Using Network Analysis to Model Fall Hazards on Construction Projects

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ABSTRACT

Safety risk quantification, integration, and management are emerging preconstruction strategies that have significant potential to impact construction safety performance. Unfortunately, current risk assessment strategies have limited practical application because every new infrastructure feature and construction method must be individually evaluated using laborious research processes and data from previous failures. In order to address this limitation, this research tested the hypothesis that the risk of worker injury in dynamic construction environments is the direct result of the temporal and spatial interactions among a limited number of identifiable and quantifiable task and object attributes. To test this hypothesis, a content analysis was conducted on 105 National Institute of Occupational Safety and Health Fatality Assessment and Control Evaluations reports. Attributes that contribute to incidents were identified and their relative risks were quantified according to frequency and severity of accidents that they have caused. Clusters and interactions among attributes were also modeled using Social Network Analysis (SNA) method. Ultimately, these research results can be used to improve the integration of safety information with building information models, project schedules, and architectural design. It is expected that the flexibility of the proposed approach will overcome most risk integration barriers that have been observed in the past decade.

Keywords: Safety Risk Management, Fall Accident, SNA

1. INTRODUCTION

Although the number of injuries and fatalities in the construction industry has decreased significantly in the past decades, construction still has the highest number of fatalities
among all industry sectors in the United States (BLS 2010). Falls account for the highest number of fatal injuries in construction among the different proximal causes (Gillen et al. 1997; Hinze et al. 2005). In fact, falls from height account for approximately a third of all injuries in the US construction industry (Weeks and McVittie 1995; Hinze et al. 2005) and typically result in severe injuries (Lipscomb et al. 2004), which require longer periods of recovery and significant medical costs (Gillen et al. 1997; Janicak 1998; and Derr et al. 2001; Lipscomb et al. 2003).

Falls in construction is a key target area for intervention and prevention (Gillen et al. 1997) and many prevention practices have been discussed by researchers including: safety harnesses, railings around opened edges and skylights, modification of equipment such as ladders, training programs, and administrative interventions (Rivara and Thompson 2000). Although the importance of safety controls such as providing guardrails and personal protective measures have been stated in the previous literature (Winder 1973; Hinze and Pannullo 1978; Tarrants 1980; Stanton and Willenbrock 1990; Toole 2002), considering safety during the design of the facility has been (shown to be particularly effective (Gambatese et al. 2005; Navon and Kolton 2006). Key concepts in designing for safety include identifying and mitigating hazardous situations during the design of the permanent facility. Therefore, careful attention should be paid to identifying hazardous situations and mapping the risk factors on the site (Salelson and Levitt 1982; Young 1996; Abdelhamid and Everitt 2000; Hallowell et al. in press). In addition to prevention through design, risk analysis has shown to be highly effective due to its quantitative and systematic nature (Hallowell et al. in press).

In previous studies, risk at the trade level (Fredericks et al. 2005; Beavers et al. 2009) and activity level (Hallowell and Gambatese 2009) have been quantified. However, some unique temporal and spatial characteristics of construction jobsites such as continuous change in work environment, the dynamic composition of work crews, multiplicity of operations, and proximity of crews expose workers to unrecognized hazards and make it difficult to accurately predict hazardous environments (Helander 1991). In fact, one of the chief limitations of previous studies that focus on predictive analysis and control is that they do not account for the fact that construction is dynamic.

To address this gap in knowledge, the authors present an attribute-based risk identification and analysis method that helps designers to identify and model the safety risk independently of specific activities or trades. The key concept of the new model is that the safety risks can be mapped for any tasks at any time by utilizing fundamental hazardous attributes. In this method, accidents are considered the outcome of interaction among physical conditions of the jobsite, environmental factors, administrative issues, and human error. To illustrate the connections among hazardous attributes in case scenarios, Social Network Analysis (SNA) is utilized. This SNA cluster analysis is a novel way to identify the areas of possible intervention that break the chain of events that lead to accidents.

In order to limit the scope of the research, the authors focused on fall fatalities; however, the presented method has the potential to be applied to other proximal causes as well. It is
expected that the presented attribute safety risk based model has the potential to enhance preconstruction safety activities for any construction environment.

2. LITERATURE

Subpart M of the OSHA standards (29CFR 1926.500 to 1926.503) provide the requirements for fall protection for general construction procedures. According to this law, construction employers are obligated to protect workers from fall hazards whenever they are exposed to a fall of 1.83m (6 foot) or more. Johnson et al. (1998) evaluated the existing regulations, construction practices, and alternative fall protection measures and found that the current state of compliance is poor, fall protection plans are not prepared as required, and positive safety measures such as guardrails and personal fall arrest systems are not used. They claimed that the extreme competitiveness within the industry, unsafe worker behavior, design challenges, conventional construction practices, productivity pressure, and a lack of knowledge are the main reasons for noncompliance.

