Construction Safety Risk Mitigation

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Abstract: Construction safety and health management has improved significantly following the Occupational Safety and Health Act of 1970. In response to this legislation, contractors began implementing safety programs to reduce occupational safety and health hazards on construction sites. Researchers recently found that the current process of selecting specific elements for a safety program is informal. This paper describes the results of a recent study designed to determine the relative effectiveness of safety program elements by quantifying their individual ability to mitigate construction safety and health risks. In order to determine the effectiveness of individual safety program elements, the following research activities were performed: (1) an appropriate safety risk classification system was created using an aggregation of relevant literature; (2) highly effective safety program elements were identified in literature; and (3) the ability of each safety program element to mitigate a portion of each of the safety risk classes was quantified using the Delphi method. The results of the research indicate that the most effective safety program elements are upper management support and commitment and strategic subcontractor selection and management and the least effective elements are recordkeeping and accident analyses and emergency response planning. It is expected that the data presented in this paper can be used to strategically select elements for a safety program, target specific safety and health risks, and influence resource allocation when funds are limited.

DOI: 10.1061/(ASCE)CO.1943-7862.0000107

CE Database subject headings: Construction management; Risk management; Safety.

Introduction

The management of occupational safety and health in construction involves unique challenges. Characteristics of the industry such as dynamic work environments, the use of heavy equipment, and seemingly unavoidable worker-hazard interactions contribute to disproportionate injury and illness rates compared to other work industries. Despite these characteristics, firms that demonstrate and communicate commitment to well-structured and well-funded safety programs can effectively reduce incident rates (Hinze 1997).

Construction safety management techniques have improved significantly following the Occupational Safety and Health Act of 1970. This legislation, which placed the responsibility for construction safety on the employer, has resulted in a dramatic increase in safety planning and management efforts in the construction industry (Hill 2004). Because construction projects are dynamic and transient in nature, safety management techniques must often be adjusted to meet the unique needs of the industry.

When designing a site-specific safety program, there are many elements to choose from. In fact, Rajendran (2006) identified over 100 distinct safety program elements. Since most firms allocate limited resources to safety management, contractors are forced to select a subset of the available elements. In a recent study, Hallowell and Gambatese (2007) found that most contractors select safety program elements in an informal fashion with little regard to relative effectiveness. Most contractors were said to rely on intuition and word of mouth when designing site-specific safety programs. Therefore, research that provides formal guidance for the selection of safety program elements is clearly warranted.

The objective of this paper is to describe a recent study designed to determine the relative effectiveness of safety program elements by quantifying their individual ability to mitigate construction safety and health risks. Using literature as guidance, highly effective safety program elements and applicable safety and health hazard risk classifications were identified. The ability of these safety program elements to reduce the frequency and/or severity of the applicable safety risks was quantified using the Delphi method. The resulting data can be used to strategically select elements for a safety program, target specific safety and health risks, and influence resource allocation when funds are limited.

Literature Review

The research study described in this paper is based largely on the concept of safety risk capacity introduced, described, and illustrated by Hallowell and Gambatese (2007). The safety risk capacity associated with a safety program element is defined as the collective safety risk mitigated by the element. Alternatively, the total risk capacity of a safety program is equal to the sum of the risk mitigated by the collective elements that comprise the program.

The concept of safety risk capacity is analogous with the structural capacity of a beam in structural engineering. In this analogy, the loading, or demand, would be represented by the total safety

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Note. This manuscript was submitted on August 12, 2008; approved on June 22, 2009; published online on June 25, 2009. Discussion period open until May 1, 2010; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 135, No. 12, December 1, 2009. ©ASCE, ISSN 0733-9364/2009/12-1316–1323/$25.00.

