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A BELIEF NETWORK TO PREDICT SAFETY PERFORMANCE OF CONSTRUCTION WORKERS-FROM THE PERSPECTIVES OF RESILIENCE

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Abstract: Resilience has been proposed to be a proactive approach to safety management for the next generation. Qualitative studies on defining resilience and using resilience rules to interpret safety practices have been widely conducted; however, relatively few quantitative studies have been done to measure resilience. Further, very few empirical studies have investigated the interactions between resilience factors and safety outcomes. This paper aims to identify the interactions among resilience factors, and their impact on individual safety performance on construction sites. In this paper, a belief network was built based on 431 self-administered surveys from 68 sites in Ontario, Canada. This paper leads to several conclusions. First, management commitment is the key promoting a strong safety culture. Second, safety awareness is the most important individual factor affecting the safety performance of construction workers. Third, support from team members has a significant positive impact on improving the safety awareness of construction workers.

1 INTRODUCTION

As a capacity for positive response when organizations face adverse events, resilience has been proposed to be a new approach for the next generation of safety improvement (Hollnagel 2015). Compared to traditional safety methods, its efforts focus on enhancing the organization's ability to respond, monitor, anticipate, and learn (Nemeth et al. 2008, Hollnagel 2009). In safety research, resilience studies have focused on defining resilience measures and quantifying resilience. With regards to resilience measures, six scales have been widely used (Woods and Wreathall 2003): management commitment, reporting culture, learning culture, anticipation, awareness, and flexibility. Compared with studies focusing on defining resilience measures, relatively few quantitative studies have been conducted. To the knowledge of the authors, only four papers in the literature focused on quantitative analysis of resilience in industrial sectors. They used three methods: principal component analysis and numerical taxonomy (Shirali et al. 2013; 2016); fuzzy cognitive mapping (Azadeh, Salehi, Arvan, *et al.* 2014); and data envelope analysis (Azadeh, Salehi, Ashjari, *et al.* 2014).

The application of resilience is particularly suitable for high-risk systems with complex characteristics (Costella et al. 2009). As a complex, dynamic, and unstable system, a construction site needs resilience to develop prevention strategies (Costella *et al.* 2009). Although there are several qualitative studies applying resilience to the construction industry, e.g. re-interpreting safety management practices using resilience principles (Saurin *et al.* 2008), few quantitative studies have been conducted in the construction industry. To the knowledge of the authors, there is one study linking resilience to construction safety performance, but focusing on safety related interactions among a construction team (Wehbe *et al.* 2016). Moreover, few studies have investigated the interactions amongst resilience indicators and individual safety performance. For example, can a good reporting culture improve construction workers' safety awareness? This paper aims to investigate the interactions among the resilience indicators and their impact on individual safety performance on construction sites. The quantitative approach used in the study is belief network (BN). The following sections define resilience indicators used in this paper.

1.1 Resilience indicators

To achieve resilience, efforts from all organizational levels including organizations, groups, and individuals are needed (Patterson *et al.* 2007, Johnsen and Veen 2013). For a construction site, resilience stakeholders are top management, site supervisors, and construction workers. Management commitment is achieved by both the top management and site supervisors. Coworkers' support is also critical for a safe work environment. Regular safety meetings are the most common formal approach to promoting a good reporting and learning culture. In this paper, resilience indicators summarized by (Woods and Wreathall 2003) were used except flexibility. The reasons we did not include flexibility is that measurements found in previous studies were for the manufacturing and industrial sectors, and are not appropriate for construction industry due to its continuously changing work environment and stakeholders. Thus, the resilience indicators used in the paper include management commitment, supervisor safety perception, coworker safety perception, reporting, learning, anticipation, and awareness.

2 METHODS

A multi-site data collection strategy was employed. In total, 431 surveys were collected from 68 construction sites between May and July 2016. Before performing any analysis, 28 cases were removed because a high proportion (>10%) of data were missing. Thus, 403 cases were used for the analysis. Missing values were replaced with the variable means in the remaining cases.

