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Simulation-based safety evaluation model integrated with network schedule

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Abstract

Construction accidents often lead to project delays. However, in practice, construction safety and schedule control are managed separately. This work develops an innovative simulation-based model, SimSAFE, that assesses the hazard (or expected accident costs) for each activity in a network schedule. Thus, at any time point, safety managers can pay considerable attention to activities (or paths or working zones) with high expected accident costs. Additionally, by breaking down the uncertainty of an accident cause occurring, SimSAFE provides factor-sensitivity information to support safety risk management. Enhancing knowledge of the safety factors (such as safety training and site environment) to which an activity (or path or zone) is sensitive, and also of the activities (or paths or zones) that are most sensitive to a particular factor can provide management with a better sense of what factors and activities (or paths or zones) need to be controlled for reducing construction accidents, especially for a large project or multiple projects.

Keywords: Construction safety; Accident cost; Schedule control; Uncertainty; Simulation

1. Introduction

The construction industry is statistically one of the most hazardous industries in many countries [1–3]. For example, in Taiwan, approximately 60% of fatal accidents in all industries between 1999 and 2001 arose in the construction industry [4]. Besides causing human tragedy, construction accidents also delay project progress, increase costs, and damage the reputation of the contractors. Therefore, appropriate safety planning that meets governmental safety regulations is an essential task before commencing construction work. During construction, contractors are asked to employ qualified safety specialists, assemble temporary safety facilities (for example, falsework and electricity), provide safety machinery/equipment (for example, cranes and excavators), supply safeguards (for example, safety signals, safety nets, and fire extinguishers), provide personal protective equipment (for example, hard hats, safety shoes, safety belts, and hearing protection), and provide workers with adequate safety instructions before allowing them on the jobsite.

However, most contractors simply see their safety plans as a burdensome necessity for avoiding government fines, and neglect their implementation [5]. The implementation of safety plans is frequently regarded as an extra task. Several safety professionals have realized that improving safety performance requires integrating safety with construction planning and control [5,6]. Namely, safety management must be treated with the same kind of thoughtful project planning and control that goes into other aspects of project management.

This study proposes a simulation-based model, SimSAFE, that incorporates safety management into schedule control. Specifically, the degree of hazard (or expected accident costs) of each activity in a construction project is evaluated; and this evaluation information is attached to the project network schedule. Simulation algorithms are used to consider uncertainties (uncertain safety factors) that are

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often ignored in safety management. The anticipated advantages of attaching safety information to project schedules are to increase knowledge of the factors to which an activity (or path or zone) is sensitive, and those that are most sensitive to a particular factor. As a result, management can better understand what factors relating to each activity (or path or zone) and of what activities (or paths or zones) to control to reduce construction accidents.

The methodology used in this investigation comprises the following phases: (1) review relevant research to identify the focuses of existing studies; (2) define the factors and the degree of hazard of construction activities; (3) present the SimSAFE model to evaluate the degree of hazard of each activity of a network schedule; (4) illustrate the detailed modeling steps using a two-activity network; (5) demonstrate model operation through application to an example project; and (6) elucidate the advantages of the model and recommend future research directions.

2. Pertinent research

Extensive research has been conducted to improve construction safety. It can be separated into the following seven categories.

Identifying root causes of injuries—for example, Hinze et al. suggested coding injuries into one of 20 possible categories of accident causes, instead of the conventional five groups of falls, struck-by, electric shocks, caught in/between, and others [7].

Identifying factors or strategies that influence safety performance—in the UK, Sawacha et al. identified that the five most important factors or strategies associated with site safety were management talks on safety, provision of safety booklets, provision of safety equipment, provision of safety environment, and appointment of a trained safety representative on site [8]. Using a questionnaire survey, Fang et al. analyzed the correlations between the safety factors and safety management performance [9].

Examining the usefulness of various safety performance measures—considering the effectiveness of a method of measuring safety performance, Laufer and Ledbetter investigated various measurement methods and concluded that the most effective measures were lost-day cases, doctor's cases, and cost of accidents [10]. Hinze et al. focused on a widely-used method, experience modification rating (EMR), for clarifying the effect of different variables on the EMR values [11]. Their results demonstrated that injury frequency impacted the EMR computation more than injury severity. Based on a survey by de la Garza et al. [12], "what gets measured, gets improved."

Designing strategies for improving safety performance—using a behavioral approach, Duff et al. showed that safety behavior can be objectively measured; goal setting and feedback interventions could significantly improve safety performance; and commitment of site managers could enhance intervention effectiveness [13]. Owing to the limitations of each measure of safety performance (including EMR and recordable incident rate), Jaselskis et al. created a questionnaire asking questions regarding the combination of measures that gave the best overall indication of safety performance at both the company and project levels [14].

Estimating the costs of accidents and injuries—Hinze and Appelgate displayed that the indirect costs often substantially exceeded the direct costs for construction injuries [15]. Everett and Frank demonstrated that the costs associated with accidents and injuries have risen from 6.5% of construction costs in 1982 to between 7.9% and 15% in 1995 [16]. Meanwhile, indirect costs, which were less tangible, included those costs associated with loss of productivity, administrative time for investigations and reports, cleanup, repairs, etc.

Addressing construction worker safety in the design phase—considering that designers generally lack the relevant knowledge and thus their involvement in construction safety is limited, Gambatese and Hinze accumulated design suggestions for developing a tool to assist designers in identifying project-specific safety hazards and providing suitable practices for eliminating construction accidents [17].

Integrating safety concerns with other management plans—for instance, Saurin et al. devised a model to integrate safety into three hierarchical levels (namely, long-term, medium-term, and short-term) of production planning [5]. Long-term safety planning started with the preliminary hazard analysis of construction processes. The long-term plans were updated and detailed at both medium (tri-weekly)- and short-term (daily or weekly) planning levels. The major performance measure adopted for safety assessment during the short-term was the percentage of work packages that were completed safely. Kartam designed a framework for a computerized safety and heath knowledge-intensive system that was integrated with current critical-path-method (CPM) scheduling software [6]. In this framework, extensive safety data and knowledge (including knowledge required by law and gathered from professionals) were coded and stored in a database system which was linked to CPM project files.

In summary, the area of research that is most relevant to this work concerns the integration of safety considerations into management plans. The model of Saurin et al. combines safety control functions with existing production planning and control processes. They regarded safety planning and control as a broad managerial process [5]. However, as stated by Saurin et al. [5], their model did not formally evaluate the uncertainty in the occurrence of causes of accidents. Also, their safety planning and control were not integrated with schedule control. The framework proposed by Kartam sought primarily to reduce the time spent searching through volumes of safety regulations using a computerized system, allowing safety information specific to individual activities to be accessed [6]. Namely, the framework did not provide a proactive safety alert (to indicate which activities are more hazardous than others).

3. Factors and degrees of hazard

During construction activity execution, one or several accident causes (simply termed "causes" herein) are likely to occur. Several factors influence the likelihood of a cause occurring during the execution of a particular activity. If factor performance strongly influences the likelihood of a cause occurring during an activity, then management had better pay attention to the effective management of the factor for the activity. Typical safety factors include safety training, site environment, subcontractor safety management ability, and safety inspection. For instance, the likelihood of occurrence of "falls from elevated position" is highly sensitive to the safety training of the workers who perform the steel-erection activity. Namely, inexperienced or poorly trained workers likely lack the safety knowledge required to minimize the risk of falling from high working places. Since factor performance is uncertain, this work treats factors as uncertainty variables.

No accidents occur without there first being a cause. When there is a cause (for example, a laborer falls from an elevation), workers may suffer different degrees of injury (such as, light injury, medium injury, severe injury, disabling injury, or death) and additional costs may be required to deal with the accident. These resulting costs are here called accident costs. (The accident costs are detailed in Section 4.2.1.)

