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A hybrid BN-HFACS model for predicting safety performance in construction projects

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ABSTRACT

Lacking a holistic framework for analyzing risk factors would result in the inaccurate assessment of safety performance and poor safety management. This research aims to establish a Bayesian-network (BN)-HFACS hybrid model to proactively predict safety performance in construction projects. First, a causation framework for analyzing the underlying factors influencing construction safety performance was established using the Human Factors Analysis and Classification System (HFACS). This causation framework incorporates 18 risk factors from organizational, environmental and human aspects that are categorized into five levels: L1: “unsafe acts of workers,” L2: “preconditions for unsafe acts,” L3: “unsafe supervision and monitoring,” L4: “adverse organizational influences,” and L5: “adverse environmental influences.” The relationships between these factors and project safety performance were then hypothesized in the BN-HFACS model, and validated by data collected with questionnaires. The proposed model was applied to a subway project with AgenaRisk software. This application demonstrated the model’s capabilities in systematically identifying risk factors, predicting the probabilities of safety states in project level and in the five specific cause levels, and diagnosing the most sensitive risk factor. This research contributes to safety assessment and management by modifying the original HFACS for the causation analysis of construction safety performance, and by establishing a BN model for quantifying the total influences of the risk factors at five distinct levels on project safety performance. The integration of HFACS and BNs may be instructive in other contexts where diverse safety risk factors are involved in a system and safety prediction of the system is necessary.

1. Introduction

The construction industry worldwide is constantly prone to injuries and accidents (Fang and Wu, 2013; Wang et al., 2016; Zou and Sunindijo, 2015, 2013). This causes great damage to the well-being of the workers and to the profitability and reputation of project parties (Zou et al., 2014). Concerning these losses, safety performance is a critical measure of project success alongside the traditional “iron triangle” view of time, cost, and quality (Alzahrani and Emsley, 2013). The best way to reach good safety performance is to mitigate or minimize risks before they occur (Fung et al., 2010). Therefore, safety performance in a construction project should be predicted and managed proactively to prevent accidents, and thus to improve the chances of project success.

An accurate prediction depends on reliable and systematic analyses of the sources of risks, i.e., risk factors that can threaten safety performance. In the construction context, extensive attention has been paid to fragmented factors, including human factors such as safety behavior (Guo et al., 2016), safety attitude (Langford et al., 2000), and risk tolerance (Wang et al., 2016), as well as organizational and environmental factors such as senior management commitment (Zou and Sunindijo, 2013) and frontline supervision (Fang et al., 2015). These studies have made valuable contributions by examining the individual effects of those factors on safety performance. However, how project safety performance can be predicted based on the collective effects of those factors remains unaddressed. Safety performance can be determined by a number of organizational, environmental and human factors (Hale et al., 2012; Zhou et al., 2014). Furthermore, existing studies have mainly focused on the unsafe behavior of frontline workers, while less attention was paid to the underlying causes behind that behavior, such as organizational factors (Fung et al., 2010; Zou and Sunindijo, 2013). Unsafe acts, as active failures, are hard to foresee, while latent variables like senior management commitment can be identified and then mitigated before an accident or incident occurs

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(Love et al., 2016). To summarize, in order to predict safety performance, together with mitigating risk factors especially adverse latent variables, a holistic causation analysis framework for safety performance is a prerequisite while it seems to lack in the current literature.

The present study, thus, aims to establish a hybrid BN-HFACS model for predicting safety performance in construction projects. First, as discussed above, the underlying factors influencing safety performance, i.e., safety risk factors in construction projects are holistically explored using the Human Factors Analysis and Classification System (HFACS) (Shappell and Wiegmann, 2000). The HFACS focuses on the underlying causes of accidents, especially the management and organization aspects, and is widely used for safety and accident analysis in various areas such as maritime, railway, and construction (Akyuz, 2017; Chen et al., 2013; Garrett and Teizer, 2009; Zhan et al., 2017). In this study, the original HFACS is modified to fit the specific context of construction projects. By integrating BNs thereafter, the model established is capable of describing the relationships between safety risk factors and project safety performance, and in predicting the probabilities of project safety states and failure, and in diagnosing the most sensitive factor causing project safety failure. BNs and HFACS have been used separately in previous construction safety research, but they are integrated for the first time in this study. Such a combination will advance our full understanding of the underlying causes of construction project safety failure, and of the interrelationships among the risk sources and their total effects on project safety performance. In the following section, main characteristics, current applications and gaps concerning HFACS and BNs, and advancement that the present study can make to these two theories are presented.