A self-administered questionnaire that comprised demographics, attitude statements, and incident reporting was used to collect data. The demographics and incident reporting were adapted from the previous research (McCabe *et al.* 2008). The demographics section included questions about the individual's characteristics, such as age and trade type. In the attitudinal section, respondents indicated the degree to which they agreed with statements using a Likert scale between 1 (strongly disagree) and 5 (strongly agree). The incident reporting section asked the respondents how frequently they experienced unsafe incidents on the job in the 3 months previous to the survey. There are three categories of incidents: physical injuries, unsafe events, and job stress. Physical injuries and unsafe events are regarded as physical safety outcomes. Job stress describes symptoms of job-related stresses. Physical injuries, such as an *eye injury*, may be associated with an unsafe event, but no connection is made by the respondent. Unsafe events, such as *struck against something fixed*, comprise events that respondents experienced but may or may not have resulted in an injury. One example of job stress is *unable to concentrate on work related tasks*.

2.1 Data collection

All surveys were collected from construction sites and at least two research assistants (RAs) were on site to distribute surveys. A strict data collection procedure was followed. First, each participant needed to sign a consent form. After consent forms were collected, the survey was distributed. RAs provided immediate help to workers if they had a question, which improved the reliability and completeness of the data. Approximately 20 minutes were taken to complete each survey. Surveys were strictly anonymous and no follow up was undertaken.

2.2 Demographics of the respondents

The respondents were from a variety of construction sectors, including residential, heavy civil, institutional, and commercial. Table 1 summarizes the demographic information of the respondents. The mean age of the respondents was 37 years and 98% were male; 68% of workers were journeymen or apprentices. The respondents had been employed by their current employer for 6 years on average, but half of them had worked with their employers less than 4 years. Respondents reported relatively high mobility between projects. The weekly working hours of the respondents were approximately 44 hours, and 32% worked more than 44 hours, which is considered overtime (Ontario Ministry of Labour 2015). Finally, 60% of the respondents were union members.

Table 1. Demographics of respondents

Demographic factors	Response range	Mean or %	Median
Gender	Male / Female	98% male	-
Age	16 to 67	37.00	36.00
Years in construction	0.5 to 46	14.29	11.00
Years with the current employer	0.01 to 45	6.01	4.00
No. of construction employers in previous 3 years	1 to 100	2.62	1.00
No. of projects worked in previous 3 years	1 to 300	9.79	4.00
Average hours worked per week	17 to 85	43.57	40.00
Was respondent a member of a union	Yes or No	65.0% yes	-
Job position	Supervisor	32.1%	-
	Journeyman	50.3%	-
	Apprentice	17.7%	-
Size of employers	Micro (1-4)	5.6 %	-
	Small (5-99)	51.0%	-
	Medium (100-499)	28.6%	-
	Large (500+)	14.8%	-

2.3 Measures

Management commitment to safety examines the priority that management puts on safety, especially when it conflicts with production. Six statements were adapted from previous research studies (Hayes *et al.* 1998, Carthey *et al.* 2001, Zohar and Luria 2005). An example is "our management provides safe equipment." The coefficient alpha of the scale is 0.87.

Supervisor safety perception is the workers' perception about whether their supervisors commit to safety. Six statements were used (Hayes *et al.* 1998). An example statement is "my supervisor spends time showing me the safest way to do things". The coefficient alpha of the scale is 0.86.

Coworker safety perception is one's perceptions about whether their co-workers follow safety rules and behave safely. Four statements were used (Hayes *et al.* 1998). One example is "my coworkers keep work area clean". The coefficient alpha of the scale is 0.72.

Reporting examines whether people on site are encouraged to report incidents without fear of retribution. Three statements were adapted from (Ostrom *et al.* 1993). An example is "people who raise safety concerns are seen as trouble makers." The coefficient alpha of the scale is 0.71.

Learning is the workers' perception about whether they are informed of past lessons and whether they can learn from past events. Four statements were used (Ostrom *et al.* 1993). Two statements were from the previous research (Ostrom *et al.* 1993, Carthey *et al.* 2001). An example is "workers' ideas and opinions on safety are solicited and used." The coefficient alpha of the scale is 0.83.

Anticipation examines whether workers on site assess the potential safety impacts caused by their decisions. Two statements were used to measure this scale (Ferreira 2011). One example is “I think about the potential impacts on safety for each of my decisions or behaviours.” The coefficient alpha of the scale is 0.68.

