Accident Analysis and Prevention 54 (2013) 122–133

Contents lists available at SciVerse ScienceDirect

Accident Analysis and Prevention

journal homepage: www.elsevier.com/locate/aap

Bayesian-network-based safety risk assessment for steel construction projects

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ARTICLE INFO

Article history:
Received 18 June 2012
Received in revised form 2 February 2013
Accepted 5 February 2013

Keywords:
Bayesian network
Fault tree
Steel construction projects
Safety risk

ABSTRACT

There are four primary accident types at steel building construction (SC) projects: falls (tumbles), object falls, object collapse, and electrocution. Several systematic safety risk assessment approaches, such as fault tree analysis (FTA) and failure mode and effect criticality analysis (FMECA), have been used to evaluate safety risks at SC projects. However, these traditional methods ineffectively address dependencies among safety factors at various levels that fail to provide early warnings to prevent occupational accidents. To overcome the limitations of traditional approaches, this study addresses the development of a safety risk-assessment model for SC projects by establishing the Bayesian networks (BN) based on fault tree (FT) transformation. The BN-based safety risk-assessment model was validated against the safety inspection records of six SC building projects and nine projects in which site accidents occurred. The ranks of posterior probabilities from the BN model were highly consistent with the accidents that occurred at each project site. The model accurately provides site safety-management abilities by calculating the probabilities of safety risks and further analyzing the causes of accidents based on their relationships in BNs. In practice, based on the analysis of accident risks and significant safety factors, proper preventive safety management strategies can be established to reduce the occurrence of accidents on SC sites.

1. Introduction

In Taiwan, steel structures have been the most common structure type for high-rise buildings. However, site accidents constantly occur because of work at heights in SC projects. The percentage of falls at SC projects in Taiwan has increased to 66% over the past decade (2000–2010). In addition to falls, object falls, object collapse, and electrocution comprise a high percentage of occupational accidents at SC sites. Fig. 1 shows a comprehensive occupational accident lists for steel construction projects in Taiwan between 2000 and 2010. Construction contractors have attempted to implement various safety measures to prevent occupational accidents, including safety training, site environment management, safety and health management, and appropriate health and safety plans. In addition, some systematic safety risk-assessment approaches such as fault tree analysis (FTA), failure mode and effect criticality analysis (FMECA), and decision trees are used to evaluate safety risks (Hartford and Baecher, 2004; Kales, 2006). However, these methods ineffectively address dependencies among safety factors at various levels that fail to provide an early warning to prevent occupational accidents. To overcome the limitations of traditional safety risk-assessment approaches, several effective approaches have been developed to define the interplay between safety variables so that preventive safety measures can be proposed. Structural equation models (SEM) and Bayesian networks (BNs) are typical examples of these approaches (Kao et al., 2009; Martin et al., 2008; Paul and Maiti, 2007). The safety of third parties during construction in multiple spaces has been assessed using BNs (Bedford and Gelder, 2003). BNs have been used to analyze workplace accidents caused by falls from heights (Martin et al., 2008). BNs, in addition to their good predictive capacity, possess satisfactory interpretative ability regarding workplace accidents (Matias et al., 2007). The critical causes of site accidents can be identified, and the relationships among these causes can be determined using BNs. Consequently, early and preventive safety measures can be defined through BN inference.

Because of the constraint of data availability, expert knowledge is typically used to develop practical BNs that describe problems with causal relationships among nodes and their conditional probabilities. However, the method to develop a BN directly is more suitable for simple problems. It is difficult to directly develop complex BNs. Several systematic approaches to BN construction using FT transformation have been proposed (Franke et al., 2009; Marsh and Bearfield, 2007; Xiao et al., 2008). The primary techniques of these approaches use "OR Gate" and "AND Gate" to change to a BN to perform probabilistic analyses of events. Most studies have regarded both events and logic gates in FT as nodes in BN. However, these have different definitions and purposes. Logic gates are

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http://dx.doi.org/10.1016/j.aap.2013.02.019

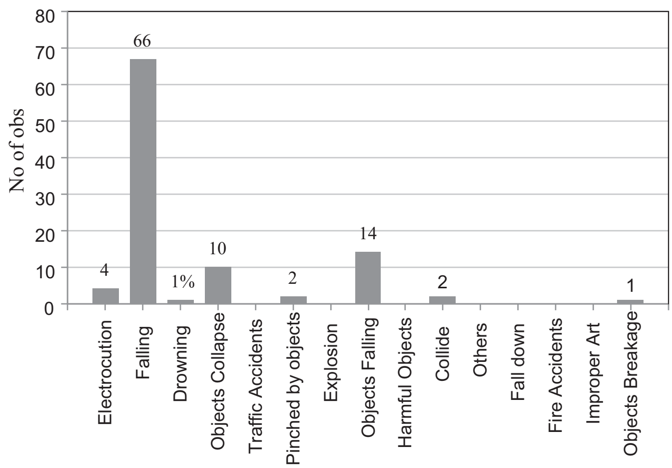


Fig. 1. Occupational accidents of steel construction projects in Taiwan (2000–2010).

primarily used to describe the relationship between events in a sequence. A BN node is used to represent a random variable in the problem domain. It is meaningless to convert logic gates to physical BN nodes. Therefore, this study combines FTA and BN to develop a more reasonable transformation process from FT to BN. A sub-BN, a fall risk-assessment model for SC building projects, was first validated against the safety inspection records of six SC building projects. The complete BN-based safety risk-assessment model was further validated against nine projects in which specific site accidents occurred. This shows that the ranks of posterior probabilities from the BN model are highly consistent with the accidents at each project site.

2. Statistics of occupational accidents in Taiwan

The construction industry in Taiwan and worldwide has a high incidence of major occupational accidents. According to the Yearbook of Labor Statistics published by the Taiwanese Council of Labor Affairs, the rate of fatalities per 1000 workers in the construction industry (excluding deaths from occupational diseases and traffic accidents) was 0.109 (i.e., 109 deaths per million workers) in 2010 (Fig. 2), which is substantially higher than in manufacturing and other industries. For occupational accidents in Taiwan, falls are the most common cause of injury (48%) among all accident types over the past decade (2000–2010). As shown in Fig. 1, the total number of deaths between 2000 and 2010 at SC project sites was 108. Particularly for steel lifting work, fall accidents at SC sites occur with a frequency of 66% because of uncertified and

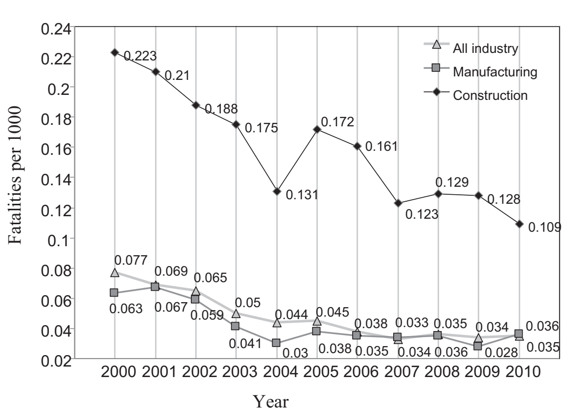


Fig. 2. Fatalities per 1000 persons in construction industry and all industries (excluding deaths from occupational disease and traffic accidents), 2000–2010.

unqualified safety equipment and unsafe behavior. Furthermore, excluding falls, object falls, object collapse, and electrocution are the top three accident types at SC project sites. Therefore, preventing these accidents from occurring is the most critical issue in safety management programs at SC project sites.