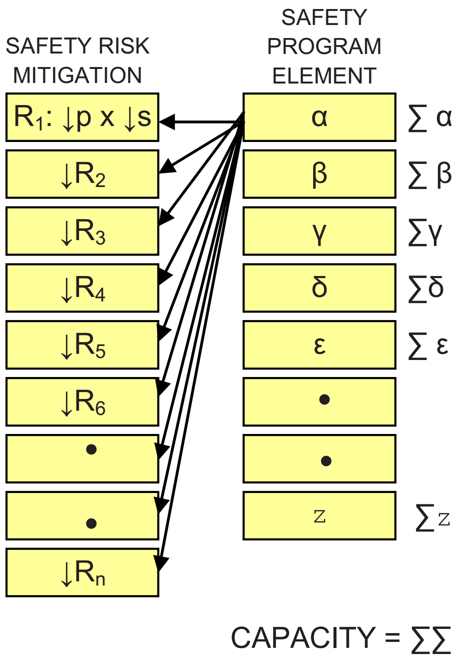

Fig. 1. Safety risk capacity

risk associated with a project. In order to prevent failure, the capacity of the system must be designed to be greater than or equal to the applied demand. For this paper, safety risk capacity will refer to the collective risk mitigated by all elements in a selected safety program. The concept of safety risk capacity was used when structuring the research process for this study.

The suggested method for quantifying the risk capacity of a site safety program is illustrated by Fig. 1 and Eq. (1), where Greek letters represent individual safety program elements. This figure illustrates the following research steps:

1. Identify common construction safety and health risks.
2. Identify commonly implemented safety program elements.
3. Quantify the ability of each safety program element to mitigate each of the risks.
4. Calculate the total risk capacity of each safety program element by summing the total risk mitigated by each element.
5. Calculate the total capacity of the safety program by summing the mitigation ability of the collective elements selected for implementation

$$\sum_{El.\alpha}^{\zeta}\left[\sum_{R1}^{Rn}(\text{Safety risk mitigation})\right] = Sn = \text{Capacity} \quad (1)$$

While Hallowell and Gambatese (2007) offer an overview and structure for the risk capacity model, a comprehensive literature search revealed no other studies that discuss the quantification of safety risk mitigation. Jannadi and Almishari (2003) and Baradan and Usmen (2006) provide methodologies for risk quantification that were used as guidance when developing the methodology for this study. Using the theory presented in these publications, the following formula was selected for implementation:

$$\begin{aligned}\text{Risk mitigation} &= \text{Reduction in frequency}(1/\text{worker-h})\\ &\quad \times \text{reduction in severity}(\text{impact})\\ &\quad \times \text{reduction in exposure}(\text{worker-h})\end{aligned} \quad (2)$$

One should note that this equation illustrates the relationships among factors contributing to the risk mitigation resulting from the implementation of a specific safety program element. Alternatively, the collective risk mitigation associated with a selected safety program is referred to in this paper as Capacity. According to Eq. (2), the risk mitigation may be achieved in one of three primary ways: (1) the frequency of incidents may be reduced; (2) the severity associated with the incidents may be reduced; and (3) the exposure to hazardous conditions that contribute to the risks may be reduced. Because reduction in exposure is largely project-dependent (i.e., requires task durations to be reduced), the study focused on the ability of safety program elements to reduce the frequency and severity of construction accidents. In order to create the structure necessary for the research study, literature was consulted to perform the first two steps in the capacity model: identification of common safety and health risks and identification of essential elements.

Three publications define construction safety accident classifications. The Bureau of Labor Statistics (BLS) organizes its yearly construction safety data reports in terms of 10 categories and the Occupational Safety and Health Administration (OSHA) defines safety risk classifications in terms of 29 primary codes in its Occupational Illness and Injury Classification System. Both OSHA and the BLS define injury and illness classifications for all industries. Hinze and Russell (1995), however, suggest a construction-specific accident classification system that highlights the highest construction-specific safety risks. Using an aggregation of these three accident classification systems, the writers selected 10 all-inclusive and mutually exclusive codes for this study. These selected safety risk classifications, with definitions consistent with the literature cited above, are as follows:

1. Struck by;
2. Struck against object;
3. Caught in or compressed;
4. Fall to lower level;
5. Fall on same level;
6. Overexertion;
7. Repetitive motion;
8. Exposure to harmful substances;
9. Transportation accidents; and
10. Other.

