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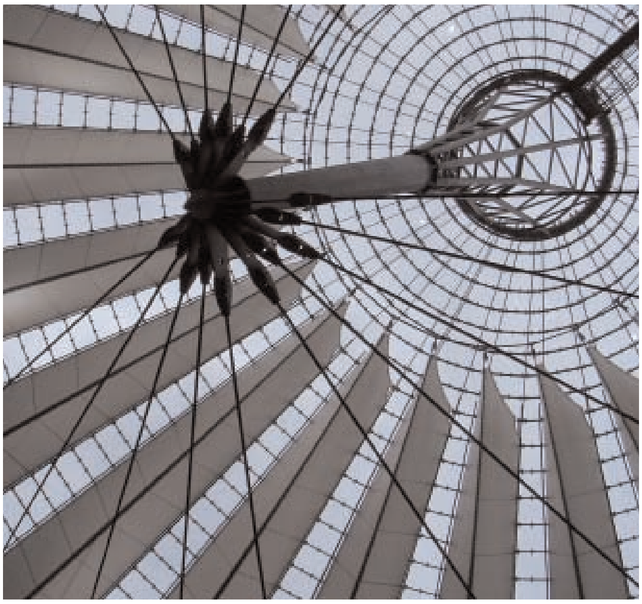

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A Formal Model for Construction Safety Risk Management

Matthew Hallowell[1] and John Gambatese[2]

ABSTRACT

Despite recent efforts to improve site safety, construction still accounts for a disproportionate number of occupational-related fatalities. Construction safety efforts often operate under the fundamental assumption that simply applying more safety program elements will produce better results. That is, program elements are applied in an informal fashion under the premise that applying a higher number will improve site safety. While some construction firms are capable of implementing a large proportion of applicable safety program elements, a vast majority of firms must operate under a limited budget and are forced to select the small subset of elements. Currently, there is no mechanism by which construction site safety professionals may formally select safety programs for a particular process. This paper presents the theory behind a formal method for strategically matching safety program elements to construction processes. This decision scheme assumes that every construction activity is associated with specific safety risks and that each safety program element is capable of mitigating a portion of such risks. Once the cumulative risk for a construction process has been assessed, safety program elements may be ranked and selected based on their ability to mitigate the risk.

Keywords: Safety, Construction, Organizational issues, Risk management

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INTRODUCTION

The construction industry accounts for a disproportionate injury and fatality rate. The construction industry, the largest single-service industry in the United States, consistently employs approximately five percent of the American workforce (Bureau of Labor Statistics, 2007). However, construction accounts for approximately twelve percent of disabling injuries and nearly twenty-five percent of work-related fatalities (National Safety Council, 2006). Despite recent efforts to improve site safety, construction still remains one of the most dangerous industries in the United States. Recent research, however, suggests a negative correlation between the number of effectively implemented safety program elements and safety performance (Rajendran, 2007). This research provides the industry with some confirmation that safety programs are, indeed, effective. Though one might expect injury rates to decrease industry-wide as a result of increased safety efforts, the proportion of fatalities and disabling injuries has steadily increased in the past fifteen years (National Safety Council, 2006). This disparity can perhaps be attributed to the fundamental assumption of construction safety research and practice.

Safety research commonly operates under the fundamental assumption that simply applying more safety programs will produce better results. Preliminary observations indicate that the practical application of safety programs mirrors research. That is, most construction safety professionals explicitly focus on the ‘birdshot approach’, where safety programs are applied in an informal fashion under the premise that applying more safety programs will improve site safety. While some construction firms have the resources to fund a safety department capable of implementing most applicable safety programs, a vast majority of firms must operate under a limited budget and are forced to select the small subset of programs believed to be most effective. Currently, there is no mechanism by which construction site safety professionals may formally choose safety programs for a particular site.

This paper aims to achieve two primary goals. The first goal is to identify the specific methodologies for selecting a subset of safety program elements using survey data collected from a group of certified experts in the field of construction safety and risk management. The second goal is to explore a suggested method for selecting safety program elements that combines techniques and theories rooted in the fields of structural engineering and risk management and apply them to construction safety planning.