Researchers found that workers usually fall when they lose their balance while walking on the roof surface (Pearson et al. 1986), stand on skylights (Bobick et al. 1994), or slip off the roof edge when stepping on loose materials on pitched roofs (Suruda 1995). Additionally, Lipscomb et al. (2004) evaluated textual descriptions of injuries from the construction of the Denver International Airport to get a better understanding of falls and found that one third of falls from height are preceded by slips/trips and another third resulted from the collapse of work surfaces such as ladders or scaffolds. In a related study, Fredericks et al. (2005) evaluated the US Bureau of Labor Statistics (BLS) data and conducted surveys on roofing companies to determine the specific tasks that are linked with incidents in roofing construction. They found that carrying heavy materials on slippery and inclined working surfaces was the main reason of fall from elevation. They also stated that falls from height involved ladders, scaffolding, roofs, work on other unsecured surfaces, unprotected openings, speed, and weather conditions.

Though previous studies have made significant progress in our understanding of falls in construction, there are several limitations that stem from two main factors: (1) the dynamic nature construction sites and (2) the data obtained and prevention frameworks developed cannot be applied effectively in preconstruction activities, especially design. Though some researchers have quantified risks for specific trades, one should note that risk varies over time depending on adjacent tasks, work in progress, mobile equipment, and other factors. According to Hallowell et al. (in press), spatial and temporal task interactions alone can increase base-level safety risk by 60 percent. Therefore, as previously mentioned, it is of great importance to find a way to quantify safety risks independent from the specific trades or tasks by considering the interactions among different attributes.
3. OBJECTIVES

The research questions of this study were: “What are the safety risk attributes that contribute to occurrence of fall accidents in the construction industry?” “What is their relative magnitude?” and “How can they be prevented and managed?” Consequently, the current study has two objectives:

1. Identify safety risk attributes that lead to fall fatalities and quantifying their relative safety risks;
2. Use cluster analysis to identify the most efficient safety intervention for a particular case.

These objectives were fulfilled in two distinct research phases. In the first phase safety risk attributes were identified by conducting content analysis on accident reports and in the second phase the interactions among attributes were analyzed using cluster analysis.

4. RESEARCH METHODS

Phase 1

In order to identify safety attributes and quantify their risk, the research team conducted content analysis on the accident reports. A rigorous content analysis protocol established by Neuendorf (2002) and Krippendorff (2004) was followed. Content analysis is a scientific method that provides valid inferences from a textual data, is empirically grounded, and helps researchers to quantify the frequency and distribution of content in text (Krippendorf 2004). Content analysis is appropriate for this research because hazardous attributes are latent in the accident report and identifying them requires recognizing patterns in written injury reports, which allows for the identification factors that are not reported in statistical data. This, in turn, helps to better understand the complete context of the environment in which injuries have occurred.

Content analysis commonly has four steps: (1) stating the research question, (2) sampling, (3) coding, and (4) reliability (Neuendorf 2002; Krippendorff 2004). For sampling, accident reports provided by the National Institute for Occupational Safety and Health (NIOSH) Fatality Assessment and Control Evaluation (FACE) program have been used for the study. The FACE program aims to prevent occupational fatalities by identifying and studying fatal occupational injuries (NIOSH). FACE reports have been chosen for this study because they provide descriptive information about the accident including facts and data on what was happening just before, at the time of, and right after the fatal injury. Therefore, it is easier to identify proximal causes of the fatalities and propose preventive strategies. In total, 105 reports related to falls have been used for this study.

As far as coding is concerned, accident codes presented in previous literature (e.g. Lipscomb et al. 2004; Beavers et al. 2009) have been reviewed. Each accident record has been coded in data sheet including but not limited to the following dimensions: safety
attribute; accident category; demographic information of the employer; victims’ experience; and activity involved. Observations were also recorded in a matrix and the frequencies were calculated for each attribute.

In order to organize the list of attributes, the authors classified them into the two main groups: primary and secondary. **Primary** safety risk attributes mostly are mostly those physical conditions that contribute to occurrence of accident and can be identified in design and planning phase (i.e. prior to breaking ground). Primary attributes are created by decisions in early stages of the project and usually do not change during the construction phase. For example, designing skylights for the building may expose workers to exposed edges or holes that will exist during construction. If a designer does not eliminate primary attributes in design phase (e.g. through prefabricating roofs), s/he should provide some kind of mitigation strategies during construction (e.g. guardrails). **Secondary attributes** are those physical, environmental, and administrative conditions or workers’ behavior that leads to falls in jobsite. Secondary attributes may change depending on construction strategies and controls. For example, trips/slips or lack of fall protection is not something that can be identified, managed, and controlled during design.