To effectively plan and promote accident mitigation strategies and appropriately allocate resources to safety and health management, it is necessary to conduct a more detailed analysis of the relationships among these four accident types and their causes, such as personnel, equipment, processes, and management. This study combines FTA and a BN to create the BN-based risk-assessment model for SC projects. Risk potential and significant causes can be identified using this model. Based on enhanced knowledge of safety risks at SC sites and their significant influences, more effective accident-preventive measures can be taken to prevent accidents.

3. Methods and process

The construction of a BN can be complex, and its network structure is problem specific. BN hierarchies should be constructed following the concept of FTA, and then transform the basic FT into a BN framework. Furthermore, meaningful supplementary links among BN nodes and a conditional probability table (CPT) were introduced by incorporating expert experiences. The proposed transformation process is shown in Fig. 3. FTA, the BN, and the transformation processes are explained in detail below.

3.1. Fault tree analysis (FTA)

FTA was developed in 1962 and is frequently used in both reliability engineering and system safety engineering. Because FTA qualitatively or quantitatively analyzes the defects and weaknesses of a system, it is applied in nearly every engineering discipline (Lindhea et al., 2009; Kales, 2006; O'connor, 2002). It is a deductive tool that uses graphics and statistics to analyze an event and to predict how and how frequently it will fail.

The construction of a FT proceeds in a top-down fashion. A particular undesired event, the top event, is first speculated by FTA. It begins with events and proceeds to their causes until basic the components are reached. The relationships between events and causes are defined and represented by AND gate, OR gate, and other logic gates (e.g., exclusive the OR gate and priority AND gate) (Franke et al., 2009; Graves et al., 2007; Xiao et al., 2008). The events in the conventional FTA methodology are assumed to be statistically independent. However, this may be unsuitable for actual cases. Some variables in complex problems are interrelated. Because FTA has a limited ability to demonstrate complex causal relationships, probabilistic network approaches, such as BNs, are an additional choice for resolving this problem.

3.2. Bayesian network (BN)

A BN is a probabilistic graphical model that represents a set of random variables and their conditional dependencies using a directed acyclic graph. Combined with probability theory and graph theory, BNs consist of nodes, joints among nodes, and conditional probability tables (CPTs). A BN has a higher efficiency and accuracy in uncertain inferences, especially when linking various forms of information: expert opinions, empirical data, and outputs from other models. Recently, BNs have been widely used in the management and engineering fields, such as disease diagnosis assistance, industrial design, financial investment, ecology, machine-failed systems, file filtering, graphical interpretation, and factory planning under uncertain conditions (Doguc and Ramirez-Marquez, 2009; Marquez et al., 2010; Stewart-Koster et al., 2010).

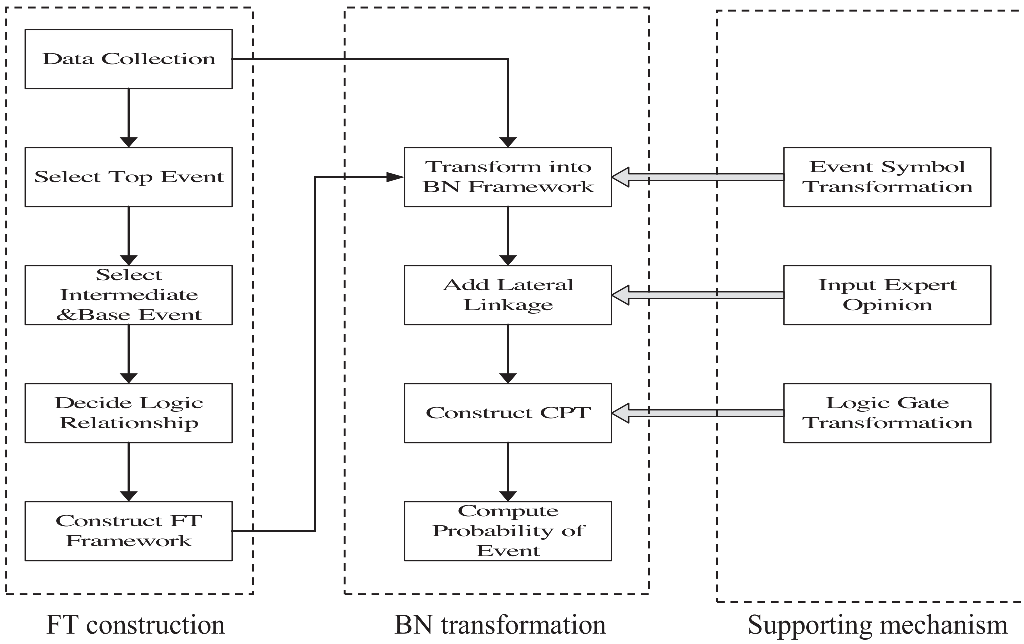


Fig. 3. Transformation workflow from FT to BN.

There are two typical approaches to the construction of BN. The first BN construction method is learning BN structures and parameters using a large amount of historical data. The second method is based on experience acquired from domain experts. The first approach frequently requires large amounts of training data and is impractical in most engineering fields. The second approach is typically used for practical BN construction because of the constraint of data availability. However, it is usually difficult to establish mutual relationships among nodes in the network solely based on the knowledge of engineers and experts, particularly for complex problems. Therefore, several FT-to-BN transformation processes have been proposed (Franke et al., 2009; Xiao et al., 2008). The traditional transformation of FT logic gates in BN is one-to-one; that is, logic gates in FT are converted into corresponding physical nodes in BN. However, there are differences between the meanings of an event node in a BN and a logic gate in an FT. An event node represents a random variable in the problem domain, whereas a logic gate in an FT describes the logical relationship between the nodes. For the transformation of an FT into a BN, separate processes should be proposed to handle the event nodes and the logic gates.

3.3. Conversion from FT to BN

The proposed conversion process consists of two steps: framework conversion and CPT calculation (Fig. 3). The fundamental framework conversion process comprises two primary steps. The first step is to directly transform the events and the vertical links in an FT into the nodes and fundamental links in a BN (logic gates are excluded). The second step is inserting supplementary links using knowledge from experts and engineers. Furthermore, CPT calculation is performed based on the FT logic gates among events. Each step is explained in detail below.

