Scheduling-Based Risk Estimation and Safety Planning for Construction Projects

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Abstract: This paper considers the issue of safety risks on construction sites. It introduces the concept of combined effect of different risk factors to the accident. For proper safety planning, safety managers need to be well aware of the direct causes of the accident as well as indirect factors that adversely effect on site safety. If it is observed that if a hazardous environment exists at the site, then either that hazardous environment must be eliminated or occupations and processes related to that hazard must be properly protected. One of the measures for evading such hazardous situations is to predict such situations and to reschedule the start time of high-risk situation so that risks are not concentrated during certain periods and at certain locations. In order to predict when and where the risk will reach its highest level, analysis should be performed based upon various information including statistical sources such as accident histories and this should be done in coordination with the activity scheduling. This paper analyzes the result of accident history and provides information about vulnerable situations. In addition, it presents a theory of safety planning method which estimates the risk distribution of a project and helps the safety manager to both estimate situations of concentrated risk and then to reschedule it when it is necessary.

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Introduction

The risk characteristics of a construction site are influenced by the amount of effort required to reduce the accident risk of the site by, for example, protecting the workforce from hazards and taking the necessary safety measures. Detecting the hazards of a site that could cause harmful effects on workers is crucial for successful safety management, because a hazardous work environment affects not only site safety but also the time and cost of the project. If the hazardous environment is incorrectly estimated and improperly protected, then the workforce will be exposed to possible dangers which could slow down their operations, undermine their productivity, and increase the possibility of unwanted accidents, thereby eventually increasing both time and costs. On the other hand, however, excessive or unnecessary safety measures may result in both delays in the schedule and in uncalled for costs.

In order to detect the hazardous environment, it is necessary to identify the type of agents that affected death and injuries of the workers. Since the work environment of construction sites varies according to the progress of the project, the schedule affects the occurrence of hazardous situations, and the estimation of possible hazards must be coordinated with the project schedule. Hazardous locations and high-risk time periods can be effectively predicted if safety management and scheduling are coordinated. If the times and places with a high risk of accidents are accurately identified, then the safety manager can plan to avoid situations of concentrated risk by taking the necessary and appropriate safety measures. Such a coordinated effort cannot only reduce the risk of accidents but also decrease project costs. If a work situation is identified as being similar to the situations where many accidents happened in the past, it can aid in determining the location and time where a high level of caution needs to be exercised and where more safety measures need to be provided.

There has been a considerable amount of research attempting to analyze the causes and patterns of construction accidents. Tam et al. (2002) state that previous research into site safety can be divided into two general categories:

1. Surveys of safety factors and performance; and
2. Sharing practical experiences of safety management.

Kartam and Bouz (1998) analyzed the occurrence and causation of accidents in the Kuwaiti construction industry and Gyi et al. (1999), claiming that accident statistics were a limited measure of safety performance, interviewed senior managers and then asserted the importance of a consistent and integrated approach. Mohamed (1999), after an empirical analysis of the relationship between the level of commitment to safety management and overall safety performance, emphasized the necessity of more effective methods to detect and manage hazards. Sawacha et al. (1999), after analyzing the factors that influenced safety on construction sites, suggested that the awareness of hazardous materials was the most significant technical factor. Kartam et al. (2000) investigated the problems of safety in the Kuwaiti construction industry and Langford et al. (2000) investigated how safety behavior and management influenced attitudes toward safety in the

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United Kingdom construction industry. Suraji et al. (2001) put forward a model of accident causation and concluded that planning and control were the major factors involved in construction site accidents. Huang and Hinze (2003) identified patterns of accidents due to falls from heights, and compared their distribution using a number of factors including the types of task, location, age, human error, and time.

There have also been efforts to improve safety management strategies and develop relevant models, for example, a number of research projects have attempted to associate the management of safety with that of design, schedule, and cost. Kartam (1997) discussed the introduction of safety measures into construction plans using critical path method (CPM) techniques which enabled project managers to identify appropriate safety performance standards and Gambatese and Hinze (1999) developed a design tool which helped designers to identify project-specific safety hazards. Cagno et al. (2001) developed an algorithm for the scheduling of measures within a safety improvement program and Tam et al., after comparing safety improvement measures developed in the construction industry, devised a method of allocating resources according to the order of priority. Hadikusumo and Rowlinson (2002) developed a tool for the visualization of the construction process which helped to identify those safety hazards which were produced during the design phase. Finally, Saurin et al. (2004) developed a safety planning and control (SPC) model which integrated safety management with the production planning and control process.

All of these studies set out to identify the risk of accidents and to devise measures to reduce them. Although an analysis of the patterns and causation of accidents provides the basic information for safety planning, it is not sufficient for predicting when and where they will occur. Such prediction needs coordination with other branches of project management, for example, scheduling provides the necessary information about the various activities in a diverse work environment for the prediction of the places and times of high risk. Although some of the previous research has emphasized the importance of coordinating the objectives of safety management with those of other branches of project management, few studies have attempted to provide a base for the adaptation of scheduling techniques to the prediction and control of high-risk situations in construction projects.

The objective is to provide information on which agent had the most effect on a worker of a certain occupation involved in a fatal fall and in what process the worker carried it out. Such information can help safety managers predict those situations where high-risk activities are concentrated in a certain period and assist in identifying the possible hazards and finding measures to reduce the risk of that situation. The relationships between those factors will help safety managers in predetecting the possible hazardous situations through the coordination of scheduling. Furthermore, the information could establish appropriate schedules for safe working conditions and the prediction and control of high-risk periods and hazardous places.

Data Collection

This paper analyzed the factors related to the accidents based on the reports of fatalities in construction due to falls from heights between 2001 and 2003 which were provided by the Korean Occupational Safety and Health Agency. Each report contains a detailed description of how, when, who, where, and why the accident happened, what caused the accident, and a brief description of the contractors and the projects, along with illustrations showing the situations when the accident occurred. Among the 835 fatality reports, 390 cases were found to be involved with a fall from height. This paper investigates these 390 fatal fall accident reports and identifies various factors related to the accidents, such as occupations of the injured workers, processes that the injured workers were involved in, and agents that affected the accident. Table 1 shows an excerpt of the collected list that was obtained from the reports.

