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

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A R T I C L E I N F O

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A B S T R A C T

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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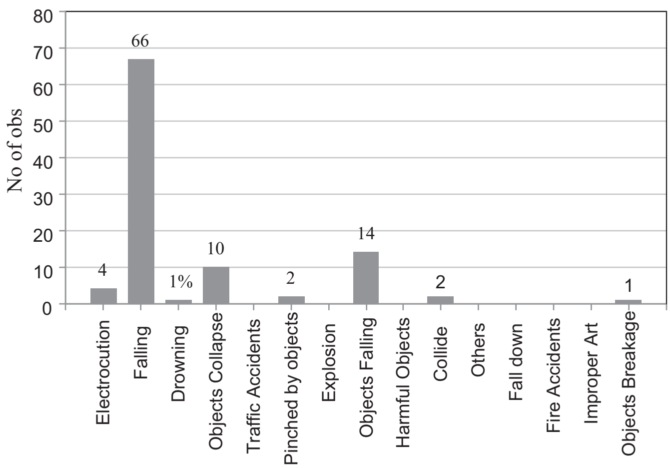

Fig. 1. Occupational accidents of steel construction projects in Taiwan (2000–2010).

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 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.

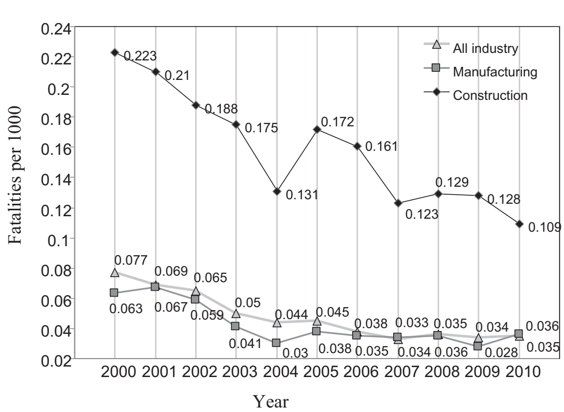

Fig. 2. Fatalities per 1000 persons in construction industry and all industries (excluding deaths from occupational disease and traffic accidents), 2000–2010.

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).