3.3.1. Framework conversion

The proposed conversion method from an FT to a BN modifies the techniques proposed in previous studies (Franke et al., 2009; Marsh and Bearfield, 2007; Xiao et al., 2008). Top events, intermediate events, and basic events in an FT are directly mapped into the nodes of a BN, and logic gates are not included in the framework conversion. Overlapping nodes are combined into one. The fundamental arrows among the BN nodes follow the definition of event relationships in an FT. Furthermore, meaningful supplementary arrows are inserted into the fundamental BN structure based on expert opinions if necessary.

3.3.2. CPT calculation

If a node in a BN has several parent nodes or each parent node and child node has several states, the CPT structure is large. For example, if a child node has three parent nodes and the number of their states is five, the total number of CPT values can be a great as 5^4 (625). In addition, the CPT values are typically defined by experts based on their experiences. The elicited probability values can be inconsistent, especially under the mentioned complex and large CPT condition. AgenaRisk software was used to mitigate the mentioned difficulties in this study (Agenarisk, 2012). Using the parameters defined by AgenaRisk, coupled with weights among the nodes defined by the experts, probability values in CPT can be calculated rapidly.

In theory, the calculation of CPT in AgenaRisk follows rank nodes (Fenton et al., 2007). Ranked nodes represent discrete variables, the states of which are expressed on an ordinal scale that can be mapped onto a bounded numerical scale that is continuous and monotonically ordered. The two basic components of rank nodes are the weight values of parent nodes to children nodes and weighted functions. The probability of a child node is defined as a weighted rank function of the parent node values. Weighted rank node functions are generally assumed to be the doubly truncated normal distribution, and its central tendency is controlled by a function parameter (i.e., mean average, minimum, and maximum). As addressed below, minimum is selected if the corresponding logic gate in FT is AND, whereas maximum is selected if the logic gate is OR. Finally, the conditional probabilities of the child node each assume different values for each combination of the values of its parents based on the weighted rank function.

As mentioned, a crucial step in defining CPTs using AgenaRisk is in describing the expression function. The FT logic gate plays a significant role in the definition. Based on the two logic gates defined in an FT, the definition of the expression function in AgenaRisk is stated as follows. In the selection of the expression function items, minimum is selected if the corresponding logic gate in the FT is

Table 1
Experts profiles.

No.	Department	Title	Work experience(yrs)
1	Industrial safety & QC dept.	Manager	11
2	Industrial safety & QC dept.	Assistant manager	30
3	H/S office	Specialist	8
4	H/S/E engineering center	Vice supervisor	27
5	Occupational H/S	Manager	20
6	Construction office	Executive V.P.	21
7	H/S dept.	Manager	16
8	Construction office	V.P.	25
9	H/S dept.	Manager	13
10	Construction office	Manager	22
11	Construction planning dept.	Junior manager	20
12	H/S section	Section manager	10
13	H/S center	Engineer	12
14	H/S section	Section manager	17
15	H/S section	Vice section manager	18
16	Labor safety & QC office	Supervisor	15
17	H/S dept.	Manager	16
18	Labor safety office	Supervisor	20
19	Environmental safety office	Senior manager	16
20	Mining engineering dept.	H/S consultant	30
21	Labor safety engineering office	Manager	20
22	H/S/E dept.	Lecturer	15

Rem: H/S, health and safety; H/S/E, health, safety and environment.

AND, whereas maximum is selected if the logic gate is OR. Based on deduction, the fault probabilities of the top event by FTA and a BN are identical. Using the AND gate as an example and assuming that there are two independent events, *A* and *B*, and their top event is *C*, they have two states: A_1, B_1, and C_1 (normal states) and A_2, B_2, and C_2 (fault states), respectively. Based on the logic of the AND gate and the assumption of independence in FT, the fault probability can be calculated as $P(C_2) = P(A_2 \cap B_2) = P(A_2) \times P(B_2)$. Based on the concept of a BN, the fault probability can be derived as

$$\begin{aligned} P(C_2) &= C_2A_1B_1 \times A_1 \times B_1 + C_2A_1B_2 \times A_1 \times B_2 + C_2A_2B_1 \times A_2 \times B_1 + C_2A_2B_2 \times A_2 \times B_2 \\ &= 0 \times A_1 \times B_1 + 0 \times A_1 \times B_2 + 0 \times A_2 \times B_1 + 1 \times A_2 \times B_2 \\ &= P(A_2) \times P(B_2) \end{aligned}$$

After the selection of the expression functions in AgenaRisk is defined based on the logic gates in an FT, the weights are determined and inputted through an opinion poll of experts based on the contribution of the parent nodes to the children nodes. The weighted score ranges from 1 to 5. A score of 1 indicates a smaller influence of a parent node on the child node, and 5 signifies the greatest effect. When the mentioned data are inputted into AgenaRisk, all CPTs in the BN can be rapidly calculated. Furthermore, the entire posterior probabilities of the top event and all intermediate nodes in a BN can be inferred by AgenaRisk.

4. BN-based safety risk assessment model for steel construction projects

Based on the proposed BN construction process, a BN-based accident risk-assessment model for SC building projects was developed. As shown in Section 2, four primary accident types (i.e., falls, object falls, object collapse, and electrocution) were selected for model development because they had the highest occupational hazard rates in SC projects during the past decade in Taiwan (Fig. 1). The model comprises four subsystems: falls, object falls, object collapse, and electrocution. Each subsystem was developed individually based on the proposed process and integrated into a primary system for safety risk assessment for SC building projects. To obtain quality knowledge support, 22 specialists with average work experiences of 18 years were interviewed for the model construction. Table 1 shows the profiles of the experts. For model validation, a sub-BN fall risk-assessment model for SC building projects was first examined and validated using the safety inspection records of six SC building projects. Furthermore, the correctness of the model was validated using nine SC building projects in which specific site accidents occurred. Finally, the significant causes affecting accident risks were assessed and examined using sensitivity analysis. The details of the model development are explained below.

4.1. Construction of FT framework

Several theories of accident causation have been proposed to help predict and prevent accidents, such as domino theory, human factors theory, accident/incident theory, epidemiological theory, systems theory, behavior theory, and combination theory (Jitwasinkul and Hadikusumo, 2011; Lingard and Rowlinson, 2005). Among these, domino theory is the most fundamental, and the origins of many widely accepted theories can be traced back to domino theory. Based on domino theory applied to safety management, the causes of accidents at SC project sites can be classified into accident locations (e.g., beams, columns, and steel decks), indirect causes (e.g., unsafe behaviors, unsafe equipment, and unsafe environments), and root causes (e.g., improper safety plan and poor safety management).