The expected accident cost of activity i due to various causes is termed the degree of hazard of activity i, denoted as H_i; and is represented as

$$H_i = h_{i(1)} + h_{i(2)} + \ldots + h_{i(j)} + \ldots + h_{i(J)} \tag{1}$$

in which $h_{i(j)}$ denotes the degree of hazard (expected accident cost) resulting from cause j ($j=1,\ldots,J$) for activity i. In Taiwan, 15 categories of causes (categories A–O) are commonly used to record accident data. The categories of causes include falls from elevation (A), falls from ground level (B), collisions (C), strikes from falling materials (D), strikes from collapsed objects (E), strikes from equipment (F), caught in/between (trapping by) equipment or material (G), stabbing or slashing (H), trampling (I), burning by high or low temperature materials (J), poisoning by toxic substances (K), electric shock (L), explosion (M), striking by breaking objects (N), and fire (O).

4. SimSAFE model

SimSAFE evaluates the degree of hazard of each activity according to the following four steps (see Fig. 1): (1) evaluating the likelihood of each cause occurring; (2) assessing the accident costs associated with each cause; (3) applying computer simulation for dealing with uncertainties; and (4) integrating safety information with the network schedule. The algorithms used for each step are detailed below.

Notably, in this investigation, the occurrence of a cause depends on the "likelihood" of such a clause occurring. Moreover, this "likelihood" is a variable represented by a distribution of likelihood (a pool of possible likelihood values). Factors affect the distribution of such a variable. A particular likelihood value is picked in a given run (or iteration), depending on how simulation draws from the distribution. For example, if simulation randomly draws a

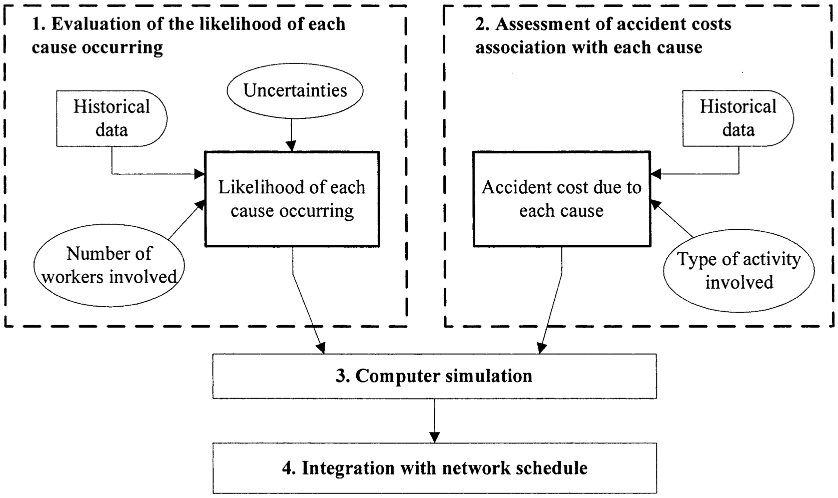

Fig. 1. Modeling steps of SimSAFE.

value of 0.6 from a distribution as the likelihood of a cause occurring, this value of 0.6 then indicates a 60% chance that the cause will occur, and a 40% chance that the cause will not occur. The following section illustrates such a distribution of likelihood.

4.1. Evaluating the likelihood of each cause occurring

For each activity, the distribution of the likelihood of a particular cause occurring is determined based on a reference likelihood and the effects of factors on that likelihood.

4.1.1. Establishing the base likelihood for each accident cause

The reference likelihood of a specific cause occurring is derived from historical data. This reference likelihood (REF_j) of cause j is defined as the total number of construction workers injured owing to cause j in 1 year divided by the total number of construction workers registered with the Taiwan Council of Labor Affairs (CLA) in that year. The Taiwan CLA, the highest governmental agency responsible for occupational safety and health, possesses an annual collection of historical data required to calculate REF_j [4]. Notably, the reference likelihood of a cause (calculated from historical data) is used as a basis for assisting the model user in evaluating the likelihood of the cause's occurring in association with a particular activity. Table 1 lists the likelihood of each cause occurring, on a per worker basis.

For example, 2581 workers were injured because of cause A (falls from evaluation) in 2000; and 722,238 workers were registered with the CLA during the same year. Therefore, the reference likelihood of cause A occurring per worker is 0.0035736 (=2581/722,238). Namely, 3.5736 workers could be injured per thousand workers. Activity execution involves multiple workers. Accordingly, the reference likelihood of cause j should be further multiplied by the number of workers performing the activity. In the above example, if ten workers are involved in an activity, then the likelihood of cause A occurring for that activity equals 0.0035736 × 10=0.035736.

Table 1
Reference likelihood associated with each cause of accidents per worker

Accident causes	Number of workers injured in a year	Reference likelihood
A. Falls from elevation	2581	0.0035736
B. Falls from ground level	1158	0.0016033
C. Collisions	99	0.0001371
D. Strikes from falling material	620	0.0008584
E. Strikes from collapsed objects	154	0.0002132
F. Strikes from equipment	446	0.0006175
G. Caught in/between equipment or material	1644	0.0022763
H. Stabbing or slashing	1892	0.0026196
I. Trampling	19	0.0000263
J. Burning by high or low temperature materials	167	0.0002312
K. Poisoning by toxic substances/gas	40	0.0000554
L. Electric shock	116	0.0001606
M. Explosion	35	0.0000485
N. Striking by breaking objects	4	0.0000055
O. Fire	14	0.0000194

4.1.2. Deriving an overall distribution of the likelihood for each cause

Three-point estimation is adopted to obtain the overall distribution ($F_{i(j)}$) of each cause j occurring for an activity i. The mean ($M_{i(j)}$) and standard deviation ($\sigma_{i(j)}$) of this overall distribution are derived as [18],

$$M_{i(j)} = \frac{\left(l_{i(j)} + 4t_{i(j)} + u_{i(j)}\right)}{6} \tag{2}$$

$$\sigma_{i(j)} = \frac{u_{i(j)} - l_{i(j)}}{3.2} \tag{3}$$

where $l_{i(j)}$, $t_{i(j)}$ and $u_{i(j)}$ denote the optimistic (or low), most likely and pessimistic (or high) likelihoods of $F_{i(j)}$ due to cause j for activity i, respectively ($i=1, 2, \ldots, I$ and $j=1, 2, \ldots, J$).

The derived reference likelihoods listed in Table 1 are used to help establish the distribution of $F_{i(j)}$. For practical considerations, a multiplier system is proposed to help determine the three-point estimations such that the model user needs only provide qualitative inputs. Table 2 shows an example of such a multiplier system including seven multipliers, each corresponding to a particular qualitative estimate. In the previous example, if the qualitative estimate of pessimistic value because of cause A for activity i is determined to be "higher than" the reference likelihood, then the derived pessimistic likelihood ($u_{i(j)}$)=reference likelihood × number of workers involved × a corresponding multiplier=0.0035736 × 10 × 2.0=0.071472. Notably, the model user can define their multiplier system using varying multiplier values.

4.1.3. Breaking down the overall distribution

Each overall distribution ($F_{i(j)}$) is disaggregated as the sum of a deterministic base likelihood and a series of zero-mean sub-distributions (called factor distributions) due to various factors. Additionally, each factor distribution with respect to a particular factor is further broken down into a family of several sub-sub-distributions (called factor-condition distributions) representing the uncertainty resulting from a specific condition (such as, good, normal, or bad) of the factor. Fig. 2 illustrates the two breakdowns of uncertainty for $F_{i(j)}$. Notably, the model user determines the number of factors involved and the number of factor-condition distributions in a family.

Mathematically, $F_{i(j)}$, a random variable, is represented by [19]

$$F_{i(j)} = f_{i(j,0)} + f_{i(j,1)} + \ldots + f_{i(j,K)} \tag{4}$$

Table 2
Multiplier system to transfer qualitative estimates of likelihood

Qualitative estimates	Extremely higher than (EH)	Higher than (H)	Slightly higher than (SH)	Almost the same as (AS)	Slightly lower than (SL)	Lower than (L)	Extremely lower than (EL)
Multiplier	2.5	2	1.5	1	0.67	0.5	0.4

where $f_{i(j,0)}$ denotes the base likelihood estimated under the expected conditions of all factors. The random variable, $f_{i(j,k)}$, is the factor distribution of cause j because of factor k ($k=1, \ldots, K$) for activity i.