LITERATURE

The vast majority of construction safety literature focuses on identifying and describing the various methods of improving site safety (i.e. safety program elements). Strategies such as job hazard analyses, record keeping and substance abuse programs are well-defined. Literature also provides excellent justification and guidance for implementation of some fifty safety program elements. Some publications, such as Hinze (1997) and Hill (2004), go as far as to identify the essential elements of effective safety programs. Another publication, Rajendran (2006), evaluates the relative ability of safety program elements to improve site safety. This research assigns a point value to approximately fifty elements in a safety rating system modeled after LEED™. None of the publications reviewed identify specific methods for selecting a subset of safety program elements.

Each of the publications discussed above operates under the same fundamental assumption: a firm should implement as many safety program elements as their budget permits. This literature also implies that safety program elements should be applied to a construction site or firm in general and does not identify their relative ability to mitigate safety risks for specific processes. Most troubling, however, is the fact that there is no guidance for constructors with limited resources that can only implement a small subset of the fifty elements. This is true despite the fact that small firms represent the vast majority of the industry.

The very small body of safety risk literature focuses primarily on risk quantification methods. For example, Barandan and Usmen (2006) discuss the comparative injury and fatality risks in the construction of buildings using data provided by the Bureau of Labor Statistics (BLS). Likewise, Lee and Halpin (2003) created a predictive tool for estimating accident risk in construction using fuzzy inputs from the user. Unlike the research of Barandan and Usmen, this paper introduces a method of assessing accident potential rather than retrospective data provided by the BLS. Both of these studies evaluate techniques for identifying and quantifying safety risks in construction. However, neither study provides guidance for mitigating safety risk.

One study combines construction safety risk identification with mitigation techniques. Jannadi and Almishari (2003) introduce *The Risk Assessor*, a knowledge-management program, which quantifies risk using the common risk formula below:

Activity Risk Score **=** (Severity) **x** (Exposure) **x** (Probability)

Using similar methods as Lee and Halpin (2003) and Baradan and Usmen (2006), this software may be used by construction professionals to identify activities of particularly high risk. Unfortunately, the software does not identify specific methods for mitigating the safety risk. Instead, the program relies heavily on the expertise of the user and assumes that viable methods of risk mitigation have been previously identified. Once a corrective measure has been selected and input into the program, *The Risk Assessor* serves as a platform that may be used to financially justify any corrective measure.

This paper aims to build upon existing literature by introducing a formal method for strategically matching safety program elements to construction processes. This decision scheme assumes that every construction activity is associated with specific safety risks and that each safety program element is capable of mitigating a portion of such risks. Before introducing this model, the current methodology for selecting safety program elements will be explored. In order to understand the implications of the proposed model, one must fully understand the current safety management practices that dominate the industry.

CURRENT METHODOLOGIES

Research Method

As part of an ongoing Delphi study, a panel of 29 construction safety experts was created and asked to identify the prevailing methods implemented by general contractors for selecting safety program elements. Potential experts were identified and selected from the ASCE Site Safety Committee and the ASSE Construction Safety Specialty Committee and from contacts provided in peer-reviewed publications. A total of 45 individuals were asked to participate in the study, 32 individuals agreed to participate and 29 were qualified as experts under the objective criteria described below.

In order to be qualified as an expert, the panelists were required to meet at least four of the eight requirements listed in Table 1. Criteria for expert qualification was obtained from guidelines from Delphi studies such as Veltri (2006), Rogers and Lopez (2002) and Rajendran (2007). In addition to these requirements, Table 1 also indicates the percentage of qualified expert panelists that met each requirement in this study. After assigning one point for meeting or exceeding each of the 8 criteria, the median score was a 6 of 8. In other words, the median expert met 6 of 8 requirements. Only the responses from the qualified experts were used in this study.

The authors believe that input from experts was desirable for this study because individuals that meet the requirements in Table 1 are likely to have a holistic understanding of the construction industry. A holistic understanding of the construction industry was necessary because one objective of the research was to collect data that would represent the behavior and experience of the entire industry. Collecting subjective data from certified experts was also the chosen methodology due to the lack of objective data.