Safety Planning and Scheduling

Coordination of Safety Planning and Scheduling

Whereas planning and control failures were the major contributory factors to accidents on construction sites, preproject and pretask safety planning are among the critical measures required to achieve a zero accident target (Saurin et al. 2004). No aspect of construction project planning is independent from any other and each aspect has its own influence on the risk of accidents. Safety planning is as much a part of construction project management as are scheduling and the management of cost and quality. It is not independent from it but is closely related to it. Since the primary objective of safety planning is to minimize the accident risk, first, the risk itself must be identified as specifically as possible and second, factors that affect that risk must be clarified. There are various factors affecting risks of the workers: human, environmental, and process. Among them, environmental factors are more directly the cause of accidents than the others.

The proper allocation of safety resources demands that hazardous environments must be identified prior to the workers starting their jobs there, and in order to do so, safety planning must be coordinated with the rest of the project management. In safety planning, it is possible to identify such hazardous situations from the work schedule and layout plan. An expedited schedule has a danger of neglecting such hazardous situations and carrying more accident risk per unit period of time than a normal schedule. Either more safety effort should be devoted to the expedited schedule, or the schedule must be delayed until the hazardous situations are sufficiently identified. This also means that project safety can be enhanced by allocating more time to each activity so that the workers can carry out their tasks not only without undue haste but also without unnecessary risk. However, if the schedule needs to be expedited, then more safety measures must be exercised in advance to increase the safety of the working environment. Finally, safety planning needs to be coordinated with scheduling in order to discover those situations during the life of the project in which the risk of accident exceeds admissible limits.

Safety Planning Process and Scheduling

Saurin et al. (2004) have shown how the safety planning process involves risk identification, evaluation, and control, and that the main steps for producing safety plans are:

1. Establishing the necessary tasks to be undertaken;
2. Identifying the existing risks; and
3. Defining how each risk will be controlled.

Step 1 is also a part of scheduling and must share information with it. Since the risk of accidents varies from situation to situation, it requires careful consideration drawing on checklists, brainstorming, past experience, and estimations from statistical data. Then, once all the risks have been identified, they can be

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Table 1. Data Collected (Excerpt)

Number	Process	Agent	Cause	Occupation	Age	Date	Time
1	In situ concrete, including falsework/ formwork/steel fixing	Openings/ends	Failure to use PPE	Formwork carpenters	46	April 5, 2001	3:45 p.m.
2	All roofing, roofing/cladding, tiling	Vehicles, plant, and earth moving equipment	Unprotected end	Roofers/slaters/tilers /sheeters/cladders	34	April 6, 2001	4:50 p.m.
3	Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Openings/ends	Both	Other finishing trades	48	April 16, 2001	4:20 p.m.
4	In situ concrete, including falsework/ formwork/steel fixing	Roofs	Both	Concrete placement/curing related trades	38	April 21, 2001	10:00 a.m.
5	Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Pylon	Failure to use PPE	Painters and decorators	55	April 23, 2001	1:30 p.m.
6	In situ concrete, including falsework/ formwork/steel fixing	Scaffold/platforms above ground	—	Nonmanual occupations	46	May 5, 2001	10:50 a.m.
7	Scaffolding	Steel beam/plate	Both	Scaffolders	47	May 5, 2001	8:00 a.m.
8	In situ concrete, including falsework/ formwork/steel fixing	Scaffold/platforms above ground	Failure to use PPE	Formwork carpenters	52	May 10, 2001	4:10 p.m.
9	All roofing, roofing/cladding, tiling	Ladders	—	Roofers/slaters/tilers/ sheeters/cladders	32	May 10, 2001	5:00 p.m.
10	Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Hanging platform	Failure to use PPE	Painters and decorators	52	May 15, 2001	2:50 p.m.

controlled by the planning of preventive measures, estimating the hazardous environments of the site, and the occupations and processes involved with them. Although the ideal solution is for optimum cost efficiency and freedom from accidents, the contractor will always retain some residual risks but these must be kept within an acceptable level (Saurin et al. 2004). Even so, it is sometimes possible to find a compromise between the ideal level and the minimum level suggested by the regulations.

Risk Estimation

Activity Factors and Risk Estimation

According to Mol (2003), since an activity is the combination of system factors, such as process, human resources, technology, and physical environment, the combined risk can be calculated by the following formula:

$$\text{total risk score} = P \times H \times T \times E$$

where P=process risk score; H=human resources risk score; T=technology risk score; and E=physical environment risk score.

In the construction process, the first three of these factors (process, human resources, and technology) are normally dependent upon the type of work being done. For example, the bricklaying and painting processes require the bricklayer and painter as the human resources and the skills of bricklaying and painting as the technology. The risk of human resources can vary according to their occupations and the process risk is determined by the technology applied to the activity. The fourth factor, the environment, is often the direct agent of accidents and is dependent upon the location or the unit where the activity is being carried out.

Risks as Constraints

Each process of a construction project has its own risk characteristic, so, if these characteristics are identified and applied to the scheduling, then it is possible to ascertain when and where excessive concentrations of risk occur and then to estimate the type and magnitude of risk for each activity. By examining the accident history of each risk factor, the high-risk situation can be identified and resolving such situations can be measured to appropriate periods of time and place.

When a high-risk situation is found, two alternative preventive measures can be taken, either providing more safety resources so that the risk capacity of the site increases, or modify the work schedule so that the high-risk situation does not occur. This second measure can be applied if a high-risk situation has arisen due to some noncritical activities.

In order to estimate the risk for each activity, those factors which affect its risk characteristics must be considered. If a construction site location has a large number of high-risk environmental elements such as scaffolds, ladders, or steel beams, then it has a high score for physical-environment risk. This means that it has a high level of inherent danger with a high probability of injury or harm. Likewise, if one process has a higher risk score than another, then this process is the more vulnerable to injury or harm. Accident risk can be affected by a number of factors simultaneously and in different combinations. For example, if a high-risk process takes place in a high-risk location then the probability of injury or harm is far higher than in the opposite case, that of a low-risk process at a low risk location. The risk characteristic of each activity needs to be considered in combination with the factors that influence the risk of accidents. For example, the environmental factors of accident risk are determined by the environment of each unit structure and affect every activity being performed at that unit. In a repetitive project, the process to which an activity belongs decides the process factor of that activity but since both process and environmental factors affect the risk characteristics of an activity, they should be considered together when estimating the risk of an activity.