The expected values of the factor distributions are assumed to be zero; $m_{i(j,1)}=m_{i(j,2)}=\ldots=m_{i(j,K)}=0$. $f_{i(j,1)}$, $f_{i(j,2)}$, …, and $f_{i(j,K)}$ are assumed to be independent of one another. Then, regardless of the statistical distribution of $f_{i(j,k)}$, the mean ($m_{i(j)}$) and variance ($\sigma^2_{i(j)}$) of $F_{i(j)}$ are as follows [19,20]:

$$\begin{aligned} M_{i(j)} &= m_{i(j,0)} + m_{i(j,1)} + m_{i(j,2)} + \ldots + m_{i(j,K)} \\ &= m_{i(j,0)} \end{aligned} \tag{5}$$

$$\begin{aligned} \sigma^2_{i(j)} &= \mathrm{SD}^2_{i(j,0)} + \mathrm{SD}^2_{i(j,1)} + \mathrm{SD}^2_{i(j,2)} + \ldots + \mathrm{SD}^2_{i(j,K)} \\ &= \mathrm{SD}^2_{i(j,1)} + \mathrm{SD}^2_{i(j,2)} + \ldots + \mathrm{SD}^2_{i(j,K)} \end{aligned} \tag{6}$$

where $\mathrm{SD}^2_{i(j,k)}$ denotes the variance of $f_{i(j,k)}$; $\mathrm{SD}^2_{i(j,0)}=0$. Restated, the mean of $F_{i(j)}$ is its base likelihood, and the variance of $F_{i(j)}$ is the sum of the variances of individual factor distributions.

4.1.4. Deriving factor distribution

The overall distribution is broken down into several factor distributions based on subjective information. That is, for each activity, the model user must qualitatively estimate the sensitivity of each factor on each cause occurring. If cause j is highly sensitive to a specific factor k, a large portion of the variance ($\sigma^2_{i(j)}$) of the overall distribution due to cause j is then allocated as the variance of the factor distribution owing to factor k.

A scale system is devised for allocating the variance of the overall distribution to the factor distributions. Namely [19,20],

$$\sigma^2_{i(j)} = \mathrm{SD}^2_{i(j,1)} + \mathrm{SD}^2_{i(j,2)} + \ldots + \mathrm{SD}^2_{i(j,K)} \tag{7a}$$

$$= \left(w_1\left[Q_{i(j,1)}\right] + w_2\left[Q_{i(j,2)}\right] + \ldots + w_K\left[Q_{i(j,K)}\right]\right) \times Y_{i(j)} \tag{7b}$$

$$\mathrm{SD}^2_{i(j,k)} = w_k\left[Q_{i(j,k)}\right] \times Y_{i(j)} \tag{8}$$

where $Q_{i(j,k)}$ denotes the qualitative estimate of cause j for factor k. Moreover, $w_k[Q_{i(j,k)}]$ represents a scale of each

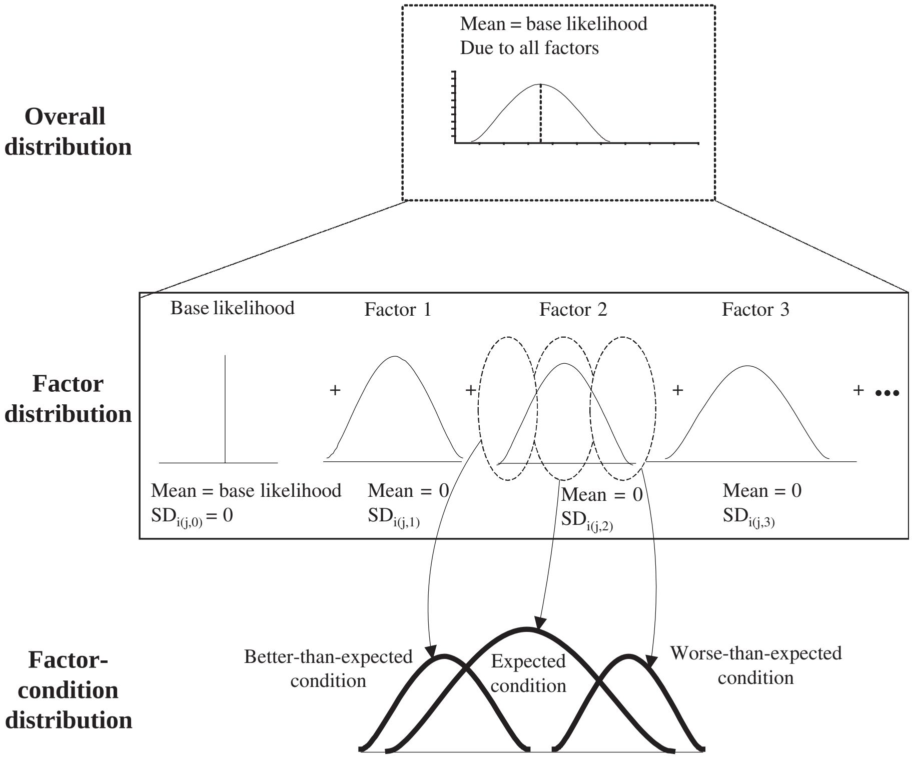

Fig. 2. Two breakdowns of the overall distribution of the likelihood associated with each cause.

level of influence. If $Q_{i(j,k)}$ represents a high level of influence,then $w_k[Q_{i(j,k)}]$ is great. The relative importance of factors determines the value of $w_k[Q_{i(j,k)}]$. $Y_{i(j)}$ is an adjustment constant that ensures that the variance ($\sigma^2_{i(j)}$) is maintained. The value of $w_k[Q_{i(j,k)}]$ remains the same for each factor and level of influence, so $Y_{i(j)}$ differs for each cause.

4.1.5. Deriving child distributions

In the second breakdown of uncertainty (see Fig. 2), the mean ($m_{i(j,k)}$) and variance ($SD^2_{i(j,k)}$) of the factor distribution equal the mean and variance of the combination of the factor-condition distributions for a family, respectively. Mathematically, this relationship is given by [19,20]

$$m_{i(j,k)} = 0 = \sum_{c=1}^{C} p_{j,k(c)} \times o_{i,j[k(c)]} \tag{9}$$

$$\mathrm{SD}^2_{i(j,k)} = \sum_{c=1}^{C} p_{j,k(c)} \times \left(\mathrm{sd}^2_{i,j[k(c)]} + o^2_{i,j[k(c)]}\right) \tag{10}$$

where C denotes the number of factor-condition distributions, and $p_{j,k(c)}$ represents the probability of occurrence of factor-condition distribution c of factor k for cause j. The mean and standard deviation of the factor-condition distribution c of factor k associated with cause j for activity i are $o_{i,j[k(c)]}$ and $sd_{i,j[k(c)]}$, respectively.

4.2. Assessing the accident costs associated with each cause

In the event of an accident, the resulting accident cost depends on the type of injury. This section illustrates the accident cost for each type of injury, the chance of each type of injury occurring, and the expected accident cost (the degree of hazard) due to each cause for each activity.

4.2.1. Accident cost for each injury type

The five-type injury classification system used by the Institute of Occupational Safety and Health (IOSH) in Taiwan is adopted in this study. This system classifies injuries as light (represented by $t1$), medium ($t2$), severe ($t3$), disabling ($t4$), and fatal ($t5$) [21]. Based on the accident cost data presented by IOSH, the average accident costs per accident for injury t ($t=t1-t5$) for a specific cause j, $\mathrm{Cost}_{t(j)}$, are estimated and listed in Table 3. Table 3 lists the accident costs in New Taiwan dollars, hereafter referred to as NT dollars. (1 US dollar≅32 New Taiwan dollars.)

Accident costs include both direct and indirect costs. The direct costs were estimated using historical data collected by IOSH between 1991 and 1993 [21]. Moreover, the direct costs per accident consisted of the compensation (e.g., wages paid to the injured workers for time not worked and consolation money) paid by the contractor to the injured workers, plus any compensation (e.g., cash payments to the injured workers and medical care) paid by the public liability insurance (namely, the Bureau of Labor Insurance of Taiwan). Notably, the analysis presented in Table 3 excluded compensation from private insurance companies. The indirect costs per accident included the costs of accident investigation, legal fees, training costs for replacement workers, equipment and materials damage, lost profits, and costs associated with loss of productivity (if any). These costs, which are comparatively difficult to quantify, were estimated by interviews (or sometimes questionnaires) with over 70 Taiwanese contractors [21].