The last part of content analysis is measuring the reliability of the results. Carmines and Zeller (1979) defined content analysis reliability as the extent of achieving the same results in repeated trials by following a certain measuring procedures. Because the goal of content analysis is to identify and record reliable objective or inter-subjective characteristics of messages, careful attention must be paid to reliability. When human coding is used in content analysis, inter-coder reliability should be assessed.

Even if the principal investigator codes all of the materials, reliability should be tested by using a second coder (Evans 1996). Inter-coder reliability can be assessed by asking another person to code the same materials. Using multiple coders ensures that the results are not one individual’s subjective judgment (Tinsley and Weiss 1975). Achieving an acceptable level of reliability of coding schemes indicates that more than one individual can use the coding scheme and reach to the similar results. Although, the number of studies that confirm the importance of reliability is increasing, evaluating and reporting the reliability of coded data has not received adequate attention in traditional research (Perreault and Leigh 1989; Kolbe and Burnett 1991).

One of the common methods of measuring inter-coder reliability is simple percent agreement (Neuendorf 2002), which has been used in this study. Percent agreement simply represents number of agreement over total number of measures from the below formula:

\[ PA_0 = \frac{A}{n} \]

Equation 1

Where \( PA_0 \) represents percent agreement, \( A \) is the number of agreements between two coders, and \( n \) is the total number of units that the two coders have coded. This test ranges from 0 (no agreement) to 1 (perfect agreement).
One of the key decisions in reliability assessment is to determine the proportion of the total sample that should be used for a reliability test. Wimmer and Dominick (1994) provided specific numbers such as 10 to 20% of the total sample. In this study, the authors asked another expert to recode 15% (16 out of 105) accident reports.

**Phase 2**

As was previously mentioned, accidents occur as a result of interaction among multiple factors. The second objective of the research was to identify the areas of possible intervention to prevent accidents by considering the relation among different attributes identified in Phase 1. In order to achieve this objective, a cluster analysis has been conducted on the safety risk attributes and their interactions were modeled using Social Network Analysis (SNA). Cluster analysis helps an individual to identify the effective ways of breaking chain of events that cause injuries when injuries are caused by multiple factors.

SNA has been chosen for two main reasons. First, it enables one to mathematically express relationship among attributes and position of an attribute in a network. Using well established mathematical indicators of the graphic theory provides the ability to analyze the relationships quantitatively and at the same time increases validity of the results (Chinowsky et al. 2008). Second, visualization techniques allow a researcher to understand patterns of interaction among different factors (Chinowsky et al. 2010). Social networks were developed in this study by substituting nodes and arcs of sociograms with identified attributes and interactions.

One of the fundamental metrics in social network analysis is centrality, which was originally introduced by Bavelas (1950) and refined by Leavitt (1951). Centrality represents potential importance, influence, or prominence of a node in a network (Freeman 1979; Borgatti et al. 2002). Measures of centrality have been developed to identify key individuals in a social network (Zemljic and Hlebec 2005). Freeman (1978) identified three main kinds of centrality measures: degree of centrality, betweenness, and closeness. From variety of measurements that can be made, the research team focused on network density and two centrality measures: degree of centrality and betweenness.

**Network density** measures the volume and intensity of the interactions among network actors. This measure represents the ratio between the actual number of links and the maximum number of possible links. Although this measure indicates the number of links in the network, it does not tell someone anything about arrangement of the links and that which attribute has the highest number of interactions. It is possible that some arcs are concentrated in the limited number of nodes. Therefore, other measures should be utilized to assess the importance of attributes and distribution of the relationships in the network. These measures are the degree of centrality and betweenness.

**Degree of centrality** is one of the key measures that indicate how interactions are distributed in the network. If the degree of centrality is high in a network, a limited number of attributes have the largest number of relationship with other attributes. In fact, the degree of centrality measures the importance of an attribute among other attributes.
Betweenness is a measure of the number of attributes that has been connected via a specific attributes. This variable indicates involvement of an attribute in occurrence of accident. In fact, betweenness tells us which attributes make a bridge between other attributes to cause accidents. In order to analyze the data and calculate the quantitative measures, UCINET5 software (Borgatti et al. 2002) has been utilized by the research team.