In a repetitive construction project, a set of activities are performed in an established sequence in order to make a unit struc-

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Table 2. Representation of Relationship between Units and High-Risk Elements

	High-risk environmental elements			
Unit	h_1	h_2	$\cdots$	h_n
u_1	I_{11}	I_{12}	$\cdots$	I_{1n}
:	:	:	$\cdots$	:
u_m	I_{m1}	I_{m2}	$\cdots$	I_{mn}

Table 4. Representation of Risk Intensities by High-Risk Environmental Elements and Type of Work

High-risk environmental elements	Type of work			
	w_1	w_2	$\cdots$	w_p
h_1	$R(h_1,w_1)$	$R(h_1,w_2)$	$\cdots$	$R(h_1,w_p)$
:	:	:	$\cdots$	:
h_n	$R(h_n,w_1)$	$R(h_n,w_2)$	$\cdots$	$R(h_n,w_p)$

ture and then these procedures are repeated as often as necessary (Moselhi and El-Rayes 1993). In other words, when the construction of a repetitive project is carried out, the same work processes occur in each unit (Wang and Huang 1998). During repetitive construction projects such as multistory buildings, pipelines, and highways, the workforce perform their tasks in each unit, one after another.

In these projects, each unit has its own physical environment which influences the accident risk for every activity that is carried out in that unit. Construction workers are more vulnerable to accidents involving falls from heights when a unit contains temporary structures such as ladders or steel beams than when it does not. Efficient safety planning for such projects must take these repetitive factors into account and deal with the similarity of work environments within the unit structures. Similarly, the accident risk of the repetitive work processes must be understood so as to avoid the same types of hazard being present at the same types of unit.

Risk Distribution and Safety Resource Scheduling

Once the risk characteristics of each factor have been established, then the combined risk profiles of an activity can be estimated. In a construction site, an activity is typically involved with several risk factors and either or all of those risk factors can affect the danger of accident occurrence. In other words, the total risk amount of an activity is the combination of the risks of individual risk factors involved with that activity. Such a combined risk of an activity assists safety managers and schedulers in understanding the risk characteristic of each activity in the schedule and determining a "safe" schedule for the project.

After estimating the risk of each activity, the risk profiles of every activity need to be examined to find out if there are any high-risk situations during which the risk exceeds the allowable limit of the site. In order to avoid such high-risk situations, enough safety resources must be input to that activity, but in some cases there are not enough resources available due to the overlapping schedule of activities. In such cases, the starting and finishing times of the activity should be adjusted backward and/or forward until enough safety resources are secured for the high-risk activity. Scheduling of safety resource is achieved by regarding the safety resources as an individual resource and then adopting the resource allocation and leveling methods used in scheduling.

When deciding on a "safe" schedule, factors that affect the site's risk capacity must be considered and a managerial decision should be made by taking into account the various factors affecting the risk characteristics of a site. These include the budget, the schedule limits, the weather, the type of project, the abilities of the workforce, and the number of people involved in safety management.

Table 3. Representation of Risk Intensities by High-Risk Environments

High-risk environmental elements			
h_1	h_2	$\cdots$	h_n
$R(h_1)$	$R(h_2)$	$\cdots$	$R(h_n)$

Estimation of Risk Intensity and Quantity

The estimation of accident risk combines occupational, environmental, and process risk factors. Each unit has the high-risk environmental elements that determine the physical environment risk, whereas the process risk for an activity is determined by the type of process. The procedure for estimating risk intensity and quantity consists of the following three steps:

1. Identifying the high-risk environmental elements for each unit;
2. Identifying the risk intensity for each environmental element and for each type of process; and
3. Preparing the activity schedule and estimating the risk quantity.

High-Risk Environmental Elements

High-risk environmental elements are defined as agents, which are dangerous and likely to cause damage, thereby affecting levels of safety or danger within each unit. In order to estimate the level of environmental factors affecting the environmental risk of an activity, it is necessary to identify which types of high-risk environmental elements are present within each unit. This paper has developed a simple matrix form, as shown in Table 2, to indicate each unit's content of high-risk elements. It consists of m rows and n columns, where m and n are the number of units and the number of high-risk environmental elements, respectively. Numerical values are assigned to each cell according to the relationship between the units and the high-risk elements. For instance, if a high-risk environmental element h_j is present at the unit u_i, the numerical value is assigned to the cell I_{ij}, located on the ith row and jth column of the table, according to the influence of h_j to the safety of the place. If high-risk environmental element h_j is not present at the unit u_i, then a nil value is assigned to the cell I_{ij}.

Table 5. Representation of Schedule for Work Process w_k by Units

	Date (period)			
Unit	1	2	$\cdots$	T
u_1	X_{1k1}	X_{1k2}	$\cdots$	X_{1kT}
:	:	:	$\cdots$	:
u_m	X_{mk1}	X_{mk2}	$\cdots$	X_{mkT}

Note: X_{ikt}=nil or 1.

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Table 6. Representation of Activity Durations by Units and Work Processes

Unit	Type of work w_1	w_2	$\cdots$	w_p
u_1	D_{11}	D_{12}	$\cdots$	D_{1p}
:	:	:	$\cdots$	:
u_m	D_{m1}	D_{m2}	$\cdots$	D_{mp}

Environment Risk Factor

Each high-risk environmental element has a different risk intensity, and there are variable chances that an accident might happen. According to the statistics (KOSHA 2003), scaffolds, work platforms, and edges have the highest risk intensity, comprising 50–60% of all the high-risk environmental elements that have caused fall fatalities on construction sites (Table 2). Using such statistical data is one of the methods of estimating risk intensity for the high-risk environmental elements. In Table 3, $R(h_j)$ is the risk intensity for the high-risk environmental element h_j. These coefficients, along with the high-risk environmental elements content table, will be used for calculating the accident risk of each unit.

In case each high-risk environmental element independently affects the probability of an accident, the risk intensity for a unit can be obtained by adding the risk intensities of high-risk environmental elements of the unit (see the following equation). This risk intensity, which is the sum of all dangers present at a unit, can be obtained by the following expression:

$$R(u_i) = I_{i1} \cdot R(h_1) + I_{i2} \cdot R(h_2) + \cdots + I_{\mathrm{in}} \cdot R(h_n) = \sum_{j=1}^{n} I_{ij} \cdot R(h_j) \tag{1}$$

where $R(u_i)$=risk intensity for unit i. As mentioned previously, $R(h_j)$=risk intensity for high-risk environmental element j. Higher risk intensity indicates that those working in the unit are more vulnerable to accidents.