Table 3
Cost of accident of each type of injury for each cause

Causes	Accident costs (in thousand, NT dollars)				
	Light injury	Medium injury	Severe injury	Disabling injury	Death
A	15	158	461	1093	2143
B	10	167	730	538	2143
C	6	68	665	311	2143
D	16.1	192.5	713.8	1151	2294.8
E	32.8	223	681	1615	3053.8
F	6.2	77.2	688.4	240	2446.6
G	6	141	653	381	2143
H	11	50	261	336	2143
I	9	62	494	168	2143
J	10.5	132	983	448	2143
K	11	98	757	309	2143
L	21.5	159.8	1201	657.6	2294.8
M	52.2	281.4	825	1187	3357.4
N	21.5	193	187.5	582.5	2902
O	56.3	252.1	742	1769	2598.4

The accident costs listed in Table 3 are calculated as follows. For example, the per accident cost of light injury for cause A is

$$\begin{aligned} \mathrm{NT}\$15{,}000 &= \text{direct costs} + \text{indirect costs} \\ &= (\text{direct costs per lightly injured worker} \\ &\quad \times \text{average number of workers injured due} \\ &\quad \text{to cause A}) + \text{indirect costs per accident} \\ &= (\$3000 \times \text{worker per accident}) \\ &\quad + 12{,}000. \end{aligned}$$

The figures of \$3000 and \$12,000 were obtained from IOSH. Moreover, the average number of workers injured was estimated based on the 3-year historical accident data from the Taiwanese Council of Labor Affairs [4]. Namely, the average number of workers injured owing to a particular cause was the total number of workers injured due to that cause during a 3-year period divided by the number of accidents because of that cause during that period. For example, the average number of workers injured due to cause A was one person per accident. (Notably, the accident cost data listed in Table 3 can be updated if additional historical data are collected. It is suggested that future research can conduct this updating work.)

4.2.2. Chance of each type of injury arising

The chance of a particular type of injury occurring following the occurrence of a particular cause can vary in executing different activities. For practicality, the model user qualitatively assesses the chances of various types of injury occurring, then transfers these qualitative assessments to quantitative values. A possible set of quantitative values for various qualitative estimates is very high (VH) = 5; high (H) = 4; medium (M) = 3; low (L) = 2; and very low (VL) = 1. For example, assume that the chances of light injury, medium injury, severe injury, disabling injury, and fatal injury occurring following the occurrence of cause A in association with a particular activity are qualitatively estimated as follows: VL, L, L, H and VH, respectively. The chances of these five types of injuries occurring following the occurrence of this cause then are 1/14 (= 1/(1 + 2 + 2 + 4 + 5)), 2/14, 2/14, 4/14, and 5/14, respectively. Notably, the model user is permitted to define their quantitative values.

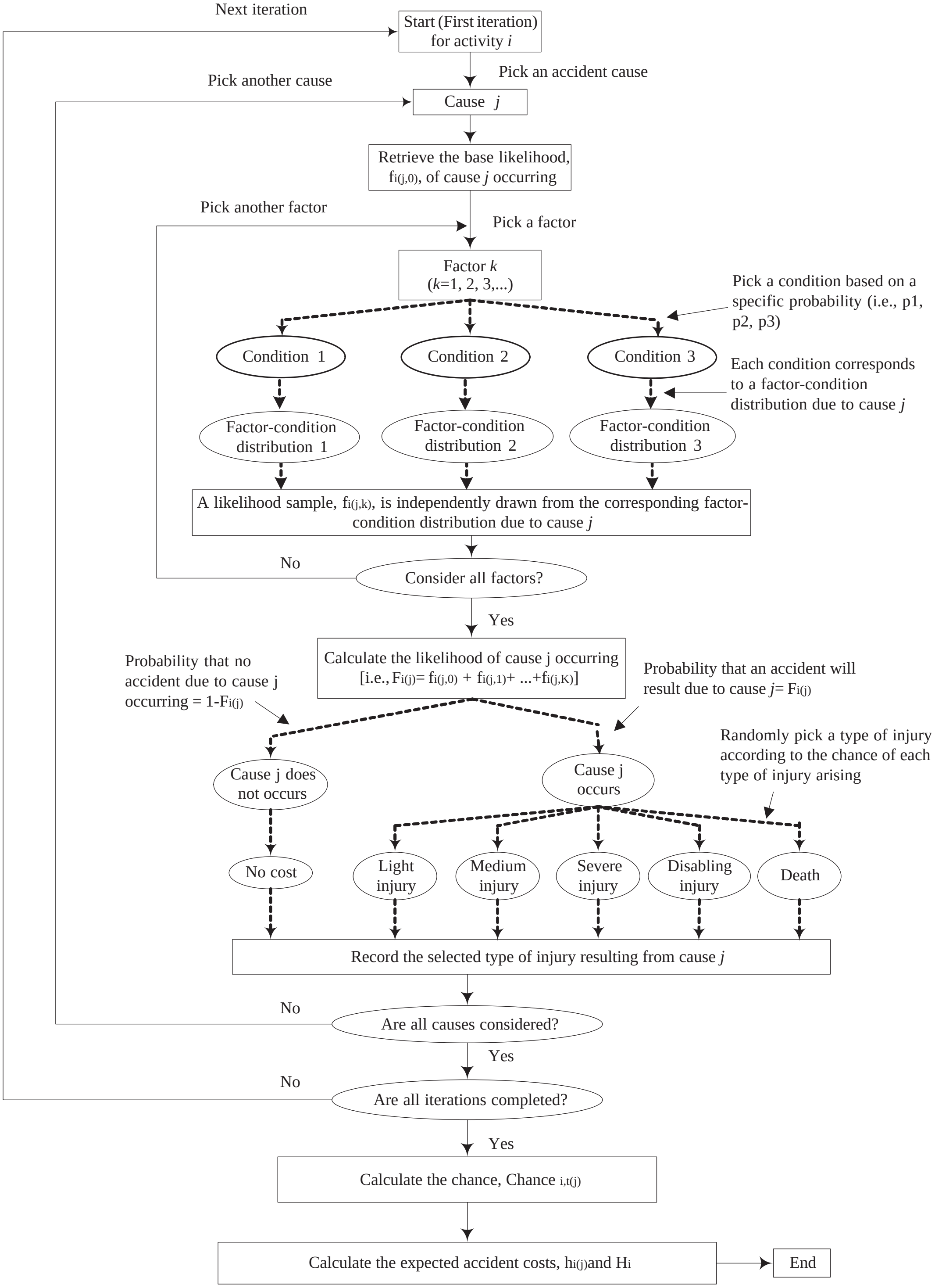

Fig. 3. Steps of computer implementation of each activity in SimSAFE.

4.2.3. Expected accident cost for each cause

The expected accident cost owing to cause j in association with activity i, $h_{i(j)}$, is calculated as follows

$$h_{i(j)} = \sum_{t=t1}^{t5} \left(\text{Chance}_{i,t(j)} \times \text{Cost}_{t(j)}\right) \tag{11}$$

where $\text{Chance}_{i,t(j)}$ is the chance of injury t occurring due to j for activity i following a certain number of simulation iterations. See Section 4.3. $\text{Chance}_{i,t(j)}$ is determined based on the likelihood of a cause j ($F_{i(j)}$) occurring, and the chance of a particular injury t (refer to Section 4.2.2) arising in association with activity i. $\text{Cost}_{t(j)}$, listed in Table 3, is the average cost per accident for injury t given a specific cause j.

4.3. Computer simulation

Fig. 3 shows the implementation strategy of the SimSAFE model. The following steps are executed during each simulation iteration for activity i.