Table 1: Expert Qualification

Requirement	Percentage
1. Primary or secondary author of a peer-reviewed journal article on the topic of construction safety or health	62%
2. Invited to present at a conference with a focus on construction safety or health	86%
3. Member or chair of a construction safety and health-related committee	93%
4. At least 5 years of professional experience in the construction industry	97%
5. Faculty member at an accredited institution of higher learning	41%
6. Author or editor of a book or book chapter	45%
7. Advanced degree from an institution of higher learning (minimum of a BS)	97%
8. Designation as a Professional Engineer (PE), Certified Safety Professional (CSP), Associated Risk Manager (ARM) or a Licensed Architect (AIA)	79%

Findings: Methods of Selecting Safety Program Elements

Experts were asked to use their experience to select the strategy that most contractors employ when choosing safety program elements for a particular construction project. As one can clearly see from Table 2 there is very little consensus, even among the experts, regarding the method of selecting safety program elements. The highest degree of consensus was that small and medium-sized contractors select elements by word of mouth and that elements are chosen based on intuition and judgment for all contractor sizes. One should note that the experts were not told what defined small, medium and large contractors. In addition to the percentages indicated in Table 2, several additional methods employed by contractors of all sizes were mentioned, such as guidance and/or requirements from insurance companies (11% of the experts), guidance from OSHA, (33%) and Owner requirements (22%).

The findings from this survey confirm the hypothesis that elements are chosen in an informal fashion and that there is no unified method currently implemented in the industry. In fact, no experts mentioned a formal method for selecting safety program elements based upon their relative ability to mitigate risks on construction sites. These findings support the premise that a formal method for selecting elements based on their relative ability to mitigate risk could be useful in the construction industry.

Table 2: Methods of selecting safety program elements (percentage of experts)

	Contractor Size		
Method	**Small**	**Medium**	**Large**
Safety program elements are chosen at random	50 %	4.5%	0%
Elements are chosen based on intuition and judgment	59 %	63.6 %	59 %
Elements are chosen based on word of mouth	63.6 %	63.6 %	22.7 %
Elements are chosen based on literature	13.6 %	50 %	77.2 %
Contractors implement as many safety program elements as the budget permits	31.8 %	50 %	45.5 %

The remaining sections of this paper will introduce and describe a formal method of construction safety management. The creation of the model involves merging concepts from structural engineering and risk management and applying them to the field of safety management. First, the basic theoretical concept of equilibrium from the field of structural engineering will be applied to safety and health. Based upon the concept of equilibrium, a model that incorporates risk management techniques will be formulated. Finally the implementation and implications of the model will be discussed.

SAFETY RISK MANAGEMENT MODEL

Equilibrium

The concept of equilibrium, based upon Newton's third law, is widely known in the fields of physics and engineering. Simply put, Newton's third law states that for every action there must be an equal and opposite reaction. In structural engineering this concept is employed when designing systems to support various loading schemes. In order to be structurally effective a system must be designed in such a way that the capacity of the system is greater or equal to the maximum anticipated load. In other words, the loading capacity must meet or exceed the loading demand. This relationship is illustrated in the following design relationship for flexure in a structural member:

$$M_u \leq \Phi M_n \quad \text{where,} \qquad \text{(Eq. 1)}$$

M_u: Ultimate Moment (i.e., maximum design demand),
M_n: Design Moment (i.e., nominal moment or capacity),
Φ: Factor of Safety

When this same concept is applied to construction safety one may recognize that the safety risk demand is equal to the sum of the safety risk on a construction site. Assuming that every safety program element offers some form of safety risk mitigation, the sum of that mitigation ability is equal to the capacity of the safety system. In theory, to reach equilibrium and make the safety system stable (i.e. accident-free), the capacity of the safety program must meet or exceed the safety demand. This relationship is expressed in the following expression (Equation 2), modeled after Equation 1.

$$S_u \leq \Phi S_n \quad \text{where,} \qquad \text{(Eq. 2)}$$

S_u: Safety Risk Demand (i.e. the cumulative safety risk on the construction site)
S_n: Safety Capacity (i.e. the cumulative mitigation ability of the safety program)
Φ: Factor of Safety

One will note that a factor of safety is included in both equations. As with any engineered system, a factor of safety should be employed to compensate for potential errors in the quantification of demand values (e.g. loading or cumulative safety risk) or capacity (e.g. strength of the system or ability of the safety program to mitigate risk).

Quantifying Demand and Capacity

In order to apply the concepts presented in the safety equilibrium equation, one must identify and define both the safety risk demand and the capacity of the safety program. Several publications provide guidance for the identification and quantification of safety risk such as Jannandi and Almishari (2003), Lee and Halpin (2003) and Baradan and Usmen (2006). Defining the capacity of the safety program is a bit more abstract. One method for quantifying both capacity and demand will be outlined below.