Process Risk Factor

The type of process also affects the risk of an activity; in each type of work process having its own risk intensity as shown by the KOSHA (2003) statistics, the most vulnerable construction process is loading/unloading followed by formwork and painting.

Risk Intensity

The level of accident risk for an activity is affected by both the work process and the environment where it is carried out. In order to estimate the risk intensity of the work process for each unit, the risk intensities of corresponding work processes and units must be multiplied and then summed all together. For instance, if there are n number of high-risk environmental elements and I_{ij} indicates the presence of the high-risk environmental elements j at the unit i, the risk intensity of unit i for work process k is obtained by the following expressions:

$$R(u_i,w_k) = I_{i1} \cdot R(h_1) \cdot R(w_k) + I_{i2} \cdot R(h_2) \cdot R(w_k) + \cdots + I_{\mathrm{in}} \cdot R(h_n) \cdot R(w_k) = \sum_{j=1}^{n} I_{ij} \cdot R(h_j) \,.\, R(w_k) \tag{2}$$

where $R(u_i,w_k)$=risk intensity of the situation that work process w_j is performed at unit u_i.

More feasible values can be obtained if the value of risk intensity is assessed individually for each case, as shown in Table 5, rather than by applying the above equation. For each ease, work process w_j is carried out in the unit that contains the high-risk environmental element h_i, and the risk intensity is marked as $R(h_i,w_j)$ as shown in Table 4.

This table enables it to obtain more feasible risk intensities, and it can be expressed as follows:

$$R(u_i,w_k) = I_{i1} \cdot R(h_1,w_1) + I_{i2} \cdot R(h_2,w_k) + \cdots + I_{\mathrm{in}} \cdot R(h_n,w_k) = \sum_{j=1}^{n} I_{ij} \cdot R(h_j,w_k) \tag{3}$$

Activity Schedule

Every activity in the schedule has its own starting and finishing time. If a work process w_k successively progresses at units u_1, $u_2, \ldots, u_m$, the schedule for work process w_k can be displayed as shown in Table 5, in which the project starts at period 1 and finishes at period T. The number 1 or 0 is assigned to X_{ikt}, which indicates whether the work process w_k is carried out at unit u_i during period t or not. If A_{ik} stands for the activity consisting of work process w_k and unit u_i which, in other words, means that work process w_k is carried out at unit u_i, and if the starting and finishing times for A_{ik} are S_{ik} and F_{ik}, respectively, X_{ikt}=1 for time period t for $S_{ik} \leq t \leq F_{ik}$ and X_{ikt}=0 for $t < S_{ik}$ or $t > F_{ik}$.

Table 7. Number of Falls that Occurred to Workers by Occupation and Process 2001-2003 (Excerpt)

Occupation	Process	Number of accidents that occurred
Formwork carpenters	In situ concrete, including falsework/formwork/steel fixing	32
Scaffolders	Scaffolding	32
Painters and decorators	Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	28
Roofers/slaters/tilers/sheeters/cladders	All roofing, roofing/cladding, tiling	19
Electrical/electronic trades	Electrical finishing processes	17
Formwork carpenters	In situ concrete, formwork stripping	16
General operatives	Transport, traveling, walking, and running	15
Plasterers	Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	13
General operatives	Handling, loading, storage (excluding docks)	11
Steel erectors	Transport, traveling, walking, and running	11

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Table 8. Number of Falls that Occurred to Workers by Process and Agent 2001–2003 (Excerpt)

Process	Agent	Number of accidents that occurred
In situ concrete, including falsework/formwork/steel fixing	Scaffold/platforms above ground	33
Scaffolding	Scaffold/platforms above ground	26
Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Scaffold/platforms above ground	24
Transport, traveling, walking and running	Scaffold/platforms above ground	18
Transport, traveling, walking and running	Steel beam/plate	13
Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Hanging platform	13
All roofing, roofing/cladding, tiling	Roofs	13
Surface treatment; painting, decorating, plastering, flooring, plumbing, joinery	Openings/ends	11
Transport, traveling, walking, and running	Openings/ends	10
Structural erection, steel, timber, concrete, including bridge building	Steel beam/plate	9

Table 9. Number of Falls that Occurred to Workers by Occupation and Agent 2001–2003 (Excerpt)

Occupation	Agent	Number of accidents that occurred
Formwork carpenters	Scaffold/platforms above ground	35
Scaffolders	Scaffold/platforms above ground	27
General operatives	Scaffold/platforms above ground	19
Steel erectors	Steel beam/plate	14
General operatives	Opening/ends	13
Roofers/slaters/tilers/sheeters	Scaffold/platforms above ground	11
Plasterers	Scaffold/platforms above ground	10
Bricklayers/masons	Scaffold/platforms above ground	10
Plasterers	Scaffold/platforms above ground	10
Painters and decorators	Hanging platform	10
Roofers/slaters/tilers/sheeters/	Roofs	10
Bricklayers/masons	Scaffold/platforms above ground	10
Plasterers	Scaffold/platforms above ground	10
Bricklayers/masons	Scaffold/platforms above ground	10
Plasterers	Scaffold/platforms above ground	10
Bricklayers/masons	Scaffold/platforms above ground	10
Roofers/slaters/tilers/sheeters/	Roofs	10

Table 10. Risk Scores Estimated in Combination of Occupation, Process, and Agent (Excerpt)

Occupation	Process	Agent	Risk score estimated
Roofers/slaters/tilers/sheeters/cladders	All roofing/roofing/cladding/tiling	Roofs	21,385
Roofers/slaters/tilers/sheeters/cladders	All roofing/roofing/cladding/tiling	Scaffold/platforms above ground	14,476
General operatives	Transport/traveling/walking/running	Scaffold/platforms above ground	5,130
Roofers/slaters/tilers/sheeters/cladders	All roofing/roofing/cladding/tiling	Opening/ends	4,113
Bricklayers/masons	Handling/loading/storage (excluding docks)	Scaffold/platforms above ground	3,463
Roofers/slaters/tilers/sheeters/cladders	All roofing/roofing/cladding/tiling	Vehicles/plant/earth moving equipment	3,290
Bricklayers/masons	Transport/traveling/walking/running	Scaffold/platforms above ground	3,117
General operatives	In situ concrete/including falsework/formwork/steel fixing	Scaffold/platforms above ground	2,508
Bricklayers/masons	Bricklaying	Scaffold/platforms above ground	2,078
General operatives	Transport/traveling/walking/running	Openings/ends	1,950