- The base likelihood ($f_{i(j,0)}$) of each cause j occurring is retrieved.
- A condition is selected for each factor k in association with each cause j based on a specific probability ($p_{j,k(c)}$) that the condition applies.
- A likelihood sample ($f_{i(j,k)}$) is independently drawn from the factor-condition distribution corresponding to the condition for cause j.
- After processing all the conditions of each factor, the overall distribution ($F_{i(j)}$) associated with each cause j is determined by summing its base likelihood and variations resulting from each factor condition. See Eq. (4).
- The probability that an accident will result due to cause j then is $F_{i(j)}$. Meanwhile, the probability of no accident occurring owing to cause j is $1-F_{i(j)}$. The model randomly determines whether an accident will occur because of cause j.
- No accident cost results if no accident occurs due to cause j. If an accident does occur owing to cause j, a particular type of injury t then is determined (see Section 4.2.2). At this step, the selected type of injury resulting from cause j is recorded.
- The above steps are repeated for all causes.

Following all iterations are considered, the chance ($\text{Chance}_{i,t(j)}$) that a particular injury t due to cause j in association with activity i is calculated. Subsequently, the expected accident costs owing to cause j ($h_{i(j)}$) and due to all causes (H_i) for each activity can be obtained based on Eqs. (11) and (1), respectively.

A simulation language, Stroboscope [22], was used to implement the simulation-relevant algorithms described herein. Stroboscope can dynamically access simulation state and includes an add-on that enables the definition of CPM networks with stochastic variables (for example, the occurrence of a cause) and the calculation of various statistics regarding the activities, paths, working zones and project. In this investigation, Stroboscope was run in the Windows 2000 environment, with a P3 850 CPU and 256 Mega Ram. Approximately 1 min was required to run 1000 iterations.

4.4. Integration with CPM network

The simulated likelihood of each cause ($F_{i(j)}$) occurring and the expected accident costs ($h_{i(j)}$ and H_i) for each activity are attached to the schedule network. Then, the sensitivities of paths (or zones) to uncertainties are assessed. The uncertainty sensitivity of factor k on a particular path for cause j is measured using the Coefficient of Variation (CV) of the occurrence of an accident along path. A path is considered highly sensitive to a factor if it has a high CV value for that factor. High factor sensitivity along a path indicates that the occurrence of an accident due to cause j for the path is strongly affected by change in that factor. Mathematically, the value of CV of a path for factor k, $\text{CV}_{\text{path},k}$, is

$$\text{CV}_{\text{path},k} = \text{PSD}_{\text{path},k}/\text{Mean}_{\text{path}} \tag{12}$$

in which $\text{Mean}_{\text{path}}$ denotes the mean occurrence of accident due to all causes for all factors along a path, and $\text{PSD}_{\text{path},k}$ is the standard deviation of accident occurrence due to all causes along a path when only factor k is assessed.

Similarly, the uncertainty sensitivity for factor k in a working zone ($\text{CV}_{\text{zone},k}$) is as follows.

$$\text{CV}_{\text{zone},k} = \text{ZSD}_{\text{zone},k}/\text{Mean}_{\text{zone}} \tag{13}$$

where $\text{Mean}_{\text{zone}}$ denotes the mean accident occurrence due to all causes for all factors within a zone; and $\text{ZSD}_{\text{zone},k}$ represents the standard deviation of accident occurrence due to all causes within a specific zone when only factor k is assessed.

5. Model operation using a two-activity network

This section illustrates the input operations for SimSAFE using a two-activity small network; activities $X \rightarrow Y$. Ten and 15 workers are involved in executing activities X and Y, respectively. Five accident causes are considered, including causes A, B, D, E, and L. Moreover, three factors are considered, including factors F1, F2, and F3.

5.1. Inputs

5.1.1. Input 1: providing three-point estimations of likelihoods

The model user qualitatively provides the optimistic likelihood ($l_{i(j)}$), most likely likelihood ($t_{i(j)}$), and pessimistic likelihood ($u_{i(j)}$) for each cause j in association with each activity i. Each qualitative estimate is then transformed to a quantitative value based on a multiplier system listed in

Table 4
Three-point estimates of the likelihood of each cause (two-activity example)

Activity	Cause	Qualitative estimates of likelihood			Transformed quantitative values of likelihood				
		Pessimistic estimate	Most likely estimate	Optimistic estimate	Pessimistic value	Most likely value	Optimistic value	Mean	Standard deviation
X	A	H	SH	SL	0.07147	0.05360	0.02394	0.051639	0.014853
	E	H	SH	SL	0.00267	0.00200	0.00089	0.001926	0.000554
	B	H	SH	SL	0.03207	0.02405	0.01074	0.023168	0.006664
	L	H	SH	SL	0.00292	0.00219	0.00098	0.002110	0.000607
	D	H	SH	SL	0.07147	0.01171	0.00523	0.020588	0.020701
Y	A	SH	AS	L	0.08041	0.05360	0.02680	0.053604	0.016751
	E	SH	AS	L	0.00300	0.00200	0.00100	0.001999	0.000625
	B	SH	AS	L	0.03608	0.02405	0.01203	0.024050	0.007516
	L	SH	AS	L	0.00329	0.00219	0.00110	0.002190	0.000684
	D	SH	AS	L	0.01756	0.01171	0.00585	0.011706	0.003658

H—higher; SH—slightly higher; AS—almost the same as; L—lower than.

Table 2. Take cause A for activity *X* for example. If the qualitative estimates of $l_{i(j)}$, $t_{i(j)}$, and $u_{i(j)}$ are "higher," "slightly higher," and "slightly lower" than the reference likelihood, respectively, then the quantitative values of the likelihoods for cause A are 0.07147 ($=2\times 0.0035736\times 10$), 0.05360 ($=1.5\times 0.0035736\times 10$), and 0.02394 ($=0.67\times 0.0035736\times 10$), respectively. Table 4 lists the values of $l_{i(j)}$, $t_{i(j)}$, and $u_{i(j)}$ for each cause in association with each activity. Additionally, the mean and standard deviation of the overall distribution are calculated using Eqs. (2) and (3) and are also displayed on the right of Table 4.

5.1.2. Input 2: providing qualitative factor sensitivities

Table 5 lists the sensitivity of each factor on the occurrence of each cause for each activity. For example, factors F1, F2 and F3 have high, low and medium sensitivities to the occurrence of cause A for activity *X*, respectively.

5.1.3. Input 3: estimating the chance of each type of injury arising

Table 6 lists the qualitative estimates and calculated values of the chance of each type of injury occurring. For example, in cause A, the qualitative estimates of the chances of occurrence for light injury, medium injury, severe injury, disabling injury, and fatal injury are very low (VL), low (*L*), low (*L*), high (*H*) and very high (VH), respectively. Then, based on a transforming system (VL=1, L=2, H=4 and VH=5), the quantitative chances of the five types of injury occurring owing to cause A are light injury=1/(1+2+2+4+5)=0.07; medium injury=2/(1+2+2+4+5)=0.14; severe injury=2/(1+2+2+4+5)=0.14; disabling injury=4/(1+2+2+4+5)=0.29; fatal injury=5/(1+2+2+4+5)=0.36. These qualitative inputs can vary according to cause and activity.

5.2. Calculating the factor and factor-condition distributions

In SimSAFE, the simulation algorithm is run to determine the likelihood of a particular cause occurring based on the families of factor-condition distributions. Deriving the mean ($o_{i,j[k(c)]}$) and standard deviation ($\mathrm{sd}_{i,j[k(c)]}$) of a family of factor-condition distributions requires first determining the variance ($\mathrm{SD}^2_{i(j,k)}$) of the factor distribution ($f_{i(j,k)}$). Take cause A for activity *X* for example. $\mathrm{SD}^2_{i(j,k)}$ is determined follows. (Table 7 lists the calculated $\sigma^2_{i(j)}$ and $\mathrm{SD}^2_{i(j,k)}$ for each factor distribution).

- Since the standard deviation ($\sigma_{i(j)}$) of the overall distribution equals 0.014853 (see Table 4), then $\sigma^2_{i(j)}=0.014853\times 0.014853=0.0002206$.