Using falls as an example, three chief situations exist at SC project sites in which falls can occur: (1) steel beam construction; (2) steel column construction; and (3) deck construction. Using falls related to steel beam erection as an example, the circumstances surrounding work tasks that trigger fall accidents were analyzed using expert interviews and a literature review. Three primary tasks exist during which falls can occur: (1) hoisting steel beams; (2) beam installation and fixation; and (3) limb discordant in operation. If necessary, tasks can be broken down into detailed subtasks. Furthermore, their indirect causes that could potentially result in a fall accident were analyzed one by one. Finally, four root causes that result in occupational accidents were added to the bottom of the FT as basic events: insufficient safety training, poor site environment management, poor safety and health management, and improper health and safety plan. Based on the occupational accident records, safety theories, and expert interviews, the links between these basic causes and the indirect causes were identified to form the overall FT. The completed FT of falls related to steel beam construction at SC project sites is shown in Fig. 4, and term

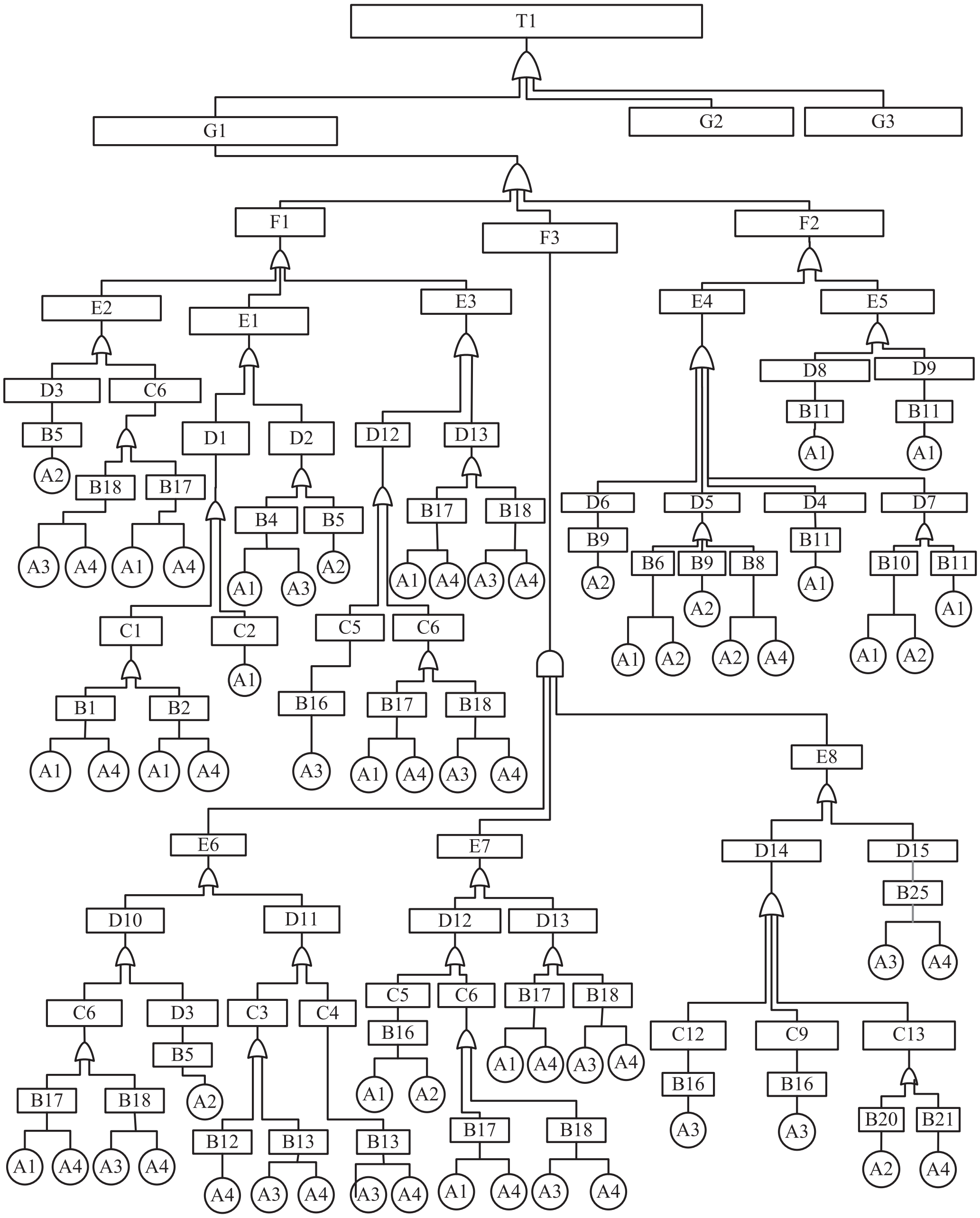


Fig. 4. FT of fall accidents at SC projects.

definitions are shown in Fig. 5. By following similar procedures, the FT diagrams for object falls, object collapse, and electrocution were established.

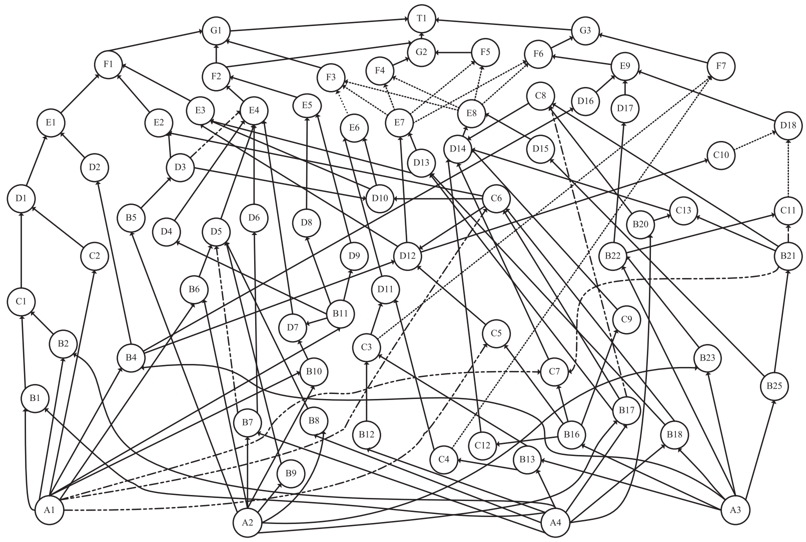
4.2. Construction of BN from FT and CPT calculation

Based on the transformation process described in Section 3, all of the shown FT diagrams were transformed to a BN. The BN frameworks of each subsystem of the BN-based safety risk-assessment model are shown in Figs. 5–8. Some supplementary links were further defined based on expert opinions and were unified into a comprehensive safety risk assessment model. In this model, the risks pertaining to the four accidents at SC project sites can be evaluated by inputting the prior probabilities of the four root causes.