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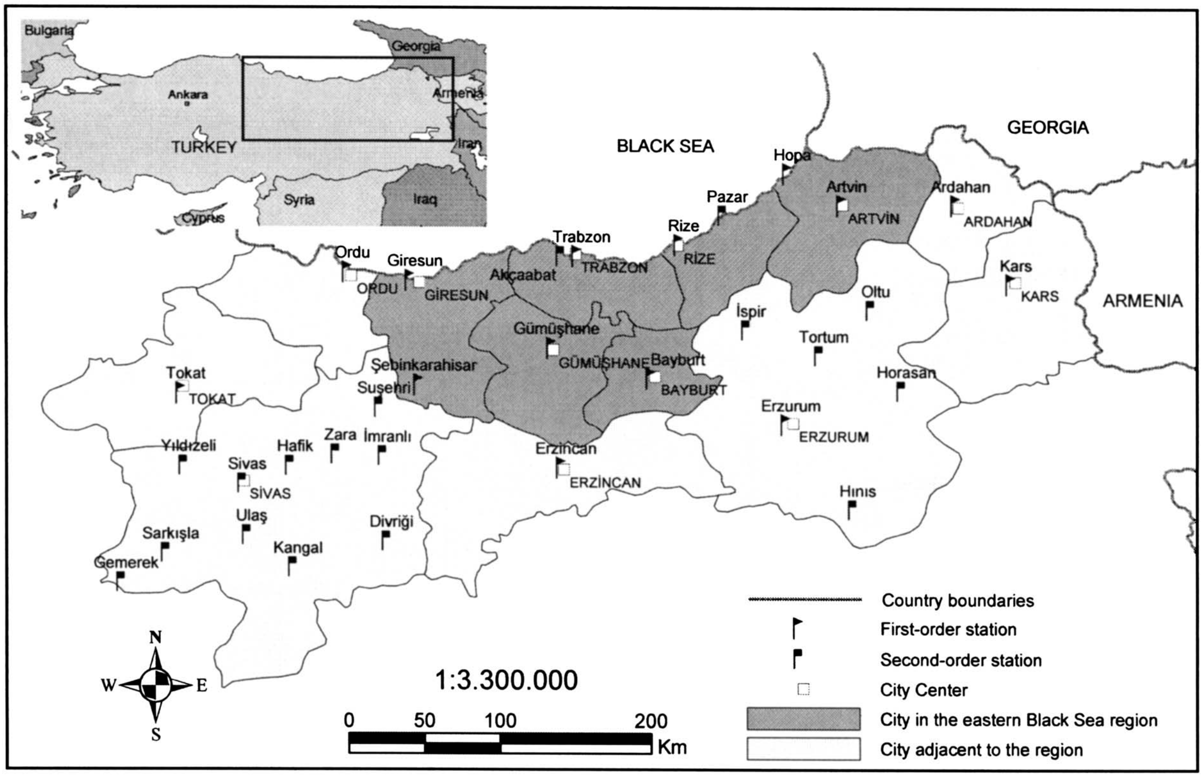

Fig. 1. First and second-order TSMS weather stations located in eastern Black Sea region and adjacent cities

If D_{ik} stands for the duration of the activity A_{ik}, D_{ik} can be obtained by the following expressions:

$$D_{ik} = \sum_{t=1}^{T} X_{ikt} \tag{4}$$

where $S_{i+1,k} \geqslant S_{i,k} + D_{i+1,k} \geqslant F_{i,k}$ (Wang and Huang 1998).

Start date S_{ik} is the smallest t value that satisfies $X_{ikt}=1$ and F_{ik} is the largest t value that satisfies $X_{ikt}=1$. The activity durations obtained by Eq. (4) can be arranged as in Table 6, which will later be used for obtaining risk quantities.

The variable X_{ikt} can also be used in obtaining the risk intensity for particular activity at a specific time. For instance, the risk intensity for activity A_{ik} at time t is as follows:

$$R(A_{ik})_t = R(u_i, w_k)_t = R(u_i, w_k) \cdot X_{ikt} \tag{5}$$

In the same manner, we can obtain the risk intensity for unit u_i at time t using the following expressions:

$$R(u_i)_t = R(u_i, w_{\forall k})_t = \sum_{k=1}^{p} R(u_i, w_k) \cdot X_{ikt} = \sum_{j=1}^{n} \sum_{k=1}^{p} I_{ij} \cdot R(h_j, w_k) \cdot X_{ikt} \tag{6}$$

Similarly, the risk intensity for time t is expressed as

$$R_t = R(u_{\forall i}, w_{\forall k}, t) = \sum_{i=1}^{m} \sum_{k=1}^{p} R(u_i, w_k) \cdot X_{ikt} = \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{k=1}^{p} I_{ij} \cdot R(h_j, w_k) \cdot X_{ikt} \tag{7}$$

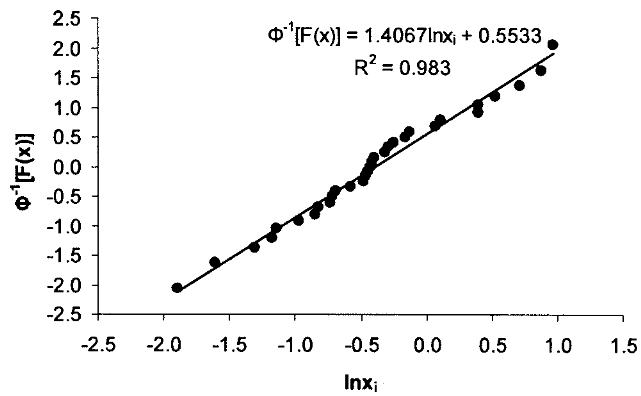

Fig. 2. Lognormal probability plot for Artvin snow load data

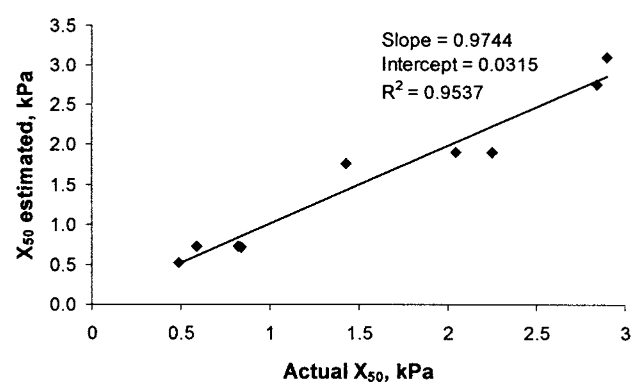

Fig. 3. Scatter diagram of actual and estimated X_{50} values and regression plot