Before continuing with the paper it is necessary to define the concept of safety risk as it applies to this paper. Here, risk is defined as a potential event that results in an outcome that is different from planned. For construction safety, risks are defined as potential accidents. There are two main components of risk: probability and severity. Probability defines the chance or rate of occurrence of an incident. For safety risk, probability may be defined in terms of worker-hours per incident. Severity, on the other hand, defines the magnitude of the outcome. Severity may be defined in monetary terms or in terms of the degree of injury (e.g. fatality, lost work-time, medical-case, etc.). The product of these two components is the risk value. This relationship is expressed in the following equation, modeled after Yi and Langford (2006):

$$\text{Risk } (R_i) = \text{Probability } (p) \times \text{Severity } (s) \qquad \text{(Eq. 3)}$$

In terms of safety, the probability of an accident is typically expressed in the form of an incident rate such as the number of worker-hours per incident. Severity, on the other hand, is more difficult to quantify. The authors offer the following severity scale:

Severity Scale: Average loss associated with an incident (industry and hazard average)									
Negligible	**Discomfort → Persistent Pain**				**Medical case**		**Lost work time**		**Fatality**
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**

Demand

Quantifying the risk demand for a construction process is not a simple task. However, literature provides significant guidance. The method of quantifying the safety risk demand involves both the identification and analysis of the safety risk. Figure 1 defines one method of identification and analysis. While this figure is purely theoretical and does not attempt to define actual quantities of activities or risks, it provides the reader with a structured method that may be applied to any construction process.

Figure 1 is intended to convey 5 steps required to quantify the collective safety demand for a specific construction process. These steps are as follows:

1. Identify common safety risks

First, one must define common construction safety risks, denoted R_1 through R_n in Figure 1. The authors suggest the Bureau of Labor Statistics and Occupational Safety and Health Administration's Occupational Injury and Illness Classification System (OIICS) as a starting point (BLS 2007). This classification system lists and defines common safety risks.

2. Identify activities required for a construction process

The second step involves defining the typical activities associated with a particular process. For example, constructing formwork may include activities such as cutting raw material, transporting material, erecting panels, etc. In Figure 1 activities are denoted A through Z. One should note that an individual close to the work, such as a foreman, is typically best qualified for identifying the activities required for any given process.

3. Identify and quantify the risks associated with each activity

For each activity identified in step 2 the common safety risks that may occur when performing each activity must be identified and quantified. For the theoretical example provided in Figure 1, activity A is associated with risks 1, 2 and 5. In order to calculate risk using Equation 3, the user must then assign a probability and severity value for each risk associated with each activity once the connections have been made.

4. Sum the quantified risks for each activity

The risk values for each activity (e.g. $\sum A$) may be calculated by summing the risk values associated with the activity. In Figure 1 the total risk value for activity A would be calculated by summing the risk values for risks 1, 2 and 5.

5. Calculate the total risk demand by summing the risk values for all activities required for the process

The total risk demand, S_u, for a particular process may be calculated by summing the total risk values of all of the activities.

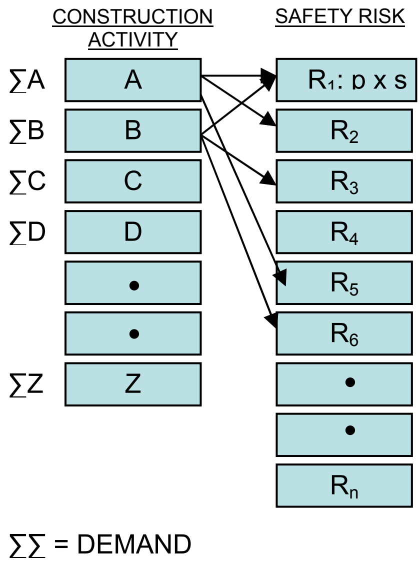

Figure 1: Safety Risk Demand

Capacity

The capacity of a safety program can be quantified in a similar method as the risk demand. Rather than calculate the risk value, one must calculate the risk mitigation when defining capacity. In a structural system, this process involves calculating the maximum load a structure may support. Similarly, in a safety system this process involves quantifying the total risk mitigation ability of the safety program. As with risk demand quantification, there are two components to consider: reduction in probability and reduction in severity. One must be careful to use the same units of probability and severity when defining both demand and capacity.