5. RESULTS AND ANALYSIS

In total, 73 attributes were identified from FACE reports. Of these attributes, 21 were primary, 51 were secondary, and one has been classified as other. The frequency with which these attributes appeared in FACE reports was also tracked. Because all of the accidents in this analysis have the same severity (death), the risk can be assumed as equal to the frequency. The primary and secondary attributes identified and their relative safety risk are shown in Table 1. One should note that due to the lack of space, not all attributes are shown. The presented attributes can be broken down in to several sub attributes. For example, the attribute ‘ladder’ can be broken to work that requires ascending or descending ladders (primary), unsecured ladders (secondary), and using ladder inappropriately (secondary).

Table 1. Frequency/Risk distribution of safety attributes

<table>
<thead>
<tr>
<th>Safety attributes</th>
<th>Safety risks (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All (73)</td>
</tr>
<tr>
<td>Working at elevation</td>
<td></td>
</tr>
<tr>
<td>Ladder</td>
<td>2.07</td>
</tr>
<tr>
<td>Unprotected edge</td>
<td>11.40</td>
</tr>
<tr>
<td>Scaffold</td>
<td>6.22</td>
</tr>
<tr>
<td>Structure frames</td>
<td>6.99</td>
</tr>
<tr>
<td>Lifted workers</td>
<td>5.44</td>
</tr>
<tr>
<td>Aerial platform</td>
<td>1.30</td>
</tr>
<tr>
<td>Confined space</td>
<td>2.85</td>
</tr>
<tr>
<td>Job site situation</td>
<td>6.74</td>
</tr>
<tr>
<td>Carrying, handling, and lifting Materials</td>
<td>4.92</td>
</tr>
<tr>
<td>Equipment</td>
<td>1.55</td>
</tr>
<tr>
<td>Environmental issues</td>
<td>0.78</td>
</tr>
<tr>
<td>Managerial issues</td>
<td>11.44</td>
</tr>
<tr>
<td>Workers behavior</td>
<td>10.62</td>
</tr>
<tr>
<td>Insufficient injury prevention practices</td>
<td>27.46</td>
</tr>
<tr>
<td>Other</td>
<td>0.26</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

The risk values provided in Table 1 are the summation of the sub-attributes’ risk value. As one can see in Table 1, insufficient injury prevention practices, unprotected edges, managerial issues, and workers behavior have the highest risk values. Safety risk values for sub-attributes were also calculated. Among primary attributes, working in proximity of unprotected openings (5.96%), working on structure frames (include tower and tanks) (5.7%), and working near unprotected edge (5.18%) have the highest safety risk values.
One of the problems regarding the uncovered openings is that their risk perception is not high among workers and managers (Lipscomb et al. 2003). Among secondary attributes lack of fall protection (19.17%) and workers being uncoordinated or clumsy (4.66%) have the highest risk value, which is consistent with the previous findings (Lipscomb et al. 2003).

One may claim that the best way to reduce hazards is to design and implement specific safety practices that mitigate the effect of high risk attributes. However, focusing only on individual primary hazard attributes does not consider the interactions among attributes. As previously mentioned, these interactions can be significant (Hallowell et al. in press). In order to obtain a more comprehensive picture of interactions among attributes, SNA was conducted for all primary and secondary attributes using UCINET 5. The results are shown in Tables 2 and 3.

Table 2. Density and centrality measures for whole network of interactions among safety attributes

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Density</th>
<th>Centrality (degree)</th>
<th>Betweenness</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>4.78</td>
<td>36.06</td>
<td>12.72</td>
</tr>
<tr>
<td>Primary</td>
<td>0.71</td>
<td>10.91</td>
<td>28.89</td>
</tr>
<tr>
<td>Secondary</td>
<td>2.76</td>
<td>22.16</td>
<td>19.17</td>
</tr>
</tbody>
</table>

Table 3. Centrality measure for interactions among safety attributes

<table>
<thead>
<tr>
<th>Safety attributes</th>
<th>Centrality degree</th>
<th>Betweenness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Primary</td>
</tr>
<tr>
<td>Working at elevation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ladder</td>
<td>2.07</td>
<td>2.73</td>
</tr>
<tr>
<td>Unprotected edge</td>
<td>18.80</td>
<td>15.46</td>
</tr>
<tr>
<td>Scaffold</td>
<td>11.09</td>
<td>5.46</td>
</tr>
<tr>
<td>Structure frames</td>
<td>14.29</td>
<td>6.36</td>
</tr>
<tr>
<td>Lifted workers</td>
<td>8.46</td>
<td>2.73</td>
</tr>
<tr>
<td>Aerial platform</td>
<td>1.69</td>
<td>0.91</td>
</tr>
<tr>
<td>Confined space</td>
<td>6.20</td>
<td>9.09</td>
</tr>
<tr>
<td>Job site situation</td>
<td>14.66</td>
<td>16.36</td>
</tr>
<tr>
<td>Carrying, handling, and lifting Materials</td>
<td>12.22</td>
<td>8.18</td>
</tr>
<tr>
<td>Equipment</td>
<td>3.76</td>
<td>0.91</td>
</tr>
<tr>
<td>Environmental issues</td>
<td>2.07</td>
<td>2.73</td>
</tr>
<tr>
<td>Managerial issues</td>
<td>24.44</td>
<td>-</td>
</tr>
<tr>
<td>Workers behavior</td>
<td>21.81</td>
<td>-</td>
</tr>
<tr>
<td>Insufficient injury prevention practices</td>
<td>46.24</td>
<td>-</td>
</tr>
</tbody>
</table>

