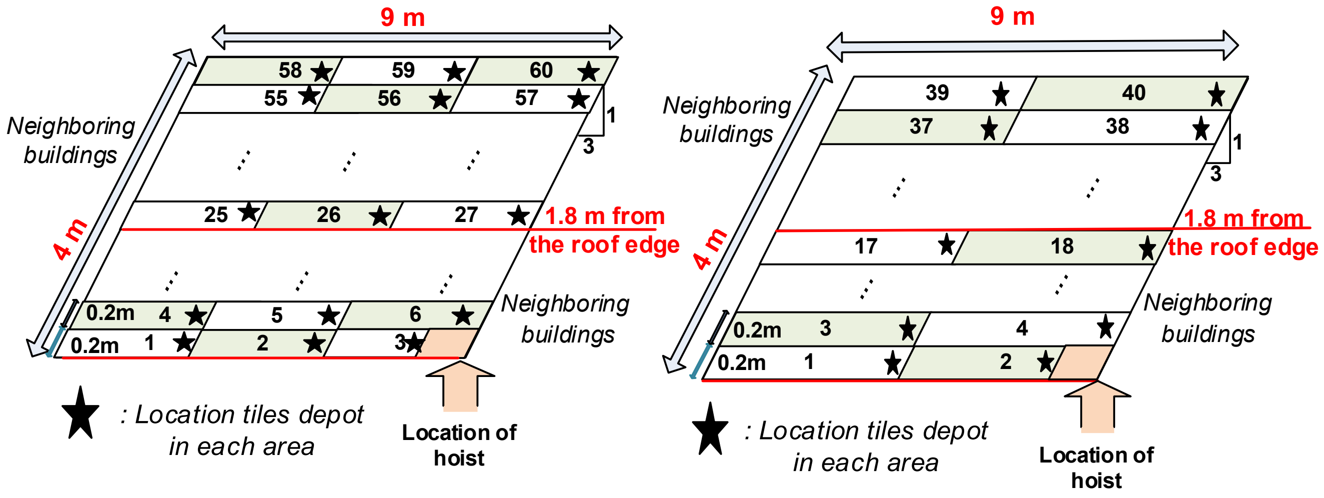
5.1 Operation description

In this operation there is one worker on the ground that loads and hoists roof tiles to the top. Another worker works on the roof top that, first, depots tiles on the roof and, then, installs them. Main specifications of the roof are:

- Roof pitch is 1 to 3
- Roof area is 9 m long and 4 m wide
- Roof has a fall protection guard on the width but is not protected on the length
- Tiles have dimension of 25 cm to 35 cm; with tiles overlapping the effective dimension is 20 cm to 30 cm

5.2 Operation scenarios

Six different scenarios are evaluated and compared in this example. Different scenarios are created as a result of using different depot arrangements and different types of hoists with different capacities and working speeds. Figure 3 illustrates the roof specifications and two main depot arrangements types on the roof used in different scenarios. Table 2 presents main characteristics of different work scenarios.



a. Depot arrangement type “a” with 60 areas

b. Depot arrangement type “b” with 40 areas

Figure 3. Two tile depot layout on the root used in different scenarios

Table 2: Main characteristics of different operation scenarios

	Scenario					
	1	2	3	4	5	6
Area arrangement	Type a (60 areas)	Type b (40 areas)	Type a (60 areas)	Type a (60 areas)	Type b (40 areas)	Type a (60 areas)
Installation time within an area (minute)	Triangular (4,5,7)	Triangular (5,7,8)	Triangular (4,5,7)	Triangular (4,5,7)	Triangular (5,7,8)	Triangular (4,5,7)
Tile depot and installation order	Installation after depot completion	Installation after depot completion	Installation after depot completion	Installation after depot within an area	Installation after depot within an area	Installation after depot within an area
Hoist bucket capacity (tiles)	10	15	20	10	15	20
Bucket loading and hoisting time (minute)	Triangular (1,3,4)	Triangular (2,4,5)	Triangular (2,4,6)	Triangular (1,3,4)	Triangular (2,4,5)	Triangular (2,4,6)

5.3 Influential factors assessment

Falling hazard is the hazard identified for this operation. Three influential factors are identified for this hazard including: the roof pitch, the distance to the not-protected edge and the workers movement. Table 3 presents influential factor assessment for the roof tile installation operation.