During a comprehensive review of literature, the writer identified eight publications that discuss the formation of an effective safety program (Coble et al. 2000; Gibb et al. 1995; Hinze 1997; Hill 2004; Jaselskis et al. 1996; Liska 1993; Occupational Safety and Health Administration 2007; Rajendran 2006). Collectively, these works identify 16 independent elements of an effective construction safety and health program. While these publications describe hundreds of safety prevention strategies, only 16 of these strategies were mentioned as essential elements. Of these 16 elements, 13 were mentioned as essential in four or more (≥50%) of the publications reviewed. These elements are listed and carefully described in Table 1.

Methodology

The Delphi method was selected as the primary research methodology for this study. The Delphi process is defined as a systematic and interactive research technique designed to obtain consensus in judgment of a panel of experts. This research technique differs from traditional surveys and interviews because respondents are certified as experts according to predefined guidelines before the

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Table 1. Essential Safety Program Elements

Safety program element	Description
Written and comprehensive safety and health plan	A safety and health plan serves as the foundation for an effective safety and health program. The plan must include documentation of project-specific safety and health objectives, goals, and methods for achieving success.
Upper management support	Participation and commitment of upper management involves the explicit consideration of worker safety and health as a primary goal of the firm. Upper management must demonstrate commitment by participating in regular safety meetings, serving on committees, and providing funding for other safety and health program elements.
Job hazard analyses and hazard communication	Job hazard analysis may be initiated by reviewing the activities associated with a construction process and identifying potential hazardous exposures that may lead to an injury. Other sources such as OSHA logs, violation reports, accident investigation reports, interviews with laborers, or simply intuition may be used to identify hazards. Hazards must be effectively communicated to workers.
Safety and health orientation and training	Orientation of all new hires may be the most important safety training. Even skilled and experienced workers should be provided with a firm-specific safety and health orientation and training. Such training and orientation informs new hires of company safety goals, policies, programs, resources, etc. This element involves the firm-specific, but not necessarily project-specific, orientation, and training of all new hires (or existing employees if a safety and health program is new to the firm).
Frequent worksite inspections	Worksite inspections may be performed internally by a contractor's safety manager, safety committee, representative of the contractor's insurance provider or by an OSHA consultant. The purpose of a safety and health inspection is to identify uncontrolled hazardous exposures to workers, violations of safety standards or OSHA regulations, or the unsafe behavior of workers. Inspections must occur on a regular basis.
Emergency response planning	Emergency response planning involves the creation of a plan in the case of a serious incident such as a fatality or an incident involving multiple serious injuries. Planning for emergencies can define the difference between an accident and a catastrophic event. Such a plan may be required by the Owner or insurance carrier.
Record keeping and accident analyses	Record keeping and accident analyses involve documenting and reporting the specifics of all accidents including information such as time, location, work-site conditions, or cause. The element also includes the analyses of accident data to reveal trends, points of weakness in the firm's safety program, or poor execution of program elements.
Project-specific training and regular safety meetings	This element involves the establishment and communication of project-specific safety goals, plans, and policies before the start of the project. Safety training may include reviewing project-specific or task-specific hazard communication, methods of safe work behavior, company policies, safety and health goals, etc. This element also involves regular safety meetings such as toolbox talks to reinforce and refresh safety and health training.
Safety and health committees	A committee made up of supervisors, laborers, representatives of key subcontractors, owner representatives, OSHA consultants, etc. may be formed with the sole purpose of addressing safety and health on the worksite. Such a committee must hold regular (e.g., weekly or biweekly) meetings to address safety and health by performing inspections, discussing job hazard analyses, or directing safety meetings and training.
Substance abuse programs	Substance abuse programs target the identification and prevention of substance abuse of the workforce. Testing is a crucial component of this safety program element. Methods of testing and consequences of failure may differ from one firm to another. However, repeated violations are typically grounds for dismissal of the employee. Testing may occur on a regular or random basis and always for employees involved with an incident that involves a medical case or lost work-time injury or fatality.
Safety manager on site	Simply, this safety program element involves the employment of a safety and health professional (i.e., an individual with formal construction safety and health experience and/or education). This individual's primary responsibility is to perform and direct the implementation of safety and health program elements and serve as a resource for employees.
Subcontractor selection and management	This element involves the consideration of safety and health performance during the selection of subcontractors. That is, only subcontractors with demonstrated ability to work safely should be considered during the bidding or negotiating process. Once a contract is awarded, the subcontractor must be required to comply with the minimum requirements of the general contractor's safety and health program.
Employee involvement safety and evaluation	Employee involvement and evaluation is a means of including all employees in the formulation and execution of other program elements. Involvement in safety and health activities may include activities such as performing job hazard analyses, participating in toolbox talks, or performing inspections. Evaluation of employees' safety performance involves considering safety metrics during regular employee performance evaluations. This may include the consideration of incident frequency, inspection results, and near misses.