AgenaRisk was used to calculate the CPT based on the constructed BN framework. The questionnaires were designed to collect information regarding the relative weights of the parent nodes to their child nodes. A total of 22 experts assessed the relative weight questions based on their practical experiences, and their answers were statistically analyzed. To reduce the influence of extreme values, the trimmed sample mean method was used. By sorting the weighted data, the upper and lower 10% of the data were excluded from the calculations of the weighted means. By combining the statistical data of the relative weights with the logic gates defined in FTs, the CPTs for all of the arcs in the comprehensive BN were calculated.

4.3. Assessment of prior probabilities

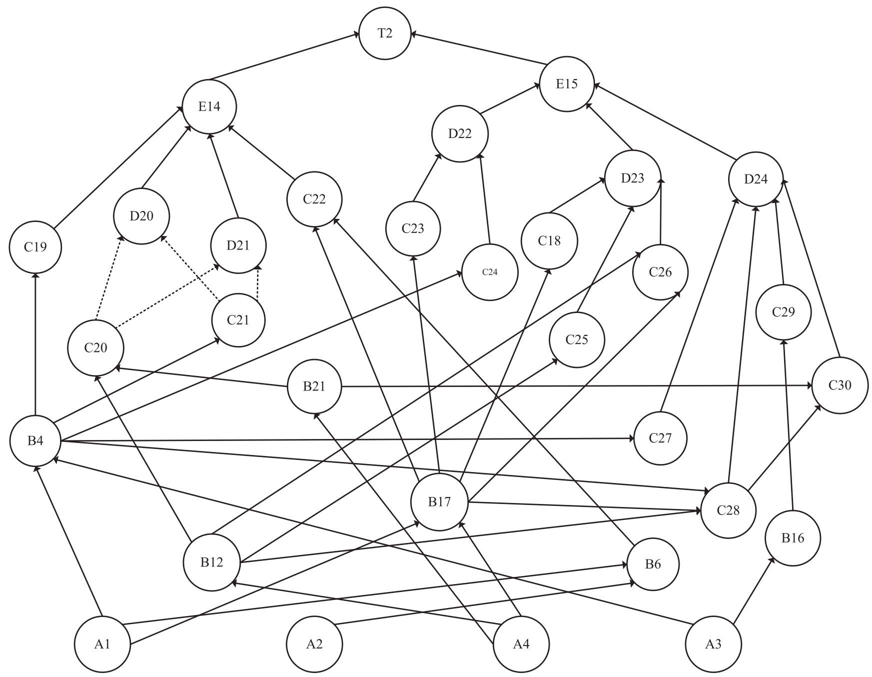
As mentioned, four significant root causes were defined in the model. To assess the prior probabilities of these causes, a safety performance evaluation table was created. If more items are marked



T1	Fall	D6	Slippery site	B2	Incorrect operation process
G1	Falling caused by steel beam construction	D7	False step	B4	Dangerous procedure or method
G2	Falling caused by steel column construction	D8	Dangerous position	B5	No provision of safety protection facilities
G3	Falling caused by deck construction	D9	Walking on dangerous path	B6	Placing unsafely
F1	Falling while steel beam lifting	D10	Screw fix job imbalance	B7	Unorganized job site environment
F2	Uncoordinated body movement	D11	Electric shock	B8	Waste not cleaned up
F3	Falling while beam Installation and fix	D12	Ineffective protective equipment	B9	Unorganized material
F4	Falling while column installation	D13	Unequipped personal safeguard	B10	Unawareness of surroundings
F5	Falling while column adjustment	D14	Ineffective safety equipment	B11	Improper behaviors or posture
F6	Falling while deck construction	D15	Lack of safety equipment	B12	Insufficient self-check
F7	Falling caused by electric shock during deck welding	D16	Welding point damage	B13	No safety device
E1	Steel components collision while lifting	D17	Insufficient stiffness of deck	B16	Unsafe equipment
E2	Steel wire rope operation error	D18	Displacement due to miss welding	B17	Failure to comply with the code of practice
E3	Temporary fixing error	C1	Error indication	B18	No personal protective equipment
E4	Standing imbalance	C2	Negligence of operator	B20	Safety measure damage due to acceleration schedule
E5	Dangerous behavior	C3	No voltage reducing device for welding	B21	Failure to implement self-management
E6	Operation error while fixing	C4	No leakage circuit breaker	B22	Insufficient material strength
E7	Improper usage of protective equipment	C5	Unqualified safety belt	B23	Lack of environmental labeling
E8	Lack of safety measures	C6	Not hook to safety belt	B25	Insufficient budget for safety
E9	Displacement or loosening	C7	Unqualified safety nets	A1	Insufficient safety training
D1	Crane operation error	C8	Safety nets being removed	A2	Poor site environment management
D2	No guide line	C9	Insufficient strength of lifeline fixture	A3	Improper health and safety plan
D3	No lifeline	C10	Welding failure	A4	Poor safety and health management
D4	Improper effort	C11	Poor warning signs		
D5	Stumble	B1	Poor control process		

Fig. 5. BN of fall accidents at SC projects.

based on site investigations, this indicates a higher probability of a poor performance regarding the root cause being subjectively evaluated. Beta distributions were used to simulate the spread of states in the root nodes. If a 10-item evaluation table is fully marked, it is reasonable to define the probability performances of poor, fair, and good as 0.9, 0.07, and 0.03, respectively. If the table is half marked, the probabilities are defined as 0.3, 0.4, and 0.3, respectively. The probabilities of the additional marks are proportionally calculated



T2	Object fall	C21	No anti-loosening rope	B6	Placing unsafely
E14	Bolts falling while fixing	C22	Material piled up near the opening edge	B12	Insufficient self-check
E15	Steel components falling while lifting	C23	Wrong lifting way	B16	Unsafe Equipment
D20	Connecting panel falling	C24	Failure to comply with lifting provisions	B17	Failure to comply with the code of practice
D21	Assembly tools falling	C25	Insufficient strength of lifting equipment	B21	Failure to implement self-management
D22	Unequal lifting point	C26	No non-slip tabs	A1	Insufficient safety training
D23	Lifting lug off the hook	C27	Over-force	A2	Poor site environment management
D24	Wire rope fracture while lifting	C28	No overdrive stop device of winch	A3	Improper health and safety plan
C18	Wrong signal while operating	C29	Wire rope wear deformation	A4	Poor safety and health management
C19	HT bolt falling while locking	C30	Overloading while lifting		
C20	No fine mesh safety net	B4	Dangerous procedure or method		

Fig. 6. BN of object fall accidents at SC projects.