Table 3: Influential factor assessment for roof tile installation

Hazard	Influential factors	Factor impact		
Height falling	Roof pitch*	Flat	Below 5:12	Beyond 5:12
		Low (1)	*Moderate (3)*	*Low (9)*
	distance to the not-protected edge	On the roof ridge	Beyond 1.8 m	Below 1.8 m
		Low (1)	*Moderate (3)*	*Low (9)*
	workers movement	No movement	Forward movement	Backward movement
		Low (1)	*Moderate (3)*	*Low (9)*

* There is no change on the roof pitch during the operation and its value is considered constant.

5.4 Simulation model assessment

Simulation models are developed in Anylogic simulation program. For productivity calculations based on Iran's construction market, equivalent hourly rate of 2.5 US$ is considered for the hoist operator and equivalent hourly rate of 5 US$ is considered for the tile installer. In addition hourly rate of hoist rental for bucket sizes of 10, 15 and 20 tiles are respectively considered as 2 US$, 2.5 US$ and 3 US$. Table 4 presents raw and normalized results achieved for productivity and safety level of each scenario. Desirable improvement for both productivity and safety levels is set as 10%. A comparison between results is also illustrated in colour coded diagram in Figure 4.

Table 4: Safety and productivity results achieved in simulation models

	Scenario					
	1	**2**	**3**	**4**	**5**	**6**
Hazard potentials	8.69	8.74	8.46	9.81	9.78	9.46
Normalized Safety level	73	70	84	16	17	33
Productivity rate (total tile installed) * $	97	94	106	93	95	103
Normalized productivity level	62	75	19	81	71	33

* This price is related to the cost of hoist rent and Labors.

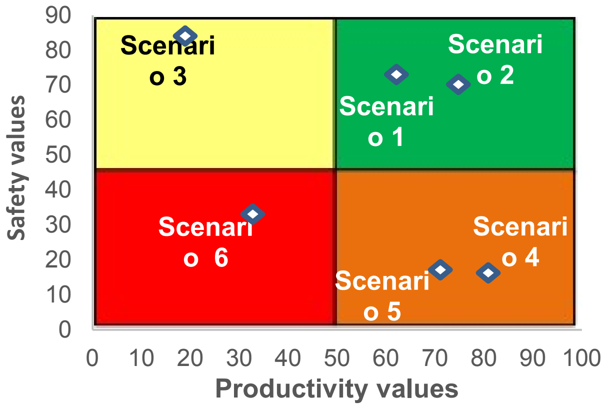


Figure 4. Colour coded diagram presenting normalized result achieved for scenarios

Among different scenarios, scenario 3 has scored the lowest hazard potential value and has the best safety level with normalized value of 84. In regard to the productivity scenario 4 has the lowest cost and highest productivity level with normalized value of 81. At a fast glance to the colour coded diagram, scenario 2 in area 1, with a relatively high safety and productivity levels, is the first scenario to be selected. However, final scenario selection can be changed due to the project team priority.

6 CONCLUSION

Safety and productivity improvement is a day after day concern of construction project managers. Although many research efforts have been done to improve safety and productivity of construction projects, the research efforts addressing these two aspects of construction projects are still missed. In this research we proposed a new simulation based framework to concurrently evaluate safety and productivity levels of construction operations. The framework helps construction project managers to select most suitable alternative operation scenarios, especially for hazardous operations within a project. It involves project team members in different steps; it uses their related past experiences and incorporates their concerns during the decision making process. In this perspective the framework tries to model and evaluate the work condition as realistic as possible. To assess different features of the framework we applied the framework to a fabricated example of a roof tile installation operation. However, more validation efforts for applying the framework to real construction projects are still in progress.

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