Awareness is about whether people on site are aware of potential safety hazards. Three statements were adapted from previous research (Ostrom *et al.* 1993, Cox and Cheyne 2000, Shirali *et al.* 2013). One example is “people are aware of the safety hazards in their work area.” The coefficient alpha of the scale is 0.80.

2.4 Analysis procedure

The analyses were performed using the free R statistics, and Bnlearn package for building and testing the belief network. Factor score was the average of the scale questions for each factor. For example, management commitment factor score was obtained by averaging the scores of its six questions. Then, the score of each factor was used as input in R to build and validate the belief network. A BN is a graphical representation of conditional dependence among a group of variables. BN is a probabilistic approach to determine the likelihood of occurrence of certain variable conditions based on Bayes' theorem. In Bnlearn package, Hill-Climbing algorithm was used to learn the structure of BN. Conditional independence tests were used to remove unreasonable arcs in the model. After the network structure was obtained, parameter learning that estimated the interactions between the nodes was done. Finally, model verification was conducted using k-fold and hold-out cross-validation methods. Bayesian Information Criterion (BIC) score that descried the uncertainty reduction of the model was also given.

3 RESULTS

3.1 Structure learning

Error! Reference source not found. shows the final belief network. Management commitment and awareness are the two nodes that have direct impact on unsafe events. Awareness is an very important conduit node, because it has parent nodes including learning, anticipation, coworker safety perception, and reporting. In addition, it is apparent that supervisor safety perception is critical, given that the impact of management commitment on other nodes were mainly achieved via supervisor safety perception.

In the process of structure learning, a set of conditional independence tests based on the mutual information were run, in order to remove unnecessary arcs. For example, management commitment and learning (reporting) were found to be conditionally independent given supervisor safety perception; management commitment and stress was found to be conditionally independent given events. Thus, these three arcs were removed when building the model. This process was repeated several times until the model in **Error! Reference source not found.** was obtained.

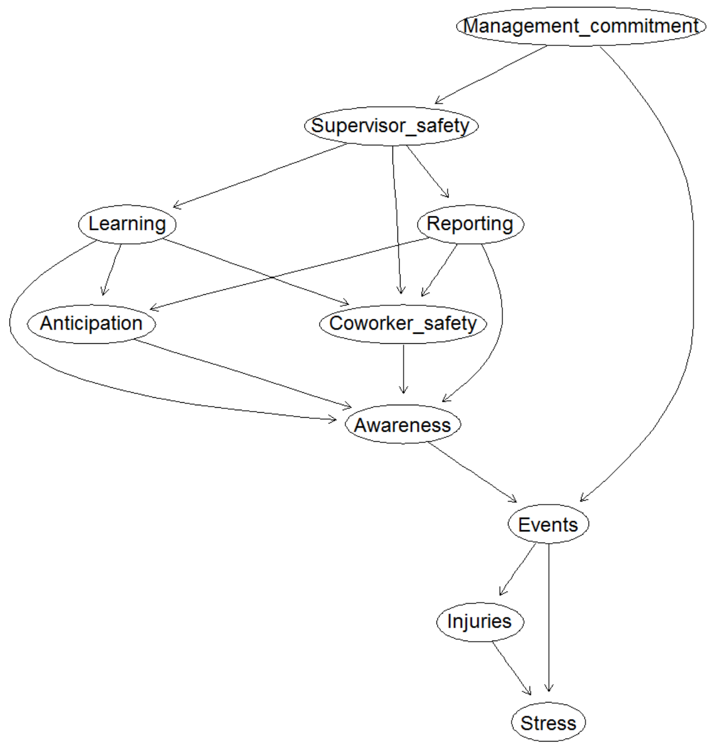

Figure 1: BN model

3.2 Parameter learning

This section examined the relationships between parent nodes and children nodes, which is actually to see the prediction relationship between the parent nodes and children nodes. Table 2 gives the non-standardized regression coefficients (i.e. B) between the parent nodes and children nodes. For example, node "Events" is predicted by Management commitment (B=-1.85) and Awareness (B=-0.82). This means that 1.85 Events will be decreased when Management commitment increases 1 unit and Awareness is controlled. Similarly, 0.82 Events will be decreased when Awareness increases 1 unit and when Management commitment is controlled for. In addition, it was found that Supervisor safety perception had a strong positive impact on learning (B=1.00). Coworker safety perception had the strongest positive impact on awareness, compared with learning, reporting, and anticipation.