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survey process begins and consensus is achieved through the use of controlled and anonymous feedback provided by the facilitator during multiple rounds of surveys. Literature that provides guidance for the implementation of the Delphi process is abundant (see Linstone and Turoff 2002).

A judgment-based research approach was chosen to define safety risk mitigation values because objective approaches were unrealistic. Confounding factors in the construction industry make it impossible to isolate the impacts of individual safety program elements. Delphi was selected over alternative subjective research techniques because academic rigor was of the utmost importance, a relative long timeline was acceptable, and the researchers desired to involve extremely well-qualified and geographically dispersed participants.

In order to reduce the potential impacts of judgment-based bias, five controls were implemented. These controls are as follows: (1) the question order and the order of safety risks were randomized on each panelist's questionnaire for each round using a random number generator in an effort to eliminate the potential for the primacy and contrast biases; (2) individual frequency and severity reduction values were required for each risk to eliminate the potential impact of the neglect of frequency bias; (3) reasons were included as a part of the controlled feedback to improve accuracy, prevent conformity, and to minimize the potential impacts of the Von Restorff effect, myside bias, and the collective unconscious; (4) multiple rounds of surveys with anonymous feedback after each round were conducted to achieve consensus and eliminate the effects of dominance bias and minimize the potential effects of the Von Restorff effect (i.e., the tendency for individuals to recall extreme events resulting in an inflated perception of probability); and (5) results were reported as medians to minimize the impact of potential outlying responses.

In addition to the bias-reduction strategies described above, the research team implemented the following controls to ensure standardization of reference and to aid with the analysis and interpretation of results:

- Panelists were provided with incident classification descriptions consistent with literature and safety program element descriptions shown in Table 1.
- Panelists were asked to provide frequency and severity reduction ratings *considering a scenario where no other safety program elements are implemented*.

Panelists were asked to provide ratings for the *average* frequency reduction and *average* severity reduction for the industry in general. Despite the abundance of literature describing the Delphi method, significant opportunity exists for variation and shortcuts; consequently, the method has been highly criticized (Sackman 1974; Armstrong 1978). Therefore, a description of the specific characteristics of the present study such as panelist qualifications, number of panelists chosen, number of rounds of questionnaires conducted, feedback, targeted consensus, and methods of measuring consensus of this study is warranted.

One of the elements that characterize the Delphi method is exclusive use of certified experts. Potential expert panelists were identified from current and historic membership lists of nationally recognized safety and health-related committees, such as ASCE's Site Safety Committee, writers of books and journal articles on construction safety and health, and involvement in previous Delphi studies investigating safety. In order to ensure the most qualified panel, potential participants were asked to complete an introductory survey that solicited information about their backgrounds and experience.

The expertise requirements for this study were based on the studies of Rajendran (2006) and Rogers and Lopez (2002). In these studies potential panelists were required to meet at least four of the following eight characteristics *related to the field under examination*:

1. Primary or secondary writer of at least three peer-reviewed journal articles on the topic of construction safety or health.
2. Invited to present at a conference focused on construction safety or health.
3. Member or chair of a construction safety and health-related committee in a nationally recognized organization.
4. At least 5 years of professional experience in the construction industry.
5. Faculty member at an accredited institution of higher learning with a research or teaching focus on construction safety and health, or risk management.
6. Writer or editor of a book or book chapter on the topic of construction safety and health, or risk management.
7. Advanced degree in the field of civil engineering, construction engineering, occupational safety and health, or other fields directly related to this study, from an institution of higher learning (minimum of a BS).
8. Designation as a professional engineer, certified safety professional, associated risk manager, or a licensed architect.