Table 5
Sensitivities of each factor to each cause (two-activity example)

Activity	Cause	Factor sensitivity		
		F1	F2	F3
X	A	High	Low	Medium
	E	High	Medium	Medium
	B	Medium	Medium	Medium
	L	Low	Low	High
	D	Medium	Low	Low
Y	A	Medium	Low	High
	E	High	Medium	Medium
	B	Medium	Low	High
	L	High	Medium	Medium
	D	Medium	Low	High

Table 6
Qualitative and quantitative estimates of the chance of each type of injury occurring (two-activity example)

Cause	Chance				
	Light injury	Medium injury	Severe injury	Disabling injury	Death
A	VL (0.07)	L (0.14)	L (0.14)	H (0.29)	VH (0.36)
E	VL (0.08)	L (0.15)	M (0.23)	M (0.23)	H (0.31)
B	VL (0.08)	VL (0.08)	M (0.23)	H (0.31)	H (0.31)
L	VL (0.08)	L (0.17)	L (0.17)	M (0.25)	H (0.33)
D	L (0.13)	M (0.19)	L (0.13)	H (0.25)	VH (0.31)

VL—very low; L—Low; H: high; VH: very high; M—medium.
The bracketed value represents the quantitative estimate of the chance of each type of injury arising.

- As indicated in Table 5, factors F1, F2 and F3 have high, low and medium sensitivities to cause A occurring for activity X, respectively. The following values are assumed: w_{F1}[high]=8, w_{F1}[low]=1, and w_{F1}[medium]=5. Then, $\sum_{k=1}^{K} W_k\left[Q_{i(j,k)}\right] = 8+1+5 = 14$.
- Based on Eq. (7a) (7b), $Y_{i(j)} = 0.0002206 \div 14 = 0.00001576$.
- Based on Eq. (8), $\mathrm{SD}^2_{i(j,F1)} = 8 \times 0.00001576 = 0.00012606$; $\mathrm{SD}^2_{i(j,F2)} = 1 \times 0.00001576 = 0.00001576$; and $\mathrm{SD}^2_{i(j,F3)} = 5 \times 0.00001576 = 0.00007879$.

Assume that the user chooses the categories better-than-expected, as-expected, and worse-than-expected to describe the conditions of the factor (F1). A family of three factor-condition distributions can then be constructed. Assume that the factor-condition distributions all have equal probabilities of occurrence. Restated, $p_1 = p_2 = p_3 = 1/3$. The following relationships thus can be identified based on Eqs. (9) and (10):

$$(1/3)o_1 + (1/3)o_2 + (1/3)o_3 = 0 \tag{14}$$

$$(1/3)\left(\mathrm{sd}_1^2 + o_1^2\right) + (1/3)\left(\mathrm{sd}_2^2 + o_2^2\right) + (1/3)\left(\mathrm{sd}_3^2 + o_3^2\right) = 0.00012606. \tag{15}$$

Assume $-o_1 = o_3 = x$ and $o_2 = 0$ so that Eq. (14) is satisfied. Let the factor-condition distributions have equal standard deviations. Eq. (15) then can be rewritten as

$$\mathrm{sd}^2 + (2/3)x^2 = 0.00012606. \tag{16}$$

The limit of the value of x is determined by requiring the variance of the factor-condition distribution to be non-negative. That is,

$$\mathrm{sd}^2 = 0.00012606 - (2/3)x^2 0. \tag{17}$$

Thus, the limit in this case is $x \leq 0.013751$ (limit = 0.013751). Namely, the values −0.013751 and 0.013751 are the two extreme means for factor-condition distributions one and three, respectively. The next step is to assign x a value between 0 and 0.013751. Rather than specifying the exact value of x, the SimSAFE model suggests selecting the value of x based on the level of factor sensitivity. For example, o_3 has the values 0.7 Limit, 0.5 Limit, and 0.3 Limit for high, medium, and low levels of influence, respectively. In this example (high level of influence), x is set to 0.7 Limit = 0.009626. Thus, the properties of the three factor-condition distributions are $p_1 = 1/3$, $o_1 = -0.00963$, $\mathrm{sd}_1 = 0.00802$; $p_2 = 1/3$, $o_2 = 0$, $\mathrm{sd}_2 = 0.00802$; and $p_3 = 1/3$, $o_3 = 0.00936$, $\mathrm{sd}_3 = 0.00802$. Table 8 lists the properties of the factor-condition distribution for factor (F1) for the two activities (Chou provides further details [19]).

Table 7
Variance of factor distribution due to each cause (two-activity example)

Activity	Cause	Variance ($\sigma^2_{i(j)}$)	Variance of factor distribution ($\mathrm{SD}^2_{i(j,k)}$)		
			F1	F2	F3
X	A	0.00022061	0.00012606	0.00001576	0.00007879
	E	0.00000031	0.00000014	0.00000009	0.00000009
	B	0.00004441	0.00001480	0.00001480	0.00001480
	L	0.00000037	0.00000004	0.00000004	0.00000029
	D	0.00042854	0.00030610	0.00006122	0.00006122
Y	A	0.00028061	0.00010022	0.00002004	0.00016035
	E	0.00000039	0.00000017	0.00000011	0.00000011
	B	0.00005649	0.00002017	0.00000403	0.00003228
	L	0.00000047	0.00000021	0.00000013	0.00000013
	D	0.00001338	0.00000478	0.00000096	0.00000765

Table 8
Properties of factor-condition distribution due to factor F1 (two-activity example)

Activity	Cause	Sensitivity	Condition 1			Condition 2	Condition 3
			p_1	sd_1	o_1	o_2	o_3
X	A	High	0.33	0.00802	−0.00963	0.00000	0.00963
	E	High	0.33	0.00026	−0.00032	0.00000	0.00032
	B	Medium	0.33	0.00333	−0.00236	0.00000	0.00236
	L	Low	0.33	0.00018	−0.00007	0.00000	0.00007
	D	Medium	0.33	0.01515	−0.01071	0.00000	0.01071
Y	A	Medium	0.33	0.00867	−0.00613	0.00000	0.00613
	E	High	0.33	0.00030	−0.00036	0.00000	0.00036
	B	Medium	0.33	0.00389	−0.00275	0.00000	0.00275
	L	High	0.33	0.00033	−0.00039	0.00000	0.00039
	D	Medium	0.33	0.00189	−0.00134	0.00000	0.00134

6. Example

To demonstrate the benefits of SimSAFE, this section applies SimSAFE to a high-tech facility construction project in northern Taiwan. The project includes a central utility building (CUB) and a fabrication building (FAB). The total floor area is 100,255 m^2. The main CUB and FAB structures are made of reinforced concrete (RC) and steel reinforced concrete (SRC), respectively. Both buildings require foundations, structure, interior finishing and wall decoration. Fig. 4 illustrates the simplified schedule network, which includes 15 activities (A1–A15), and the logical relationships among the various project activities. The figure also displays the five major working zones for this project, including zone 1 (foundation for CUB; including A1–A4), zone 2 (bottom RC structure for CUB; including A5 and A6), zone 3 (foundation for FAB; including A7 and A8), zone 4 (SRC for FAB; including A9–A11) and zone 5 (finishing and decoration for both CUB and FAB; including A12–A15). Table 9 also lists the duration of each activity and the number of workers involved.