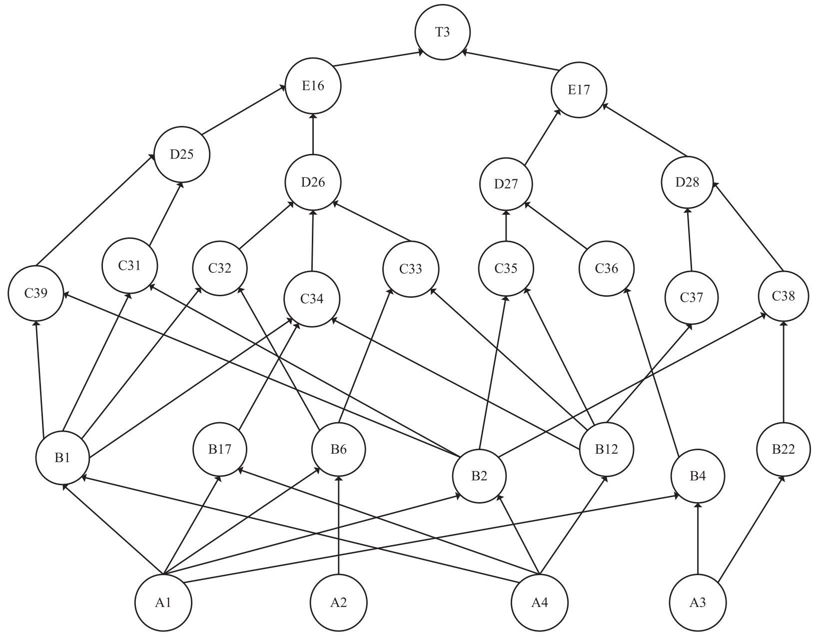
based on beta distribution. By inputting prior probabilities into BN, safety risks at SC building projects and their significant causes are identified using a BN inference.

5. Model validation and sensitivity analysis

5.1. Model validation

The model validation comprised two steps. The first step was the preliminary validation. A sub-BN fall risk-assessment model for SC building projects was first examined and validated using the safety inspection records of six SC building projects. The second step was the comprehensive model validation. By comparing the results of the accidents at nine SC building projects with the posterior probabilities of the top node in each BN subsystem, the proposed BN model was validated.

Using results from the safety inspection records of six SC building projects and the posterior probabilities of the top node in each sub-BN of fall risk assessment, the proposed BN model was validated. The basic information of the six SC projects and a summary of their safety inspection records are shown in Table 2. Using the data in the mentioned safety performance evaluation tables, the prior probabilities of the four root causes of six projects were subjectively assessed and inputted to AgenaRisk to infer the posterior probabilities of the nodes in BN. Table 2 shows a comparison of the analytical results of the BN model to the safety inspection records. A higher posterior probability indicates higher risk. However, a lower assessment value indicates poorer safety management. The ranks of the posterior probabilities from the BN model were highly consistent



T3	Object collapse	C32	Materials stacking messy and untied	B4	Dangerous procedure or method
E16	Steel members collapse while moving	C33	Unstable stacking yard	B6	Placing unsafely
E17	Steel components collapse while installation	C34	Over-stacking of steel members	B12	Insufficient self-check
D25	Steel members being knocked	C35	Ineffective fixing of steel columns	B17	Failure to comply with the code of practice
D26	Improper steel members stacking	C36	Improper effort while wire adjustment	B22	Insufficient materials strength
D27	Steel columns collapse while adjusting	C37	Lifting not to the right place	A1	Insufficient safety training
D28	Steel components collapse while fixing	C38	Loose and unstable Supports	A2	Poor site environment management
C39	Steel members collide with while lifting	B1	Poor control process	A3	Improper health and safety plan
C31	Steel structure hit by construction machinery equipments	B2	Incorrect operation process	A4	Poor safety and health management

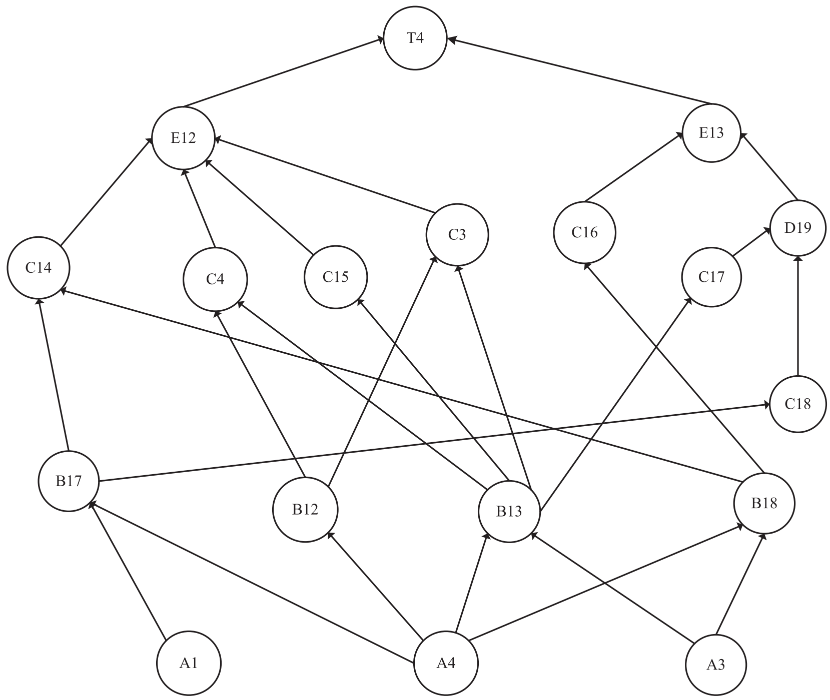
Fig. 7. BN of object collapse accidents at SC projects.

with those of the safety performances obtained from the records. Only Projects 3 and 4 differed slightly. The proposed BN-based safety assessment model possessed accuracy and applicability for sub-BN fall risk assessment.

Furthermore, the BN model was comprehensively validated. The basic information of nine SC projects and their accidents is shown in Table 3. By referencing the safety performance evaluation tables, the prior probabilities of the four root causes at the nine projects were subjectively assessed and inputted into AgenaRisk to infer the posterior probabilities of the nodes in the BN. Table 3 shows a comparison of the analytical results of the BN model to the accidents that occurred at each SC site. A higher posterior probability indicates higher risk. The ranks of the posterior probabilities for each project were highly consistent with the accidents at each project

Table 2
Comparison between BN and real site assessment.

Project no.	Building type	Total floor area (M_2)	Weight of steel (T)	Floor (superstructure/ substructure)	Fall risk (%) from BN	Risk rank by BN	Real site assessment	Real safety rank
1	Residence	59,900	11,200	41/6	46.5	5	85.64	5
2	Residence	30,444	8200	38/1	86.4	1	82.00	1
3	Residence	32,465	6150	23/5	46.2	6	86.22	6
4	Residence	21,530	3600	23/6	47.9	4	85.31	3
5	Residence	25,960	3132	21/3	59.2	2	84.67	2
6	Training center	9000	1200	6/3	53.8	3	85.46	4



T4	Electrocution	C14	Welder without personal protective equipment	B17	Failure to comply with the code of practice
E13	Electric shock while installation	C15	No grounded conductor of generator	B18	No personal protective equipment
E12	Electric shock while welding	C16	Electric shock by static electricity	A1	Insufficient safety training
D19	Inadvertent touch of high voltage power	C17	No high voltage power protective device	A3	Improper health and safety plan
C3	No voltage reducing device for welding	B12	Insufficient self-check	A4	Poor safety and health management
C4	No leakage circuit breaker	B13	No safety device		

Fig. 8. BN of electrocution accidents at SC projects.