In total, 15 individuals qualified and 13 agreed to participate. In the resulting panel, seven different states (California, Georgia, Illinois, Michigan, Missouri, Oregon, and Washington) and almost every major geographical region of the United States was represented. The panel was well-educated; one individual possesses a Ph.D., three possess an M.S., and five possess a B.S. as their terminal degree in a related field of study. Furthermore, two individuals are employed at the associate professor rank and one is employed at the assistant professor rank in related programs at accredited academic institutions. Also, the panel has produced a total of 19 publications in peer-reviewed journals and 11 books on the topic of construction safety and health or risk management. The panel also has a wealth of professional knowledge. Collectively, these experts have over 278 years of field experience in the construction industry, five have P.E. licenses, three have C.S.P. licenses, and one is a certified risk manager.

The Delphi process was executed over the course of three rounds of questionnaires with approximately one month between rounds. Various forms of controlled and anonymous feedback were provided between rounds. After the first round, panelists were given the median responses from the previous round in subsequent surveys. If the panelists believed that the true response was two or more units on the risk scales, Tables 2 and 3, from the first round median response, they were asked to provide reasons for their outlying response. In the third round, panelists were

Table 2. Frequency Scale

Worker-hours per incident	Frequency rating
Negligible or 0	1
10–100 million	2
1–10 million	3
100,000–1 million	4
10,000–100,000	5
1,000–10, 000	6
100–1,000	7
10–100	8
1–10	9
<1	10

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Table 3. Severity Scale

Subjective severity level	Severity score	Relative impact score
Temporary discomfort	1	2
Persistent discomfort	2	4
Temporary pain	3	8
Persistent pain	4	16
Minor first aid	5	32
Major first aid	6	64
Medical case	7	128
Lost work-time	8	256
Permanent disablement	9	1024
Fatality	10	26,214

provided with the median response from the second round and the reasons for any outlying responses.

Designing simple questionnaires that solicited ratings of frequency and severity reduction proved to be challenging. To provide context and reference when quantifying frequency and severity reduction, risk scales that divide the spectrum of possible frequency and severity of incidents into easily identifiable levels were necessary. Augmented versions of the scales developed by Hallowell and Gambatese (2008) were used. These scales have been reproduced in Tables 2 and 3. One should note that frequency is represented by the number of incidents expected over time (incidents/w-h) and severity is represented by a subjective interpretation of impact per incident (S/incident). Frequency reduction, therefore, is represented by an increase in duration between incidents while severity reduction is the decrease in impact of each potential event. The product of these two elements represents the risk mitigation (−S/w-h).

For each of the essential safety program elements, the experts were asked to use their experience and judgment to rate the average reduction in frequency and/or severity of each of the provided safety risk hazard classifications. The frequency and severity scales were to be used for reference

One may note that using the scales to rate frequency and severity mitigation is quite confusing. Therefore, the writer provided the expert panel with detailed instructions for using the scales. For example, if an expert believed a particular safety program element is capable of reducing the average frequency of transportation incidents from one incident per 50 worker hours (8) to one incident per 3,000 worker hours (6), they were asked to rate the frequency mitigation as a “2” $(8-6=2)$. Likewise, if an expert believed a safety program element may reduce the severity of falls to a lower level from lost work-time (7) to persistent pain (4), they were asked to rate the severity mitigation a “3” $(7-4=3)$. Great care was taken to ensure that the experts understood the ratings that they were being asked to provide. Phone conversations or e-mail correspondence was used to explain the rating system when necessary.

Results

Participation in the study was strong and consistent. Ten of the 13 participants completed all three rounds resulting in a response rate of 77%. Considering that the panelists were asked to provide frequency and severity reduction ratings for 10 risk classifications for each of the 13 safety program elements (i.e., 260 ratings per respondent per round) in addition to any documentation of reasons for outlying responses, the writers believe that the participation rate may be judged as excellent. In total, 7,800 ratings were obtained during this study.

After the first round of questionnaires, the absolute deviation of the ratings was 1.72 units for the frequency reduction ratings and 1.80 units for the severity reduction ratings. Since the target consensus was less than one unit, Round 2 surveys, which included median results as feedback, were created and administered. As previously indicated, respondents were asked to consider their previous ratings in light of the group median and provide reasons for outlying responses.