As is stated before, the centrality and betweenness values indicate the amount of participation of an attribute in occurrence of accidents via interaction with other
attributes. For primary attributes, unprotected edges and jobsite situation are the two attributes that have the highest centrality and betweenness values. This means that these attributes play a more important role in accident occurrence because they interact in a strong, negative way with other hazardous attributes. One very interesting finding is that though jobsite situation is not a high risk attribute by itself, its high centrality and betweenness values indicate a very strong interaction with other attributes.

In the graphical representation, each attribute was represented by a node and each line in the network indicates interactions among attributes that lead to an accident that was identified and coded using content analysis. The frequencies of connections that have been shown to cause injuries are represented by the strength of each connection. The graphical representation is of great importance, because as Chinowsky et. al. (2010) noticed that some targeted networks may present similar numerical evaluations, but the actual graphical representation reveals variances, trends, and patterns not otherwise visible in the analysis.

The sociograms for primary and secondary attributes are illustrated in Figures 1 and 2, respectively. The sociogram of all attributes has not illustrated here, because it has 73 nodes and is bushy. As shown, unprotected edges and jobsite situation has the strongest link with other attributes for primary attributes. For the secondary attributes, insufficient injury prevention practices, managerial issues, and workers behavior have the strongest links. By removing these nodes one can break the link among the attributes and enhance safety in the jobsite.

![Figure 1. Sociogram of primary attributes](image-url)
In order to measure and illustrate the influence of removing safety attributes (i.e., ‘links’ in the chain of events that cause injuries), unprotected edge and jobsite situation were removed from the primary attributes and insufficient injury prevention practices, managerial issues, and worker behavior were removed for secondary attributes. After these changes, the densities of the networks have been decreased to 0.42 and 0.22 for primary and secondary attributes, respectively. Lower densities in safety interaction networks indicate the fewer number of interactions (links) and as a result, lower safety risk in the jobsite. The new sociograms are illustrated in Figures 3 and 4. As one can see, the effect of interactions (links) decreases.
One should note that insufficient injury prevention practices, managerial issues, and worker behavior are secondary attributes and a designer does not have much control over them. Therefore, the designer should focus more on primary attributes such as unprotected edges, jobsite situation, configurations that require carrying, handling and lifting materials, and confined spaces and simply communicate to the constructor how they might remove the secondary attributes that exist within the final design.

6. VALIDATION

Unfortunately, there is no published ‘acceptable’ level of inter-coder reliability for content analysis (Krippendorff 2004; Perrault and Leigh 1989; Popping 1988; and Riffe, Lacy and Fico 1998). Krippendorff (2004) claimed that if meticulous attention has been paid to calculations, 67% agreement among coders can be considered reliable. However, other researchers reported that agreement should exceed 70% to be considered reliable (Ellis 1994; Frey, Botan, and Kreps 2000; Popping 1988). After obtaining the recoded data from the second coder, simple agreement has been calculated. The percent agreement between the two coders was 77.64%, which the writers consider to be an acceptable level of inter-coder reliability, according to the previous literature.

7. CONCLUSIONS

Construction accidents are costly (Everitt and Frank 1996) and falls from height is one of the prominent causes of fatalities in construction (Hinze et al. 2005). A risk attribute analysis technique was proposed to identify and model safety risk for potentially dynamic
work environments. In addition, SNA was utilized to model clusters of interactions among attributes to find the most impactful intervention. The proposed model has several advantageous: (1) fall hazard can be identified and risk can be quantified in early phases of the project; (2) there is a unique focus on relationships among attributes; (3) the method is capable of illustrating the relationships among attributes in a graphical form and; (4) a bridge has been established between safety studies and social science. Finally, the flexibility of the presented approach makes it an applicable platform to be used for integrating safety risk data in to sensing technology and building information modeling.

8. REFERENCES