6.1. Inputs and evaluations

Table 10 shows the three-point estimations of the likelihood for each cause in association with each activity. Based on Eqs. (2) and (3), Table 10 also lists the values of $M_{i(j)}$ and $\sigma_{i(j)}$ of the overall distribution due to each cause. Three factors are considered in the example, including

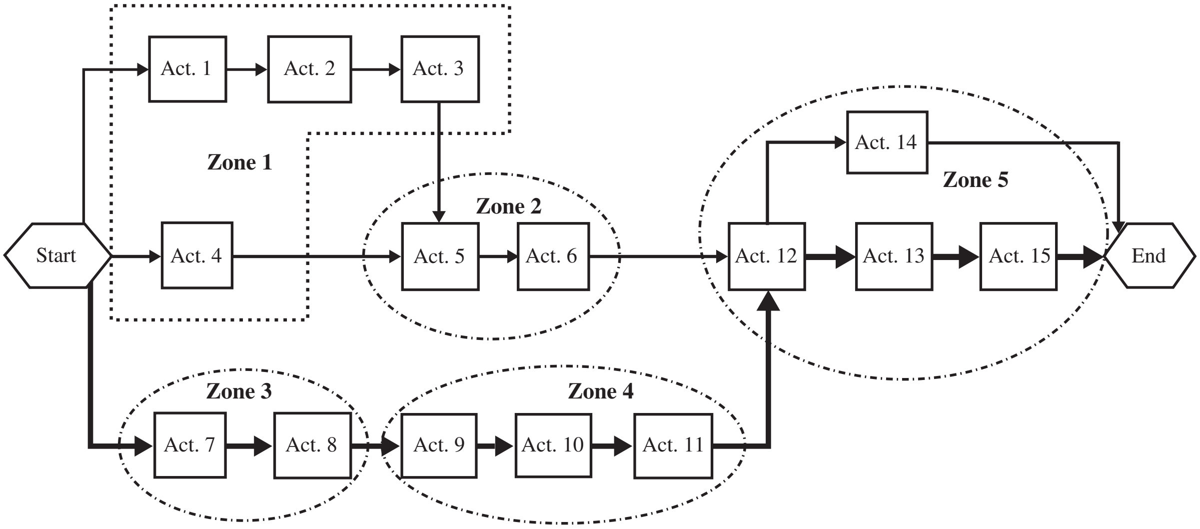

Fig. 4. Simplified schedule network for example project.

safety training (F1), site environment (F2), and subcontractor safety management ability (F3). (Again, the number of factors is not restricted in SimSAFE.) Table 11 lists the sensitivity of each factor on the occurrence of each cause for each activity. Additionally, Table 12 shows the qualitative estimates of the chances of various types of injury occurring due to each cause for each activity.

6.2. Results

The inputs were processed and simulated for 1000 iterations. Table 13 presents the expected accident cost (H_i) associated with each activity. The table also lists the mean occurrence of accident due to all causes for all factors in association with each activity, and the standard deviation of accident occurrence due to all causes for a particular factor in association with each activity. Accordingly, the sensitivities of the likelihood of an accident's occurrence to each factor can be calculated for each activity. Based on Eq. (13), Table 14 displays the sensitivities of the likelihood of an accident's occurrence to each factor, for each zone.

Table 9
Duration of, and number of workers involved in, each activity of the example project

Activity number	Description	Duration (days)	Number of workers involved
1	Excavation (CUB)	24	20
2	Anchored retaining walls (CUB)	18	15
3	Reinforced-rebar piling (CUB)	20	15
4	Steel piling (CUB)	12	8
5	Installing reinforced rebars and forming (basement, CUB and FAB)	45	30
6	Concreting (basement, CUB and FAB)	29	10
7	Reinforced-rebar piling (FAB)	23	18
8	Foundation	20	24
9	Steel erection (FAB)	55	15
10	Deck erection (FAB)	26	15
11	Concreting (FAB)	34	8
12	Installing reinforced rebars and forming (upper structure, CUB)	130	42
13	Concreting (upper structure, CUB)	76	16
14	Interiors (CUB and FAB)	113	55
15	Walls (CUB and FAB)	53	30

6.2.1. Managing activities

The top five activities in the example project, to which most attention should be paid to prevent accidents are activities A14 (H_i=NT$115,046), A12 ($73,888), A5 ($69,758), A9 ($54,206) and A15 ($53,821). Therefore, whenever these activities are ready to be begun or are in progress, safety inspections must be performed frequently. Moreover, in controlling the safety of each activity, the factor that dominates the occurrence of accidents must be known. For instance, activity A14 is most sensitive to F1, and then F3 and F2. Hence, improving safety training (F1) is the most effective way to control the safety of A14.

6.2.2. Managing paths

In the example project, the critical path contains activities A7, A8, A9, A10, A11, A12, A13 and A15. As well as paying attention to controlling the duration of the critical activities, management should also note that on the critical path, F1 most strongly affects the occurrence of accidents, followed by F3 and F2. Effectively ensuring that the critical activities do not involve construction accidents ensures that work can be performed smoothly. Furthermore, in this example project, a near-critical path has 16 days of float and comprises activities A7, A8, A9, A10, A11, A12 and A14. This near-critical path is most sensitive to F3, followed by F1 and F2. The expected accident cost on this near-critical path is $371,881—even higher than that on the critical path ($335,586).

Table 10
Three-point estimates, mean and standard deviation of the likelihood for each cause in association with each activity

Activity	Cause	Likelihood				
		Pessimistic	Most Likely	Optimistic	Mean	Standard deviation
1	A	H	SL	L	0.061704	0.033503
	B	AS	SL	L	0.022340	0.005010
	F	H	AS	SL	0.011441	0.004278
	H	SH	AS	SL	0.053877	0.013589
2	A	SH	AS	L	0.053604	0.016751
	B	AS	SL	L	0.016755	0.003758
	E	EH	H	SH	0.003998	0.000625
	F	H	AS	L	0.008362	0.003618
3	A	L	SL	EL	0.031984	0.001675
	D	SH	AS	L	0.011706	0.003658
	F	SH	AS	L	0.007719	0.002412
4	D	AS	SL	EL	0.004245	0.001171
	F	AS	SL	L	0.002868	0.000643
5	A	SL	L	EL	0.054855	0.009046
	B	H	AS	L	0.052109	0.022547
	D	AS	SL	EL	0.015920	0.004390
	H	H	AS	SL	0.087365	0.032664
	L	SH	AS	EL	0.004307	0.001506
	O	SL	L	EL	0.000229	0.000038
6	E	H	AS	L	0.001444	0.000625
	N	H	AS	L	0.000040	0.000017
7	A	L	SL	EL	0.038381	0.002010
	D	SH	AS	L	0.014047	0.004390
	F	SH	AS	L	0.009263	0.002895
8	B	H	AS	L	0.041687	0.018038
	D	AS	SL	L	0.013048	0.002927
	E	SL	L	EL	0.001637	0.000270
	H	SH	SL	L	0.049040	0.019647
9	A	H	AS	SL	0.059590	0.022279
	D	AS	SL	L	0.008155	0.001829
	L	SH	SL	L	0.001708	0.000684
10	A	H	AS	SL	0.059590	0.022279
	D	AS	SL	L	0.008155	0.001829
	L	SH	AS	L	0.002190	0.000684
11	A	H	AS	L	0.030971	0.013401
	D	AS	SL	EL	0.004245	0.001171
12	A	AS	SL	L	0.104564	0.023452
	B	SL	L	EL	0.034456	0.005682
	D	SH	SL	L	0.025566	0.010243
	H	AS	SL	L	0.076651	0.017191
	L	SH	SL	L	0.004783	0.001916
	O	H	AS	SL	0.000696	0.000260
13	A	SL	L	EL	0.029256	0.004824
	E	H	AS	SL	0.002370	0.000886
	N	SL	L	EL	0.000030	0.000005
14	A	SH	AS	L	0.196549	0.061421
	H	H	SH	SL	0.208195	0.059883
	K	SH	AS	L	0.003046	0.000952
	L	SH	AS	SL	0.008258	0.002083
	O	H	SH	AS	0.001230	0.000256
15	A	SH	SL	EL	0.081836	0.036853
	D	AS	SL	L	0.016310	0.003658

EH—extremely higher; H—higher; SH—slightly higher; AS—almost the same as; L—lower; EL—extremely lower.

6.2.3. Managing working zones

Construction safety sometimes is managed by working zones. In the example project, zone 5 has the greatest hazard (expected accident cost = $269,287), followed by zone 4 ($145,374), zone 1 ($103,398), zone 3 ($70,911) and zone 2 ($58,615). In managing zone 5, activity A14 has the most serious hazard. Additionally, the factor sensitivities in Table 14 reveal the key zones in managing the performance of a particular factor. That is, F1 is most sensitive to zone 4; F2 is most sensitive to zone 1, and F3 is most sensitive to zone 4.