In Round 2, experts tended to choose ratings that were closer to the median response from the first round. Despite the fact that many panelists chose to revise their ratings in the second round, the second round median ratings were identical to those obtained in the first. Consequently, the group came closer to consensus while the median ratings remained the same. The second round absolute deviation was 0.95 units for frequency reduction ratings and 0.94 for severity reduction. Despite the achievement of targeted consensus in the second round, the writers conducted a third round of Delphi surveys because of the compelling reasons provided for outlying responses and to decrease the potential impacts of identified biases.

The results of the third round of surveys represent the final results of the study. While the median values did not change from the second round, the expert panel came even closer to achieving consensus. The absolute deviation for the frequency reduction ratings was 0.83 units and 0.81 units for the severity reduction values. This level of consensus met the original objective of less than one unit absolute deviation as determined in the beginning of the study.

The raw frequency and severity ratings for this study are included in Table 4. These ratings are in the original 1–10 scales and may be interpreted using Tables 2 and 3. In order to produce actual risk mitigation ratings several conversions were required.

The original frequency reduction ratings, provided in terms of a range of increase in worker-hours per incident, were found to be easy to comprehend and estimate by the expert panel. However, the writers believed that point values with units of decrease in incidents per worker-hour were easier to use in data analysis. In order to obtain the desired units the raw ratings were converted using the following steps:

1. The midpoint of the range was determined for each rating and the median value in the range represented the point value for the given rating (e.g., an increase of 0.1 to 1 worker-hours per incident becomes an increase of 0.55 worker-hours per incident).
2. The frequency reduction values were converted from an increase in worker-hours per incident to a decrease in incidents per worker-hour by finding the inverse of the values determined in Step 1 (e.g., an increase of 0.55 worker-hours per incident becomes a decrease of 1.8 incidents per worker-hour).

Severity reduction values on the 1–10 scale were not converted. One should note, therefore, that the severity reduction used in this analysis is described in terms of the original 1–10 scale, not the interpreted geometric scale in Table 3. The writers found that it would be inappropriate to analyze the severity reduction in terms of the geometric scale because the true value of severity reduction would be largely dependent on the original severity of the risk that is reduced. For example, the severity reduction from a fatality to a medical case injury is significantly higher than the reduction from minor first aid to temporary pain despite the fact that both scenarios would receive a rating of 2 in

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Table 4. Risk Mitigation Scores ($n=10$, $r=3$)

	Struck by		Struck against		Caught in		Fall to lower		Fall to same		Overexertion		Repetitive motion		Toxic exposure		Transportation		Other	
Safety program element	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S	F	S
Upper management support	6	5	6	4	6	4	7	6	4	4	5	4	4	4	6	5	5	4	5	4
Written and comprehensive SH plan	5	3	5	3	4	3	5	4	5	3	3	2	3	2	5	3	4	3	3	2
Project-specific training	5	5	5	4	5	4	6	6	5	4	5	4	5	4	6	6	5	4	4	3
Employee involvement	6	5	5	5	6	4	6	4	6	4	5	4	5	4	6	5	5	5	4	4
Subcontractor selection and mgt	6	4	5	4	5	4	7	6	5	3	4	3	4	3	6	4	6	4	4	3
JHAs	6	4	5	4	6	4	6	5	5	4	5	4	5	4	6	4	5	4	5	4
Record keeping and accident analysis	3	3	2	2	3	3	3	3	3	2	3	2	3	2	3	3	3	2	2	2
Emergency response planning	2	4	2	3	2	3	2	4	2	2	2	3	2	1	2	3	3	3	2	2
Frequent worksite inspections	5	5	5	5	5	4	6	5	5	4	5	4	5	3	5	4	5	5	5	3
SH committees	5	4	5	3	5	3	5	4	5	3	4	3	5	3	5	4	5	3	4	3
SH orientation and training	5	3	5	3	5	3	5	4	5	3	4	3	4	3	5	4	5	3	3	3
Substance abuse programs	5	5	5	4	5	4	5	4	5	4	5	3	3	3	5	4	5	4	5	3
Safety manager on site	5	4	5	4	5	4	5	5	5	4	5	4	5	4	6	5	5	5	4	3
Total	64	54	60	48	62	47	68	60	60	44	55	43	53	40	66	54	61	49	50	39

Note: F=raw frequency reduction score (interpret using Table 2) and S=raw severity reduction score (interpret using Table 3).

the survey. This, perhaps, represents a limitation of the study but does not impact the ability to produce relative risk ratings associated with the program elements.