Unlike safety risk demand, there has yet to be an attempt to quantify the mitigation ability of a safety program. However, quantifying this value is necessary to use the equilibrium equation. Figure 2 may be used as guidance when calculating the risk capacity of the safety program. The specific process required for the quantification of capacity can be summarized in the following 5 steps:

1. Identify common safety risks (e.g. OIICS)

See step 1 for the quantification of safety demand.

2. Identify viable safety program elements

A safety or risk manager should identify the safety program elements that their firm is currently capable of implementing or those that the firm is considering for implementation. Significant guidance is provided in literature, such as Hill (2006) and Hinze (1997).

3. Identify and quantify the ability of safety program elements to mitigate a portion of the common safety risks

In theory every safety program element is capable of mitigating a portion of the probability or severity of safety risks. For example, job hazard analyses may be extremely effective in reducing the probability of a particular safety risk and somewhat effective in reducing the severity of the risk. The mitigation ability of each safety element should be defined for each risk. The risk mitigation may be calculated using a modification of equation 3 where the risk mitigation is equal to the product of the probability reduction and severity reduction.

4. Sum the mitigation ability for each safety program element

The risk mitigation values for each safety program element (e.g. $\sum \alpha$) may be calculated by summing the risk reduction values associated with the element. In Figure 2 the total risk mitigation value for element α would be calculated by summing the risk mitigation values for risks 1 and 6.

5. Calculate the total capacity of the safety system by summing the mitigation ability of the safety program elements planned for implementation

The total risk capacity, S_n, for a particular safety program may be calculated by summing the total risk mitigation values of all of the safety program elements.

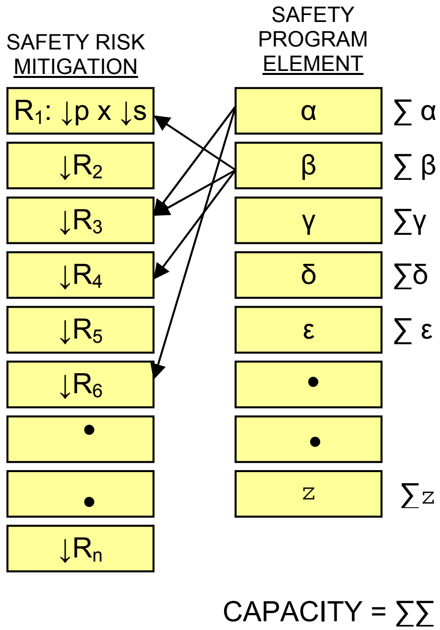

Figure 2: Safety Risk Mitigation

Application of the equilibrium concept

Once the safety risk demand has been quantified, the equilibrium equation (Equation 2) may be applied. By using the concept of equilibrium and the quantified risk mitigation capacity of each safety program element, one may define the relative effectiveness of safety program elements and identify when equilibrium between safety risk demand and the capacity of the safety program has been achieved. The concept of equilibrium is illustrated in Figure 3.

The practical application of this model requires the knowledge of an expert or experts in the field of construction safety. The individual or group that identifies and quantifies the risks that comprise the safety demand and capacity must have extraordinary knowledge of the work process, safety risk implications of the activities and the effectiveness of individual safety program elements. For this reason it is suggested that multiple individuals should be involved when implementing the model. For example, a foreman may be the most knowledgeable employee for defining the activities required for a process, the safety manager may be the most effective person for identifying the risks associated with the construction activities and a risk manager may be the most effective person for quantifying the risk demand and mitigation values. Collectively such a safety risk task force may be extremely effective.