Table 11
Sensitivity of each factor on the occurrence of each cause for each activity

Activity	Cause	Sensitivity		
		Factor 1	Factor 2	Factor 3
1	A	Low	High	Medium
	B	Low	High	Medium
	F	Medium	High	Low
	H	High	Medium	Low
2	A	Medium	High	Low
	B	Medium	Medium	Medium
	E	Low	High	Medium
	F	Low	High	Medium
3	A	Medium	High	Low
	D	High	Low	Medium
	F	High	Low	Medium
4	D	High	Low	Medium
	F	High	Low	Medium
5	A	High	Low	Medium
	B	Low	High	Medium
	D	High	Low	Medium
	H	High	Low	Medium
	L	Medium	Low	High
	O	High	Low	Medium
6	E	Medium	Low	High
	N	Medium	No	High
7	A	Medium	High	Low
	D	High	Low	Medium
	F	High	Low	Medium
8	B	Medium	High	Low
	D	High	Low	Medium
	E	High	Low	Medium
	H	Medium	High	Low
9	A	Medium	Low	High
	D	Medium	Low	High
	L	High	Low	Medium
10	A	High	Low	Medium
	D	High	Low	Medium
	L	Medium	Low	High
11	A	Low	High	Medium
	D	Medium	Low	High
12	A	High	Low	Medium
	B	Low	High	Medium
	D	High	Low	Medium
	H	High	Low	Medium
	L	Medium	Low	High
	O	High	Low	Medium
13	A	Low	Medium	High
	E	Medium	Low	High
	N	Medium	No	High
14	A	Medium	Low	High
	H	High	Medium	Low
	K	High	Low	Medium
	L	Medium	Low	High
	O	Medium	Low	High
15	A	Medium	Low	High
	D	Medium	Low	High

Table 12
Qualitative estimates of the chances of various types of injury occurring due to each cause for each activity

Activity	Cause	Chance				
		Light injury	Medium injury	Severe injury	Disabling injury	Death
1	A	H	VH	M	L	VL
	B	H	VH	L	L	VL
	F	H	VH	L	L	VL
	H	VH	H	L	VL	VL
2	A	L	VH	H	L	VL
	B	M	H	L	VL	VL
	E	L	M	H	H	L
	F	VL	M	VH	H	L
3	A	VL	L	H	M	L
	D	L	M	VH	M	VL
	F	VL	H	VH	M	L
4	D	L	VH	H	L	VL
	F	M	H	VH	L	VL
5	A	M	VH	M	L	VL
	B	VH	H	M	L	VL
	D	H	VH	M	L	VL
	H	VH	H	M	L	VL
	L	VL	L	H	M	VL
	O	VL	L	VH	H	M
6	E	VL	L	VH	H	M
	N	H	VH	M	L	VL
7	A	VL	L	H	M	L
	D	L	M	VH	M	VL
	F	VL	H	VH	M	L
8	B	H	VH	M	L	VL
	D	M	VH	H	L	VL
	E	M	H	VH	L	VL
	H	H	VH	M	L	VL
9	A	VL	VL	M	H	VH
	D	VL	L	VH	H	M
	L	M	H	VH	L	VL
10	A	VL	VL	M	H	VH
	D	VL	L	VH	H	M
	L	M	H	VH	L	VL
11	A	VL	VL	M	H	VH
	D	VL	L	VH	H	M
12	A	M	VH	M	L	VL
	B	VH	H	M	L	VL
	D	H	VH	M	L	VL
	H	VH	H	M	L	VL
	L	VL	L	H	M	VL
	O	VL	L	VH	H	M
13	A	M	VH	M	L	VL
	E	VL	L	VH	H	M
	N	H	VH	M	L	VL
	A	M	VH	M	L	VL
14	H	VH	H	M	L	VL
	K	L	M	VH	H	L
	L	VL	L	H	M	VL
	O	VL	L	VH	H	M
15	A	VL	VL	M	H	VH
	D	VL	H	VH	M	L

VH—very high; H—high; M—medium; L—low; VL—very low.

6.2.4. Managing the project

The project is most sensitive to F1, followed by F3 and F2. Effective safety training is most important for preventing accidents in this example project. Additionally, the total

Table 13
Expected accident costs and sensitivities to factors for each activity

Activity	Expected accident cost	Factors	Accident occurrence			
			Standard deviation (1)	Mean (2)	CV (1)/(2)	Rank
A1	22,656	F1	0.012	0.085	0.141	3
		F2	0.020		0.235	1
		F3	0.018		0.212	2
A2	31,490	F1	0.009	0.056	0.161	2
		F2	0.010		0.179	1
		F3	0.005		0.089	3
A3	28,853	F1	0.003	0.043	0.070	1
		F2	0.001		0.023	3
		F3	0.002		0.047	2
A4	1228	F1	0.002	0.005	0.400	1
		F2	0.000		0.000	3
		F3	0.001		0.200	2
A5	69,758	F1	0.019	0.136	0.140	2
		F2	0.015		0.110	3
		F3	0.021		0.154	1
A6	33	F1	0.001	0.010	0.100	2
		F2	0.000		0.000	3
		F3	0.002		0.200	1
A7	38,072	F1	0.004	0.051	0.078	1
		F2	0.002		0.039	3
		F3	0.003		0.059	2
A8	13,533	F1	0.014	0.059	0.237	2
		F2	0.015		0.254	1
		F3	0.007		0.119	3
A9	54,206	F1	0.011	0.041	0.268	2
		F2	0.006		0.146	3
		F3	0.012		0.293	1
A10	43,288	F1	0.013	0.043	0.302	1
		F2	0.006		0.140	3
		F3	0.012		0.279	2
A11	24,951	F1	0.003	0.018	0.167	3
		F2	0.008		0.444	1
		F3	0.007		0.389	2
A12	73,888	F1	0.007	0.181	0.039	3
		F2	0.008		0.044	2
		F3	0.016		0.088	1
A13	18,124	F1	0.001	0.025	0.040	3
		F2	0.002		0.080	2
		F3	0.003		0.120	1
A14	115,046	F1	0.044	0.280	0.157	1
		F2	0.035		0.125	3
		F3	0.036		0.129	2
A15	53,821	F1	0.018	0.053	0.340	2
		F2	0.009		0.170	3
		F3	0.019		0.358	1

Table 14
Sensitivities of the likelihood of an accident's occurrence to each factor for each zone

Zones	Sensitivity		
	F1	F2	F3
Zone 1	0.079	0.116	0.095
Zone 2	0.136	0.107	0.150
Zone 3	0.125	0.125	0.071
Zone 4	0.165	0.107	0.175
Zone 5	0.095	0.069	0.086

expected cost of accidents for the entire project is $589,788, indicating the amount of contingency required for dealing with potential accidents.

7. Conclusions

This investigation presents an innovative simulation-based safety evaluation model (SimSAFE) that is integrated with the network schedule of a construction project. SimSAFE has two sources of theoretical strength. First, using qualitative model inputs is more practical than directly using quantitative inputs because practitioners are more familiar with qualitative estimates. Second, the uncertainty of an accident cause occurring is systematically disaggregated by safety factors and factor conditions according to a two-breakdown structure. This systematic structure eases the assessment of the influences of individual factors on accident occurrence.

Unlike earlier studies on integrating safety into planning, SimSAFE formally assesses the uncertainty in occurrence of causes of accidents (caught in and stuck by) and the hazards associated with each activity. It also explicitly combines safety information to schedule networks. Therefore, safety alerts can be proactively implemented at each time during the project. Moreover, the advantages of SimSAFE can be enhanced if it is applied to multiple projects with many activities. In that case, the efficiency of safety inspection will increase substantially, because a safety inspector or safety division (having a limited number of inspectors) can attend to highly sensitive activities, paths, zones and projects at any time.

Although the model inputs are designed to be qualitative (Tables 10, 11 and 12); the implementation of the model is found to be time-consuming. A user-friendly computer interface must be devised to simplify the use of SimSAFE in the future. Furthermore, additional historical data can be used to update the reference likelihood of each cause occurring (Table 1), as well as updating the historical accident costs for each accident cause (Table 3).

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