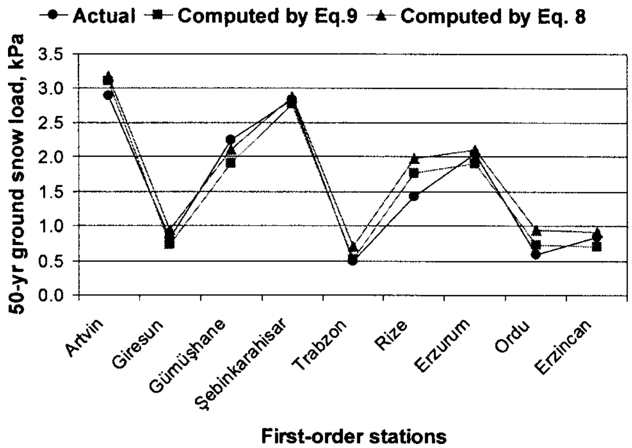

Fig. 4. Comparison of 50 year snow loads generated by Eqs. (8) and (9) with actual 50 year snow loads for first-order stations with no exceptional snow data

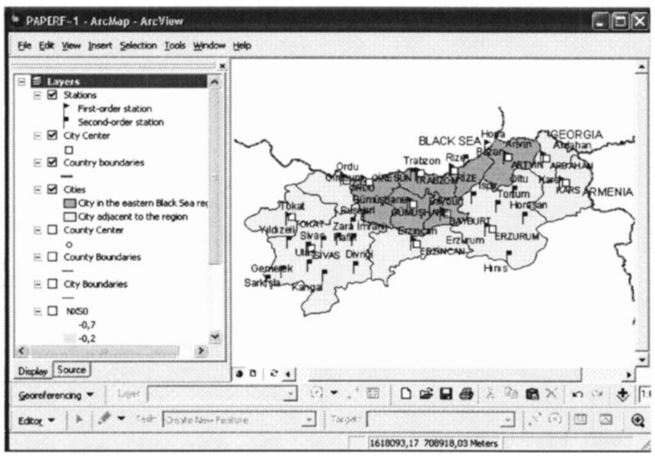

Fig. 5. Map layers developed for study

Risk Quantity

Although risk intensity is the degree of danger present in an activity for the moment, it does not express the total amount of danger for the whole duration of the activity. As the duration of an activity is increased, the greater the amount of time that the workforce is exposed to a risky environment, i.e., the risk quantity is the time integration of risk intensity. The risk quantity for an activity A_{ik}, the total amount of danger for the workforce involved in that activity for its duration, is expressed as follows:

$$Q(A_{ik}) = Q(u_i,w_k) = Q(u_i,w_k,\ \forall\ t) = R(u_i,w_k) \cdot D_{ik}$$

$$= \sum_{j=1}^{n} I_{ij} \cdot R(h_j,w_k) \cdot D_{ik} \tag{8}$$

And the risk quantity for the unit u_i is given by

$$Q(u_i) = Q(u_i,w_{\forall k},\ \forall\ t) = \sum_{k=1}^{p} R(u_i,w_k) \cdot D_{ik}$$

$$= \sum_{j=1}^{n} \sum_{k=1}^{p} \sum_{t=1}^{T} I_{ij} \cdot R(h_j,w_k) \cdot X_{ikt} \tag{9}$$

similarly, the risk quantity for the work process w_k is expressed as

$$Q(w_k) = Q(u_{\forall i},w_k,\ \forall\ t) = \sum_{i=1}^{m} R(u_i,w_k) \cdot D_{ik}$$

$$= \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{t=1}^{T} I_{ij} \cdot R(h_j,w_k) \cdot X_{ikt} \tag{10}$$

Once all the risk intensities have been estimated, then the risk profile for each day is calculated by summing up the risk intensities of all the activities scheduled to be performed during that day. The next step is to determine the admissible risk limit. If a