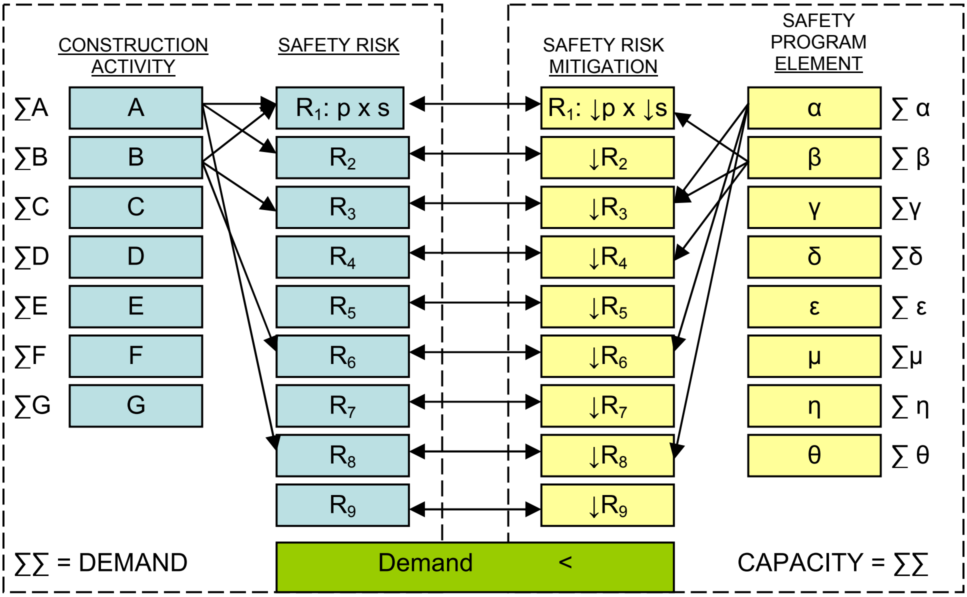

Figure 3: Safety Equilibrium Model

IMPLICATIONS AND LIMITATIONS

As previously discussed, the current methods for selecting safety program elements is informal and variable. Data collected from construction safety and risk management experts indicates that a variety of selection techniques are implemented and few of these methods are based on anything but the premise that "more is better." The use of the proposed model may improve safety management in a variety of ways, such as:

- Identify the relative effectiveness of safety program elements
- Provide guidance for resource allocation to selected program elements
- Determine the necessary degree of safety management required to mitigate risk for a particular construction process
- Formally select a subset of the available 50 safety program elements based on the risks posed by a process and the ability of individual safety program elements to mitigate a portion of such risk

Despite the potential implications of the proposed model, there are many confounding factors that must be considered. For example, interaction may occur among safety program elements. That is, some program elements may be more or less effective when used in combination with other elements. Likewise, the ability of certain safety elements to mitigate a portion of the safety risk may be heavily dependent on what other elements have already been implemented. Other confounding factors may include: weather, geographic location, the ability of the construction crew to work safely, effectiveness of the safety manager, and many others. When implemented effectively this model may be used as guidance, however. Like any engineering method, the model and equation attempts to simplify and standardize a complex natural phenomenon in a manageable tool or equation that can be put to practical use.

FUTURE RESEARCH

The study from which this paper has been written attempts to create a useable, data-driven model. Using the same methods outlined in this paper, the Delphi process, with a panel of approximately 25 certified experts, will be implemented to identify and quantify both the safety risk demand and capacity for the process of constructing concrete formwork. Expert panelists have been asked to participate in the study by defining and quantifying the OIICS risks for each predetermined activity associated with forming concrete or by defining and quantifying the ability of safety program elements to mitigate a portion of the same OIICS risks. While the risk demand will be unique to the process of forming concrete and will serve as an example for the use of the model presented in this paper, the capacity will be applicable to any process.

Additional research would be necessary for creating a robust model for general industry. Investigations into the interactions of safety program elements would be of immediate use and would have direct implications on the accuracy and precision of the model. Also, techniques for quantifying other confounding variables such as relative crew ability, relative safety management ability, and relative ability within specific geographical regions, would be necessary as current research only attempts to identify values for the general construction industry.

CONCLUSIONS

This paper has been divided into two main parts. The first part described and assessment of investigated the current method of selecting safety program elements using the input from a panel of 29 certified experts in the field of construction safety. This investigation revealed that there are a variety of methods currently implemented, none of which are formal or structured. Additionally, it was found that the methods were highly variable and even certified experts in the industry expressed difficulty in identifying a common method.

The second portion of this paper introduced and described a formal method for selecting safety program elements. This method combines theory from the field of structural engineering with risk management techniques and applies them to construction safety management. This model involves the quantification of the collective risk associated with a process (Demand) and the ability of the safety program elements to mitigate a portion of the individual risks (Capacity). It is believed that practical use of this model may help to identify the relative effectiveness of safety program elements for a given process, provide guidance for resource allocation to safety programs, and identify the level of safety intervention required for a given process.

Ongoing research into the development, refinement and validation of this model is currently under way. This research employs the Delphi process as a means to quantify risk demand and capacity values for the general construction industry. Additional research into the interaction of safety program elements and the quantification of adjustment factors to account for variation in contractor ability, geographic location and safety management ability would be useful in further refining the model.

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