Table 3
Evaluation comparison between AgenaRisk and real site.

Project no.	Building type	Safety risk prediction from AgenaRisk (%)				Real site accidents
		Fall	Object fall	Object collapse	Electrocution	
1	Factory buildings	77.47 3	85.06 2	**86.87** 1	43.00 4	Object collapse
2	Factory buildings	**89.97** 1	86.24 2	79.45 3	75.79 4	Fall
3	Factory buildings	79.16 2	73.09 3	72.48 4	**85.37** 1	Electrocution
4	Rapid transit machinery station	89.70 2	**89.73** 1	87.23 3	59.39 4	Object fall
5	Residential building	**89.07** 1	87.11 2	84.1 3	70.17 4	Fall
6	Residential building	84.59 4	90.07 1	**86.38** 2	85.45 3	Object collapse
7	Mall building	86.38 2	**90.72** 1	79.38 3	75.79 4	Object fall
8	Information technology building	86.31 2	84.49 3	77.94 4	**87.85** 1	Electrocution
9	Station building	94.41 3	**95.02** 2	91.74 4	95.09 1	Object fall (first accident)
		89.64 2	88.57 3	83.56 4	**90.67** 1	Electrocution (second accident)

Table 4
Top sensitive factors of four accidents types at SC Projects.

No.	Accident type	Top sensitive factors at each level		
		Direct	Indirect	Root
1	Fall	(G1) Falling caused by steel beam construction (F1) Falling while steel beam lifting	(E7) Improper usage of protective equipment (D14) Ineffective safety equipment (C7) Unqualified safety nets (B13) No safety device	(A3) Improper health and safety plan (A4) Poor health and safety management
2	Object fall	(E15) Steel components falling while installation	(D24) Wire rope fracture while lifting (C28) No overdrive stop device of Winch (B17) Failure to comply with the code of practice	(A4) Poor health and safety management
3	Object collapse	(E16) Steel members collapse while moving	(D26) Improper Steel members stacking (C34) Over-stacking of steel members (B2) Incorrect Operation Process	(A4) Poor health and safety management
4	Electrocution	(E12) Electric shock while welding	(C3) No voltage reducing device for welding (B13) Ineffective safety device (D19) Inadvertent touch of high voltage power	(A4) Poor health and safety management

site. For example, in Project 2, the posterior probabilities of the four safety risks were 89.97% (falls), 86.24% (object falls), 79.45% (object collapse), and 75.79% (electrocution). Falls were the greatest risk in this project, which was consistent with the accident at the site. However, regarding Project 6, the posterior probability of object collapse was ranked second, which is not totally consistent with the actual accident in Project 6. Nevertheless, the probability of object collapse was still quite high. More attention must be given to this accident type. Based on the appraisal and verification using the eight SC projects, the proposed BN-based accident risk-assessment model is accurate and can be used for safety risk assessment at SC project sites.

The model in this study was validated against eight SC projects in which a site accident occurred. The soundness of the model can be further demonstrated if the model is tested against SC projects with more than one site accident. Statistically, SC projects with more than one site accident are considered rare events. In Taiwan, only one SC project with two site accidents occurred between 2005 and 2012 (i.e., a 0.012% occurrence rate). The first accident is object fall and the second one is electrocution. The time interval between the two accidents was approximately 2 years. These two accidents can be regarded as independent events. By inputting prior information about the two site accidents into the model, the posterior probabilities of the four safety risks were 94.41% (falls), 95.02% (object falls), 91.74% (object collapse), and 95.09% (electrocution) for the first accident; and 89.64% (falls), 88.57% (object falls), 83.56% (object collapse), and 90.67% (electrocution) for the second accident. The posterior probability of object falls in the first accident was ranked second among the four risks, which was inconsistent with the actual accident. Nevertheless, the probability of object falls was quite high. Electrocution was the greatest risk for the second accident, which was consistent with the actual site accident. The four safety risks were kept high at this site compared with single-accident projects. It is apparent that accidents could constantly occur at the site because of the poor safety program. Especially Electrocution was ranked the highest for risk in both safety risk assessments. This indicates that the safety program related to electrocution was poorly operated, and only slightly improved between two accidents.

In addition to the validation using single-accident projects, this study further compared the model output using a project with more than one site accident. It seems that the model can reasonably predict the safety risks for such a rare event. However, only one project with two accidents was evaluated in this study; thus, it is inappropriate to claim the soundness of the model. If more accident data are available in the future, the BN-based safety risk assessment model must be more comprehensively evaluated.

5.2. Sensitivity analysis and discussions

To further investigate the causes that affect the occurrences of the four accident types at SC project sites, sensitivity analysis was performed. In BN sensitivity analysis using AgenaRisk, a single target node and one or more sensitivity nodes must be selected. Several sensitivity reports can be generated using AgenaRisk, including sensitivity tables, tornado graphs, and receiver operating characteristic (ROC) curves. The top sensitivity nodes were selected based on the rank of the sensitivity nodes in the tornado graph, as shown in Table 4. A summary of the tornado graphs related to root causes is shown in Fig. 9. Overall, the most significant direct cause of falls was hoisting steel beams and a lack of safety facilities. When hoisting steel beams, the main causes of falls include the inability to erect a safety net, limited construction pedal boards, and a lack of ideal fixed points for lifelines and safety belts. Consequently, falls can occur easily when workers are not careful. In addition, a statistical survey of the occupational accidents at SC projects indicated that hoisting steel beams is a crucial stage in SC projects because the occurrence percentage of occupational accidents during the steel component hoisting and assembling process is highest (39%).

The most significant indirect causes of falls include improper usage of personal protective equipment (E7), ineffective safety equipment (D14), unqualified safety nets (C7), and not having a safety device (B13). Improper use of safety equipment and a lack of effective safety facilities (e.g., personal safeguards and safety devices) are major causes that affect the occurrence of falls. Based on the statistics of occupational accidents at SC projects, approximately 50% of occupational accidents during steel component assembling are caused by the improper use of personal safeguards (Fig. 10). More attention should be given to safety facilities to reduce falls.