Table 2: Parameter estimates

Children nodes	Parent nodes									
	MC	SS	CS	LN	RP	AN	AW	Events	Injuries	Stress
SS	0.93									
CS		0.39		0.10	0.12					
LN		1.00								
RP		0.27								
AN				0.44	0.11					
AW			0.64	0.16	.15	0.17				
Events	-1.85						-0.82			
Injuries								0.91		
Stress								0.20	0.35	

3.3 Model verification

In this section, the stability of the model was verified using k-fold cross-validation and hold-out cross-validation methods. The major aim of this process is to investigate whether the model will be significantly affected when the sample size decreases a lot. For k-fold cross-validation, the data are randomly partitioned into k subsets (Scutari 2013). Each subset is used in turn to validate the model fitted on the remaining k - 1 subsets. For our model, the data were partitioned into 10 subsets, which resulted in around 40 cases for each subset. Then, models fitted on the10 subsets were compared, which resulted in a loss (11.76 in Table 3). For hold-out cross-validation, the data are repeatedly (randomly) partitioned in a training and test subset of a given size m and n - m, with observations assigned randomly to each subset at each repetition. Each test subset is used to validate the model fitted on the corresponding training subset. For our model, the data were spit into 25 subsets, and three different sizes of the subsets were tested (100, 200, and 300, respectively). The testing results are given in Table 3. The expected losses for all of the four tests ranged from 11.76 to 11.91, which did not have a large variation. Thus, it was concluded that the model structure is stable.

Table 3. Model verification results

	Num. of folds (splits)	Size of the test subset	Loss function	Expected loss
k-fold cross-validation	10	-	Log-Likelihood Loss (Gauss.)	11.76
Hold-out cross-validation	25	100		11.78
	25	200		11.80
	25	300		11.91

4 DISCUSSION

This paper aims to build a BN model in the context of the construction industry to investigate the interactions among the resilience indicators and their impact on individual safety performance. Management commitment had the strongest impact on unsafe events, which confirmed its central role in affecting safety performance of workers (Zohar 1980, Jaselskis *et al.* 1996). Awareness is one's perceptions of the elements in their work environment within a volume of time and space (Endsley 1988). It had the second strongest impact on unsafe events, and was the conduit variable through which the other influences traveled to affect safety outcomes in the model. The implications of situational awareness for safety has been broadly realized in other sectors in the past 20 years, e.g. chemical processing (Kaber and Endsley 1998). However, little attention has been paid to the construction industry. This is the first empirical study to validate the direct and pivotal impact of awareness on construction workers' safety performance.

Coworker safety perception significantly positively affected awareness, which suggests its important role in promoting safety awareness. Literature suggests communication within or among teams (Kaber and Endsley 1998) can improve the individual, intra-team, and inter-team levels safety awareness. A structured feedback system can inform the employees that their suggestions or concerns have been reviewed and what kind of actions, if any, will be taken to address the problem, which has the potential to improve workers' reporting, learning, and safety performance. Our findings suggest the critical role of team members in one's safety awareness, and confirm the role of efficient reporting and learning in promoting a higher level of safety awareness. In addition, the impact of management on reporting and learning was achieved via supervisor safety perception (Figure 1), which highlights the important role of supervisors in the operation level of promoting a good reporting and learning culture.

5 CONCLUSIONS

In this study, 431 surveys were collected from 68 construction sites in Ontario, Canada. The impact of resilience on construction safety performance was tested. A stable belief network model was built and verified. This study demonstrated that management commitment is critical to promote a strong safety culture. As a conduit for the other factors, awareness is the most important individual factor affecting the safety performance of construction workers. Support from team members has a significant positive impact on safety awareness improvement of construction workers. Given these findings, top management of construction organizations may consider focusing safety programs to improve employees' safety awareness by promoting a site or team level safety culture and a good reporting and learning culture.