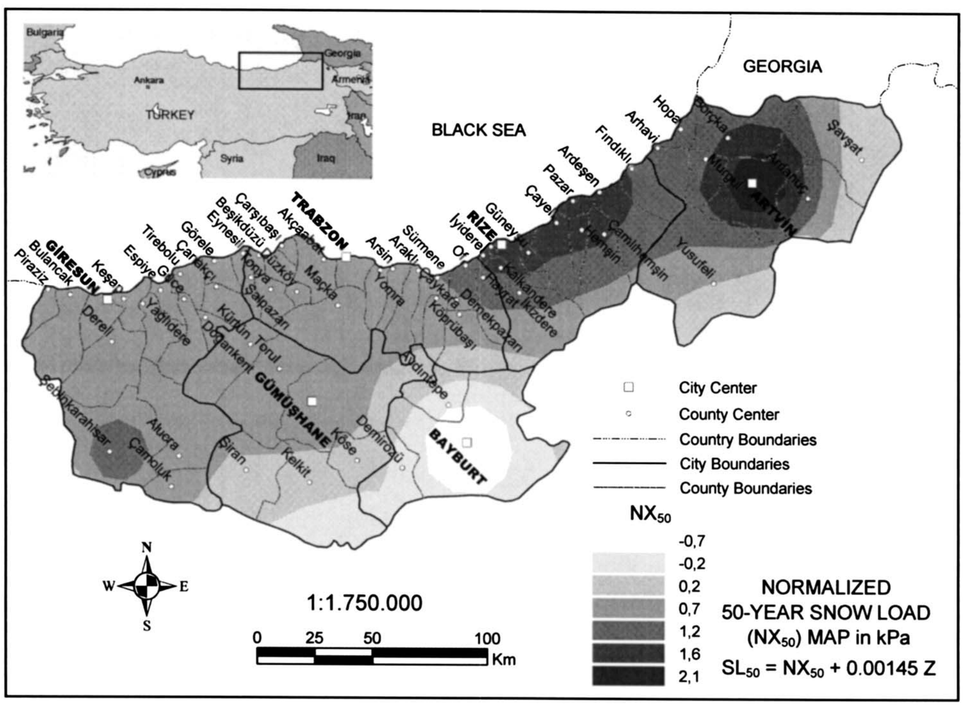

Fig. 6. Normalized 50 year ground snow load map for eastern Black Sea region

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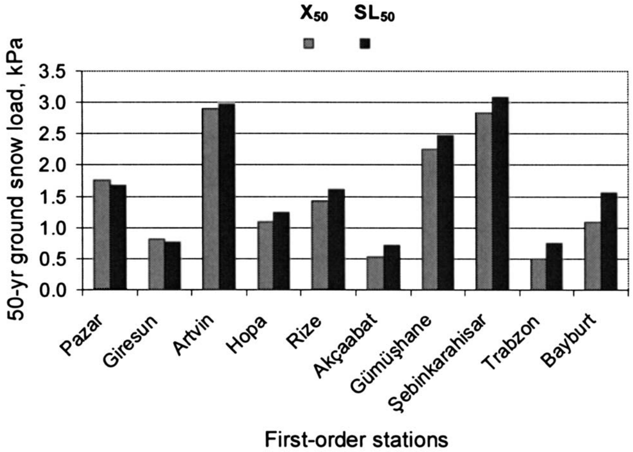

