Population and Initial Validation of a Formal Model for Construction Safety Risk Management

Matthew R. Hallowell, A.M.ASCE[1]; and John A. Gambatese, A.M.ASCE[2]

Abstract: The transient, unique, and complex nature of construction projects makes safety management exceptionally difficult. Most construction safety efforts are applied in an informal fashion under the premise that simply allocating more resources to safety management will improve site safety. Currently, there is no mechanism by which construction-site safety professionals may formally evaluate safety risk and select safety program elements for implementation. This paper introduces and validates a risk-based safety and health analytical model that can be used to evaluate expected risk given specific worker activities, strategically select highly effective safety program elements for implementation when resources are limited, and quantify resulting risk once the identified safety elements have been implemented. Specifically, the paper has three primary objectives: (1) introduce a risk-based construction safety and health analytical model; (2) validate relevant data used to populate the model; and (3) illustrate the applications of the model in practice. The findings of this research indicate that the values used to populate the model are reliable and that the model has the potential to significantly improve construction safety management.

DOI: 10.1061/(ASCE)CO.1943-7862.0000204

CE Database subject headings: Occupational safety; Construction safety; Labor; Risk management; Models.

Author keywords: Occupational safety; Labor issues; Risk; Risk management.

Introduction

Much has been published on the topic of construction safety and health management. The essential elements of an effective safety and health program have been identified and described in detail and several analytic models that illustrate the relationship of various factors that contribute to construction accidents have been created (Hinze 1997; Hill 2004). For example, Hinze (1997) described accidents in terms of a distractions theory. Similarly, Mitropoulos et al. (2005) described safety and health in terms of a system model that illustrates a complex network of contributing factors. Despite this work, there has yet to be a formal model of construction safety risk management. A predictive risk-based model may be useful for comparative analyses of safety impacts resulting from specific construction activities or processes and for evaluation of the impacts of innovation, organizational change, and alternative means and methods on safety risk. In other words, such a model may be used by practitioners to move safety management efforts earlier in the project lifecycle.

As indicated in a recent publication by Hallowell and Gambatese (2007), the current safety management process is typically informal. Specifically, safety program elements are identified and selected for a site-specific safety program primarily by word of mouth and intuition. Fortunately, this issue normally has a minimal impact on large firms that have the resources and infrastructure to implement a comprehensive safety and health program containing a large proportion of the applicable program elements. For small contractors, however, scarce resources limit the scope of the safety program.

The Bureau of Labor Statistics (BLS) estimates that 40% of construction firms employ 20 or fewer workers. Furthermore, these firms often lack a safety management system [Bureau of Labor Statistics (BLS) 2006]. Typically, these small firms operate with a severely limited safety and health management budget and are forced to select a small subset of the applicable safety program elements. Current literature provides little to no guidance that aids small firms in their decision-making process. This paper introduces a risk-based model that can be used by all firm types to formalize and improve safety and health management practices. Specifically, the paper has three primary objectives: (1) introduce a risk-based construction safety and health analytical model; (2) validate relevant data used to populate the model; and (3) illustrate the applications of the model in practice. The model can be used to evaluate expected risk given specific worker activities, to strategically select highly effective safety program elements for implementation when resources are limited, and to identify the resulting risk once the identified safety elements have been implemented.

Risk-Based Model

In a previous publication, Hallowell and Gambatese (2007) introduced the concept of risk equilibrium based on Isaac Newton's third law. Simply put, Newton's third law states that for every action there must be an equal and opposite reaction. In structural

[1]Assistant Professor, Civil, Environmental, and Architectural Engineering, Univ. of Colorado, Boulder, CO 80309-0428 (corresponding author). E-mail: matthew.hallowell@colorado.edu

[2]Associate Professor, School of Civil and Construction Engineering, Oregon State Univ., Corvallis, OR 97331. E-mail: john.gambatese@oregonstate.edu

Note. This manuscript was submitted on September 7, 2008; approved on February 5, 2010; published online on February 11, 2010. Discussion period open until February 1, 2011; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, Vol. 136, No. 9, September 1, 2010. ©ASCE, ISSN 0733-9364/2010/9-981–990/$25.00.