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REFERENCES

Azadeh, A. *et al.* 2014. Assessment of resilience engineering factors in high-risk environments by fuzzy cognitive maps: A petrochemical plant. *Safety Science*, **68**: 99–107.

Azadeh, A. *et al.* 2014. Performance evaluation of integrated resilience engineering factors by data envelopment analysis: The case of a petrochemical plant. *Process Safety and Environmental Protection*, **92**(3): 231–241.

Carthey, J., de Leval, M.R., and Reason, J.T. 2001. Institutional resilience in healthcare systems. *Quality in health care : QHC*, **10**(1): 29–32.

Costella, M.F., Saurin, T.A., and de Macedo Guimaraes, L.B. 2009. A method for assessing health and safety management systems from the resilience engineering perspective. *Safety Science*, **47**(8): 1056–1067.

Cox, S.J. and Cheyne, A.J.T. 2000. Assessing safety culture in offshore environments. *Safety Science*, **34**(1–3): 111–129.

Endsley, M. 1988. Design and evaluation for situational awareness enhancement. *In*: *Proceedings of the Human Factors Society 32nd Annual Meeting*. Santa Monica.

Ferreira, P.N.P. 2011. Resilience in the planning of rail engineering work. University of Nottingham.

Hayes, B.E. *et al.* 1998. Measuring Perceptions of Workplace Safety: Development and Validation of the Work Safety Scale. *Journal of Safety Research*, **29**(3): 145–161.

Hollnagel, E. 2015. *Safety-I and Safety-II, the past and future of safety management*. Ashgate.

Jaselskis, E.J., Anderson, S.D., and Russell, J.S. 1996. Strategies for Achieving Excellence in Construction Safety Performance. *Journal of Construction Engineering and Management*, **122**(1): 61–70.

Johnsen, S.O. and Veen, M. 2013. Risk assessment and resilience of critical communication infrastructure in railways. *Cognition, Technology and Work*, **15**(1): 95–107.

Kaber, D.B. and Endsley, M.R. 1998. Team situation awareness for process control safety and performance. *Process Safety Progress*, **17**(1): 43–48.

McCabe, B. *et al.* 2008. Individual safety and health outcomes in the construction industry. *Canadian Journal of Civil Engineering*, **35**(12): 1455–1467.

Ontario Ministry of Labour. 2015. Overtime Pay [online]. Available from: https://www.labour.gov.on.ca/english/es/pubs/guide/overtime.php [Accessed 15 May 2016].

Ostrom, L., Wilhelmsen, C., and Kaplan, B. 1993. Assessing safety culture. *Nuclear Safety*, **34**(2): 163–172.

Patterson, E.S. *et al.* 2007. Collaborative cross-checking to enhance resilience. *Cognition, Technology and Work*, **9**(3): 155–162.

Saurin, T.A., Formoso, C.T., and Cambraia, F.B. 2008. An analysis of construction safety best practices from a cognitive systems engineering perspective. *Safety Science*, **46**(8): 1169–1183.

Scutari, M. 2013. Bayesian networks and cross-validation.

Shirali, G.A., Mohammadfam, I., and Ebrahimipour, V. 2013. A new method for quantitative assessment of resilience engineering by PCA and NT approach: A case study in a process industry. *Reliability Engineering and System Safety*, **119**: 88–94.

Shirali, G., Shekari, M., and Angali, K. 2016. Quantitative assessment of resilience safety culture using principal components analysis and numerical taxonomy: A case study in a petrochemical plant. *Journal of Loss Prevention in the Process*, **40**: 277–284.

Wehbe, F., Hattab, M. Al, and Hamzeh, F. 2016. Exploring associations between resilience and construction safety performance in safety networks. *Safety Science*, **82**: 338–351.

Woods, D.D. and Wreathall, J. 2003. Managing Risk Proactively : The Emergence of Resilience Engineering. *Psychology*, (November).

Zohar, D. 1980. Safety climate in industrial organizations: theoretical and applied implications. *The Journal of Applied Psychology*, **65**(1): 96–102.

Zohar, D. and Luria, G. 2005. A multilevel model of safety climate: cross-level relationships between organization and group-level climates. *The Journal of applied psychology*, **90**(4): 616–628.