Using Eq. (2), risk mitigation values can be calculated by multiplying the converted frequency reduction values by the original severity reduction values on the 1–10 scale. The resulting risk reduction values, with units of −S/w-h, represent the final data. Again, one should note that, for this paper, the severity component of the −S/w-h units describes the reduction of severity on the original 1–10 scale, not the interpreted geometric scale in Table 3. The final risk mitigation ratings for each element were calculated by summing the risk mitigated in each risk classification code.

All of the risk values obtained through the Delphi process are limited in the following ways due to the specific directions given to the Delphi panelists:

- The values represent the average for all firms in the industry regardless of characteristics such as size, geographic location, or safety record.
- The risk values represent average risk levels that would occur *if no other safety programs are implemented.*
- The risk values represent the judgment of safety experts and are not empirical data.

Analysis

The data included in Table 4 is significant in its own right as it allows one to determine the expected risk reduction of any of the 10 all-inclusive, mutually exclusive risk classifications resulting from the implementation of any of the 13 safety program elements investigated. The objective of this analysis section is to use the data to identify the relative effectiveness of the elements and to identify the total risk mitigated by each program element. The resulting data analysis can be used to quantify the expected capacity of a safety program.

To determine the relative effectiveness of the safety program elements, the risk reduction values for the 10 safety classification codes were summed for each element. The resulting capacity of the safety program elements, in units of −S/w-h, can be found in Table 5. These values were calculated by (1) converting the frequency and severity reduction values presented in Table 4 to appropriate units using the scales provided in Tables 2 and 3, respectively; (2) calculating the risk mitigation value for each risk code by finding the product of the converted frequency and severity reduction values; and (3) determining the total risk mitigated by each element by finding the sum of the risk mitigated by each element. According to this analysis, the two most effective elements are upper management support (−0.0144 S/w-h) and strategic subcontractor selection and management (−0.0133 S/w-h). These two program elements are nearly an order of magnitude more effective than the next highest program element: Employee involvement in safety and health management and planning (−0.000433 S/w-h).

A careful analysis of Table 5 reveals that the safety program

Table 5. Risk Reduction Ratings Associated with Essential Safety Program Elements

Tier	Safety program element	Risk reduction (−S/w-h)
1	Upper management support	1.44×10^{-2}
1	Subcontractor selection and management	1.33×10^{-2}
2	Employee involvement	4.33×10^{-3}
2	Job hazard analyses	3.53×10^{-3}
2	Training and regular safety meetings	2.71×10^{-3}
2	Frequent worksite inspections	1.58×10^{-3}
2	Safety manager on site	1.53×10^{-3}
3	Substance abuse programs	6.37×10^{-4}
3	Safety and health committees	5.02×10^{-4}
3	Safety and health orientation	4.30×10^{-4}
3	Written safety plan	3.03×10^{-4}
4	Record keeping and accident analyses	3.71×10^{-6}
4	Emergency response planning	1.00×10^{-6}

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elements exist in four tiers of effectiveness with each tier being separated by nearly an order of magnitude. As one can see, the most effective safety program elements, upper management support and commitment and subcontractor selection and management, have risk reduction scores between −0.01 and −0.1 S/w-h. The second-tier elements, employee involvement in safety management and planning, job hazard analyses, training and regular safety meetings, frequent worksite inspections, and a site-specific safety manager, have risk reduction scores between −0.001 and −0.01 S/w-h. The third-tier elements, substance abuse programs, safety and health committees, safety and health orientation, and a written safety plan, have risk reduction scores between −0.0001 and −0.001 S/w-h. Finally, the fourth-tier elements, record keeping and accident analyses and emergency response planning, have risk reduction scores between −0.000 001 and −0.000 01 S/w-h. This information may be very valuable for construction safety managers that must strategically allocate limited resources to their safety program.