Different site accidents have various direct and indirect causes. Overall, except for the falls mentioned, the most sensitive indirect cause of electrocution is ineffective safety devices, such as poor earth leakage circuit breakers. The most sensitive indirect cause of object falls and object collapse is failure to comply with codes of practice. Furthermore, sensitivity analysis of the BN-based safety risk model indicated that safety and health management play critical roles in the prevention and mitigation of accidents at SC project sites. Recent research has shown that the most influential factor in accidents is management issues, and that these may provide more effective measures for preventing accidents (Abdelhamid and Everett, 2000; Aksorn and Hadikusumo, 2008). To prevent accident reoccurrence at SC project sites, management procedures should be designed to identify and remove unsafe conditions and procedures

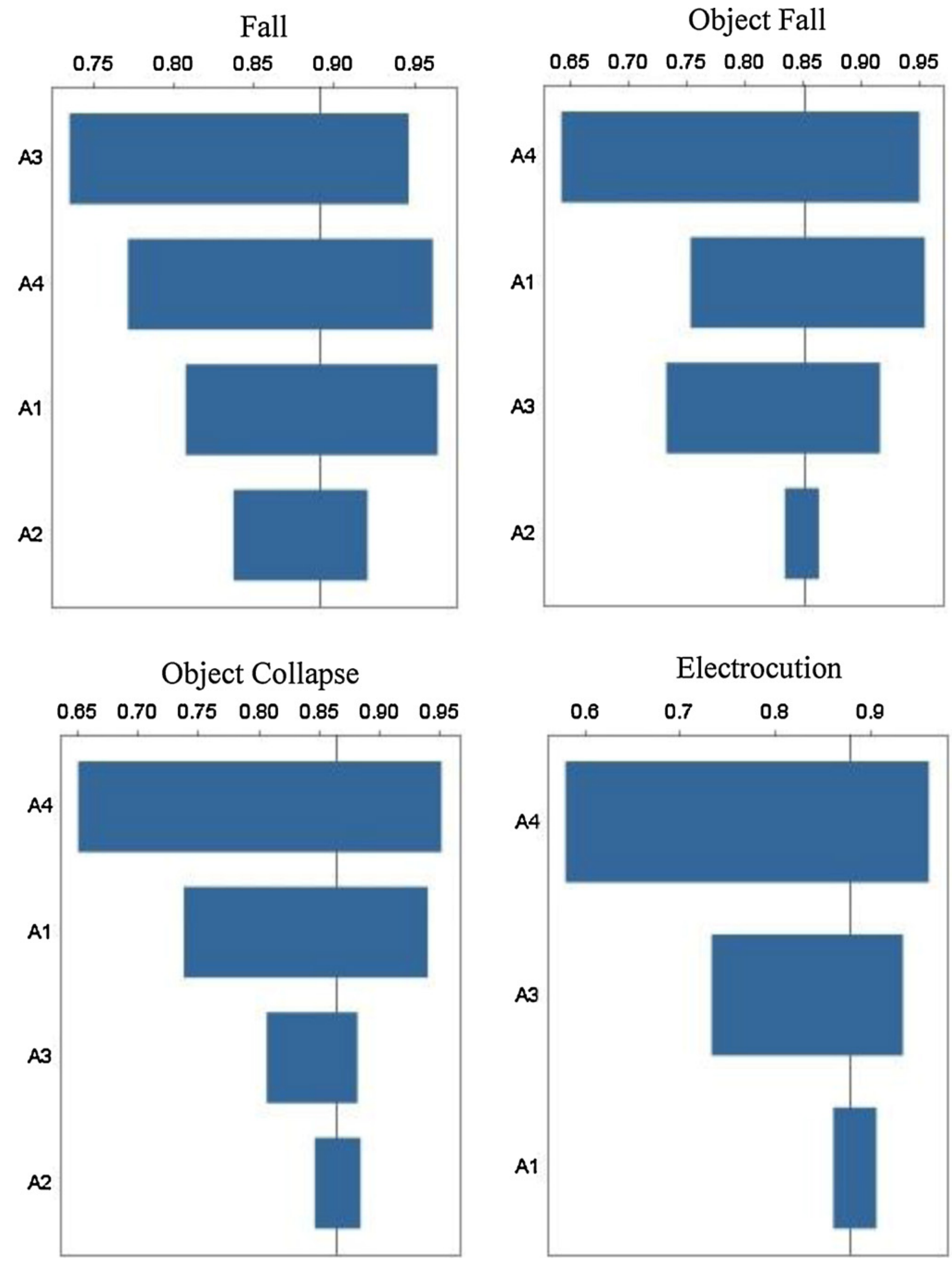


Fig. 9. Tornado diagram of root causes.

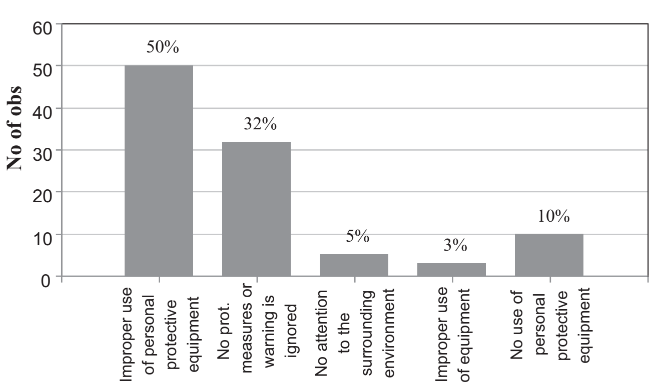


Fig. 10. Occupational hazard statistics of indirect factors of fall in Taiwan (2009–2010).

in a proactive manner in addition to appropriate safety planning and training. Furthermore, management should always reinforce the value and importance of safety.

In summary, this model not only assesses safety risks at SC building sites, but identifies the sensitive causes of four major accident types using sensitivity analysis. Based on the mentioned analysis, project managers can propose preventive safety measures to reduce accidents. In addition, safety risk assessment and sensitivity analyses enable the allocation of resources to critical safety causes to alleviate safety risks at SC project sites.

6. Conclusion and future developments

This study developed an effective method to construct a BN-based safety risk-assessment model for SC building project sites.

The inference results of the BN were validated against nine SC building projects in which specific accidents occurred at each SC site. The analysis and comparison showed that the results of the BN inference were highly consistent with actual accidents at the sites. This indicates that the transformation process from an FT to a BN can create a realistic and accurate safety risk-assessment model. Consequently, based on the model assessment and sensitivity analysis, site project managers can prepare preventive safety measures and allocate resources to significantly reduce the risks of site accidents in SC projects.

Although the transformation mechanism from an FT to BN has been thoroughly examined, the use of a BN relies on the inputs of expert experiences for the BN structures and CPTs in the BN. The information provided by experts directly affects the accuracy and assessment quality of the BN. More studies should explore expert elicitation. In addition, the BN can be learned from raw data combined with expert experiences. If reliable safety data are available, a sound BN framework and parameters can be explored and established. Finally, the proposed BN-based safety assessment model demonstrated its contribution to site accident prediction and assessment. It may be useful to extend the application scope of the BN to cover additional construction projects and to use the BN for overall safety diagnoses to enhance safety operations and management.

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