Fig. 7. X_{50} and SL_{50} values for each station in eastern Black Sea region

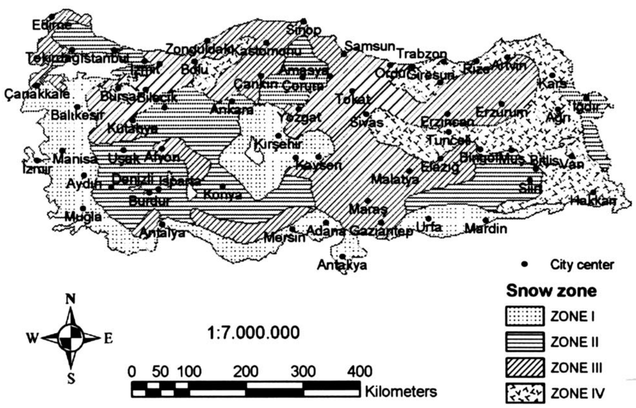

Fig. 8. Snow zone map of Turkey according to *TS 498*

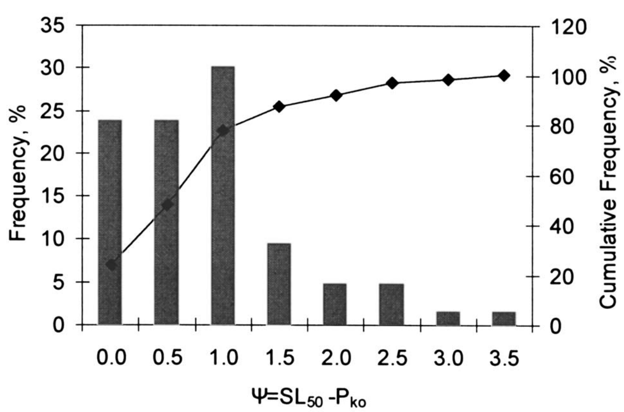

Fig. 9. Histogram of $\Psi = SL_{50} - P_{ko}$ values

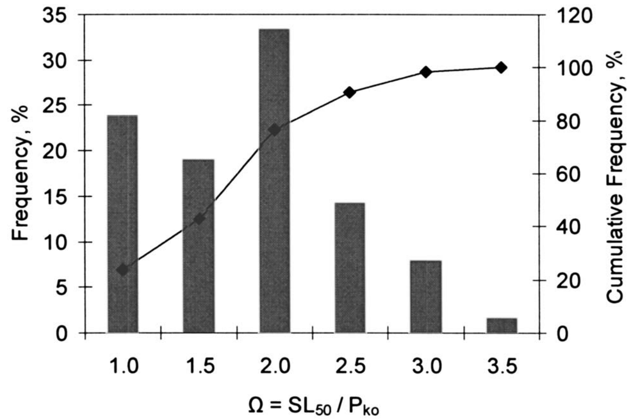

Fig. 10. Histogram of $\Omega = SL_{50}/P_{ko}$ values

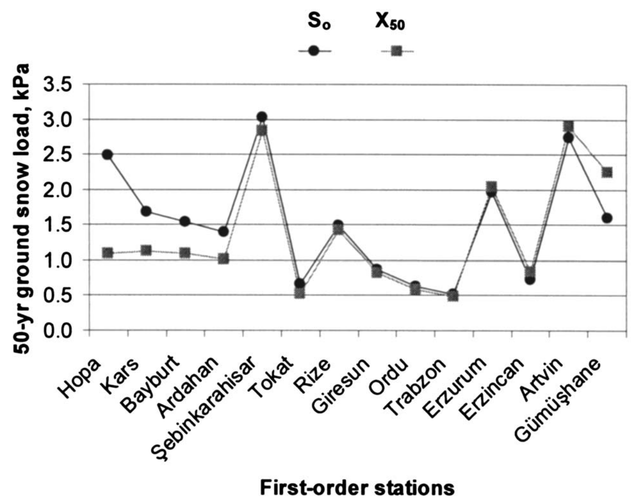

Fig. 11. Comparison of X_{50} values with S_0 values for first-order stations

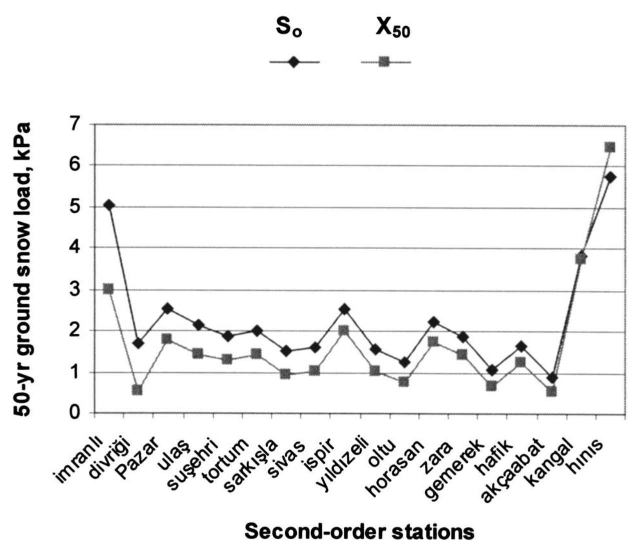

Fig. 12. Comparison of X_{50} values with S_0 values for second-order stations

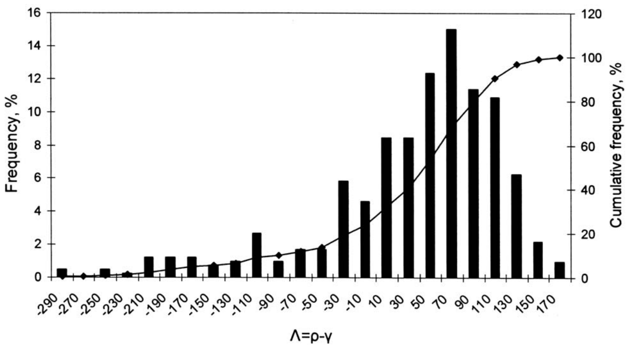

Fig. 13. Histogram of $\Lambda=\rho-\gamma$ values

high-risk period is found, more safety resources should be planned or the activity schedule needs to be rescheduled in order to avoid such a risk-concentrated situation. This risk reducing endeavor involves delaying the schedule of some high-risk activities within a float time, thereby evading the excessive risk. This "safety resource scheduling" procedure is performed using patterns which are similar to the resource leveling technique of scheduling. If after safety resource scheduling the maximum risk score is still higher, then the project duration should be extended and the same procedure applied again until the safety management approves the site's risk level as being sufficiently low enough.

Risk Analysis for Fatalities due to Falls from Heights

The construction industry has the greatest number and rate of occurrence of accidents involving falls from heights (BOMEL 2003) and these falls have been the cause of the greatest number of injuries and fatalities in the construction industry. Not only did they account for 47.0% of all fatal accidents in 2001 and 52.5% in 2002 (KOSHA 2003), there were also similarities in the type and pattern of fatal incidents. About 17.5% of all construction fatalities occur in multistory residential building construction projects, and more than half of these are falls from heights (KOSHA 2003).

Among the 835 fatality reports, 390 cases were found to be involved with falls from the heights. This research analyzed these 390 cases about the occupations, processes, and agents they were involved with and the results. In order to understand the risk characteristics according to the factors involved, the number of fall fatalities occurred was listed for the combinations of occupation-process, process-agent, and agent-occupation, as shown in Tables 7–9. The risk scores are estimated by multiplying each factor and the ten most risky situations in construction are listed in Table 10. These tables illustrate that the risk level can be different according to the combination of risk factors (see Figs. 1–13).

Conclusion

The aim of this paper was to incorporate the ideas of scheduling with safety planning, and to show how the estimation of risk could contribute to safety planning for construction projects. The objectives of these methods were to enhance understanding of when and where the workforce may be vulnerable to serious accidents and to assist the coordinated efforts of safety management and scheduling toward the reduction of accident risk. These methods are applicable to safety planning at the scheduling phase because they introduce appropriate scheduling ideas as tools for safety planning. The tables of risky situations provide information about the risk intensities for each combination of occupation, process, and agent and can help to predict the periods of concentrated risk. These results offer useful information, which facilitates the early prediction of expected vulnerable periods and situations, thereby both enhancing the safety of the workforce and improving productivity.

References

BOMEL Ltd. (2003). *Falls from height-prevention and risk control effectiveness*, Health and Safety Executive.

Cagno, E., Giulio, A. D., and Trucco, P. (2001). "An algorithm for the implementation of safety improvement programs." *Safety Sci.*, 37, 59–75.

Gambatese, J., and Hinze, J. (1999). "Addressing construction worker safety in the design phase-designing for construction worker safety." *Autom. Constr.*, 8, 643–649.

Gyi, D. E., Gibb, A. G. F., and Haslam, R. A. (1999). "The quality of accident and health data in the construction industry: Interviews with senior managers." *Constr. Manage. Econom.*, 17, 197–204.

Hadikusumo, B. H. W., and Rowlinson, S. (2002). "Integration of virtually reality construction models and design for a safety-process database." *Autom. Constr.*, 11, 501–509.

Huang, X., and Hinze, J. (2003). "Analysis of construction worker fall accidents." *J. Constr. Eng. Manage.*, 129(3), 262–271.

Kartam, N. A. (1997). "Integrating safety and health performance into construction." *J. Constr. Eng. Manage.*, 123(2), 121–126.

Kartam, N. A., and Bouz, R. G. (1998). "Fatalities and injuries in the Kuwaiti construction industry." *Accid. Anal Prev.*, 30(6), 805–814.

Kartam, N. A., Flood, I., and Koushki, P. (2000). "Construction safety in Kuwait: Issues, procedures, problems, and recommendations." *Safety Sci.*, 36, 163–184.

Korea Occupational Safety and Health Agency (KOSHA). (2003). "Industrial accident report." *Rep. submitted to Ministry of Labour, 2001–2003*, Korea.

Langford, D., Rowlinson, S., and Sawacha, E. (2000). "Safety behaviour and safety management: Its influence on the attitudes of workers in the UK construction industry." *Eng., Constr., Archit. Manage.*, 7(2), 133–140.

Mohamed, S. (1999). "Empirical investigation of construction safety management activities and performance in Australia." *Safety Sci.*, 33, 129–142.

Mol, T. (2003). *Productive safety management*, Butterworth-Heinemann, Oxford, U.K.

Moselhi, O., and El-Rayes, K. (1993). "Scheduling of repetitive projects with cost optimization." *J. Constr. Eng. Manage.*, 119(4), 681–697.

Saurin, T. A., Formoso, C. T., and Guimaraes, L. B. M. (2004). "Safety and production: An integrated planning and control model." *Constr. Manage. Econom.*, 22(2), 159–169.

Sawacha, E., Naoum, S., and Fong, D. (1999). "Factors affecting safety performance on construction sites." *Int. J. Proj. Manage.*, 17(5), 309–315.

Suraji, A., Duff, A. R., and Peckitt, S. J. (2001). "Development of causal model of construction accident causation." *J. Constr. Eng. Manage.*, 127(4), 337–344.

Tam, C. M., Tong, T. K. L., Chiu, G. C. W., and Fung, I. W. H. (2002). "Non-structural fuzzy decision support systems for the evaluation of construction safety management systems." *Int. J. Proj. Manage.*, 20, 303–313.

Wang, C., and Huang, Y. (1998). "Controlling activity interval times in LOB scheduling." *Constr. Manage. Econom.*, 16(1), 5–16.

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