2. Theoretical background and research gapsm

2.1. Human Factors Analysis and Classification System (HFACS)

In most cases, accidents result from various factors which can be classified (Reason, 1990; Shappell and Wiegmann, 2000; Wiegmann and Shappell, 2001). Among existing classification methods, one particularly appealing approach is the Human Factors Analysis and Classification System (HFACS) originally designed within the aviation accident setting (Shappell and Wiegmann, 2000). HFACS describes four levels of failure: unsafe acts, preconditions for unsafe acts, unsafe supervision, and organizational influences, with the first level (unsafe acts) being closest to the accident itself. Since its initial development, HFACS has been demonstrated to be a valid tool for human error analyses in various fields, such as railways (Zhan et al., 2017), mining (Patterson and Shappell, 2010), maritime shipping (Chauvin et al., 2013), health-care (Diller et al., 2014), and aviation (Daramola, 2014). Despite its validity and wide-ranging applicability, the framework was less commonly applied in the context of the construction industry (Garrett and Teizer, 2009). This may be attributable to the inadequate focus on the underlying causes of safety failure and accidents in this industry, as argued previously.

HFACS is valuable in providing a systematic analysis of accident causes. However, it considers merely the sequential influences from the higher levels on the lower levels. In reality, influencing relationships may exist among the cause levels that are not neighboring. For example, safety failures at the organizational factor level can lead directly to unsafe acts by employees (Hofmann and Stetzer, 1996). Given this, this study develops a more deliberate influencing network. Furthermore, the extant application of HFACS in the construction setting appears to remain mainly on a qualitative basis. Therefore, the present study utilizes Bayesian networks (BNs) to construct an interrelated network among the risk factors at different levels in HFACS, and between the risk factors and project safety performance. Based on this, a BN-HFACS model for quantitative prediction of safety states and failure in construction projects can be built. This quantitative application for performance prediction can add knowledge to quantitative analyses of the HFACS framework that currently remain at identifying the core risk factors of accidents (Akyuz, 2017; Soner and Asan, 2015; Zhan et al., 2017).

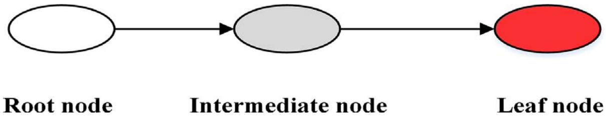

Fig. 1. Example of a Bayesian Network.

2.2. Bayesian Networks (BNs)

BNs, also called belief networks, Bayesian belief networks, influence diagrams, or causality diagrams, are directed acyclic graphical models that represent a set of random variables (i.e., nodes) and their conditional dependent or influencing relationships (McCabe et al., 1998). Fig. 1 describes a simple example of a BN. The nodes acting as independent variables are also called *parent nodes* (root nodes), while nodes acting as dependent variables are also called *child nodes* (intermediate and leaf nodes).

BNs are especially well suited to risk assessment and reliability problems (Francis et al., 2014), including the construction field. Luu et al. (2009) incorporated a BN into a schedule risk model to quantify the probability of project delays and proved its effectiveness. Nasir et al. (2003) also focused on schedule risk assessment, while Khodakarami and Abdi (2014) focused on cost risk. Concerning construction safety, Leu and Chang (2013) established a BN-based model for assessing safety risk in steel projects by combining a fault tree approach, whereas Zhang et al. (2013, 2014), and Wu et al. (2015) put forward a BN model for providing decision support relating to accident prevention and safety control in the event of tunnel-induced damage during construction. Focusing on individual safety behavior, Jitwasinkul et al. (2016) established a BN model for identifying the most critical organizational factors to enhance safe behavior. Although these applications were in different settings, it can be concluded that BNs are capable of risk and safety analysis, including prediction, diagnosis, decision-making, and the provision of insights into relationships among variables. In addition, BNs have been seldom utilized to predict safety performance of construction projects, despite the wide application in the construction setting. This study, thus, aims to introduce BNs as a suitable method for predicting safety states and failure in construction projects, and for diagnosing the causes of safety failure in a proactive manner.

3. Research framework

In order to depict clearly how HFACS and BNs can be combined in carrying out safety performance prediction, a systematic framework is proposed in Fig.2. Phase 1 is concerned with establishing a general BN-HFACS model for safety performance prediction, including establishing an HFACS framework for describing and categorizing accident causes in construction projects (Step 1), and developing an influencing network among the variables in the HFACS with BNs (Step 2). In Phase 2, this model can be applied to a specific project to examine the feasibility and capability of the BN-HFACS model in real cases (Step 3). In applications, modifications should be made to the general BN-HFACS established in Phase 1 to reflect specific characteristics of different projects.

Step 1. The first step is to establish a modified HFACS framework for analyzing safety risk factors specific to construction projects. To this end, the original HFASC framework was revised based on a literature review of the relevant knowledge of HFACS and safety and accident management in construction. We also consulted six experts who had been working in construction safety management for more than 15 years. These experts had participated in a large number of accident investigations in the construction industry. Details of Step 1 are provided in Section 4.