Application in Practice

The data collected for this manuscript can be used as guidance for safety and health and risk mangers when selecting the safety efforts to implement on construction sites. For example, a firm that is deciding whether to include widespread implementation of job hazard analyses (−0.003 53 S/w-h) or establishing safety committees for a project (−0.000 502 S/w-h) may use the findings from this study to make an objective decision to select job hazard analyses. These findings would also be useful to new firms that are developing a new safety program. Such firms could use the findings presented in this paper to ensure that the most effective elements (e.g., upper management support and commitment and subcontractor selection and management) are established first and funded appropriately before implementing less effective elements (e.g., unrequired recordkeeping and accident analyses).

Furthermore, the findings presented in this paper could be used by firms to approximate the cost-effectiveness of the 13 elements. Since cost information may vary significantly among firms, the writers suggest that firms use the effectiveness ratings in Table 5 and their own accounting methods to approximate the cost-effectiveness of their current efforts. Such information would be useful when making safety-related funding decisions and to justify expenditures on specific elements. This information could also be used to guide resource allocation to highly effective elements when a comprehensive safety program has been developed.

Last, the data in Table 4 could be used to address specific issues. For example, a firm may be experiencing a high rate of caught-in injuries. According to Table 4, the three most effective strategies to reduce the frequency of these injuries are upper management support, employee involvement, and job hazard analyses. Similarly, a firm that wishes to reduce the severity of injuries associated with toxic exposure should focus on involving employees in safety management and planning. A firm could use the findings in presented Table 4 to identify the appropriate accident prevention strategy for any combination of risk types.

Limitations and Recommendations

The primary objective of this study was to evaluate the relative effectiveness of essential safety program elements by measuring the amount of risk mitigated by each element. In order to achieve this objective, instructions were provided where panelists were asked to consider each element in isolation. While this limits some of the application of these results to practice, it provides baseline risk reduction ratings that can be used to inform future studies. To address this limitation, the writers suggest future research that specifically investigates the interactions among safety program elements (e.g., the influence of a safety manager on the effectiveness job hazard analyses), and the diminishing returns of the elements when implemented in a collective safety program. Such data could be used along with the risk reduction ratings presented in this paper to create a safety decision support system.

Conclusions and Recommendations

The primary purpose of this manuscript was to quantify the construction safety risk mitigation associated with essential safety program elements. Thirteen safety program elements were identified in literature as essential to an effective safety program. Once these elements and applicable safety risk classifications were identified and defined, the Delphi process was implemented in an effort to quantify the frequency and severity reduction resulting from the independent implementation of each essential program element.

During the Delphi process described for this phase of the research, an initial group of 13 individuals were certified as experts according to predefined criteria. Ten of the 13 experts completed all rounds of the Delphi process. During the three rounds, the expert panel closely approached consensus, with an absolute deviation of approximately 0.82 units on a 1–10 scale.

The data matrix that resulted from the Delphi study was presented and converted to usable units of frequency and risk. The subsequent analysis indicated that the safety program elements existed in four levels of effectiveness. The first-tier safety program elements are upper management support and commitment and subcontractor selection and management. The second-tier elements are employee involvement in safety management and planning, job hazard analyses, training and regular safety meetings, frequent worksite inspections, and a site-specific safety manager. The third-tier elements are substance abuse programs, safety and health committees, safety and health orientation, and a written safety plan. Finally, the fourth-tier elements are record keeping and accident analyses and emergency response planning.

Using the data presented in this manuscript and the cost-effectiveness calculations one may strategically and formally select safety program elements for implementation. In other words, one can use the data and the simple projected cost calculations to design the most effective safety program given the resources available. The research effort described in this manuscript aims to quantify the risk mitigation associated with the implementation of safety program elements using the concepts of demand and capacity. The writers believe that this information can be used for strategic and formal selection of elements, especially when a small subset of elements must be chosen due to limited resources.

Acknowledgments

The writers would like to thank the 10 expert panelists for their time investment, candor, and significant contributions to this study.

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