J. Constr. Eng. Manage., 2010, 136(9): 981-990

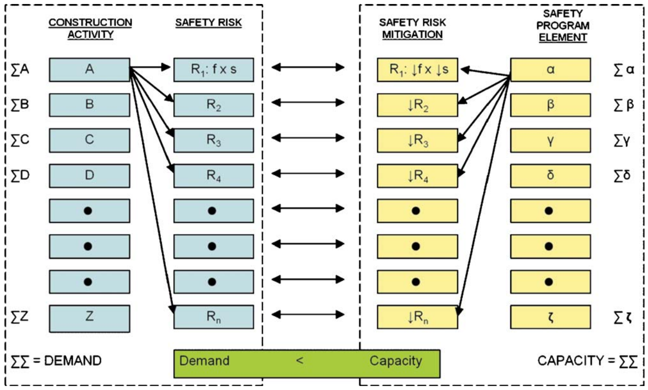

Fig. 1. Safety equilibrium model

engineering, this concept is employed when designing support systems for 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 than 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 equation for flexure in a structural member:

$$M_u < \Phi M_n \tag{1}$$

where M_u=ultimate moment (i.e., maximum design demand); M_n=design moment (i.e., nominal moment or capacity); and Φ =factor of safety.

The safety risk model suggested in this paper applies the concept of equilibrium in a similar manner. In this application, the concept of demand, analogous with M_u, is represented by the expected safety risk for a construction process and is equal to the sum of the risks associated with the activities required to perform the given construction process. For example, risk demand may be calculated for the process of erecting steel on a project.

The concept of capacity, analogous to M_n, is represented by the collective risk mitigated by the safety program implemented. The safety risk capacity is determined by the sum of the risk mitigated by the collective safety program elements chosen for implementation. In theory, to reach equilibrium and to 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 described by the following expression [Eq. (2)] modeled after Eq. (1):

$$S_u < \Phi S_n \tag{2}$$

where 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); and Φ=factor of safety.

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 structural system or ability of the safety program to mitigate risk).

Once the safety risk demand and capacity have been quantified, Eq. (2) may be applied. Using this model allows one to evaluate the relative effectiveness of safety program elements and to quantify residual risk (i.e., demand capacity). The structure of the equilibrium model is illustrated in Fig. 1. In this model, the construction activities are denoted in Arabic letters A through Z, risks are denoted R_1 through R_n, and safety program elements are denoted by Greek letters α through ζ. The process of quantifying risk demand is illustrated by the connection of each activity to the applicable safety risks. These risks are defined by the product of the average frequency of occurrence and the associated severity of the outcome. The cumulative risk demand for the activity is represented by the sum of the risks connected to the given activity. The risk demand for the process as a whole is calculated by summing the risks associated with all expected activities. Cumulative risk may be calculated by applying Eq. (3).

Table 1. Comparison of Risk Values among Formwork Construction Activities (Hallowell 2008)

Formwork construction activity	Safety risk score (S/w h)
Lubrication/preparation	18.67
Ascend/descend ladder	1.86
Crane materials	0.51
Motorized transport	0.48
Hammer materials	0.25
Lift/lower materials	0.19
Excavation	0.11
Plumb/level forms	0.11
Cut materials	0.05
Manual transport	0.04
Nail/screw/drill	0.03
Static lift	0.03
Inspect/plan	0.01

Likewise, the safety risk capacity of a safety program element may be calculated by summing the risk mitigation associated with risks R_1 through R_n. The total capacity of the safety program is equal to the sum of the risk mitigation associated with all safety program elements chosen for implementation. One will note in Fig. 1 the arrows that connect Activity A and safety program element α to each of the related safety risks. These connections would exist for all elements and activities in the model; however, arrows were omitted in the figure to preserve the clarity of the figure.

The method of quantifying capacity is similar to the process of quantifying demand. Cumulative risk capacity may be calculated using Eq. (4). Finally, the residual risk may be evaluated by applying Eq. (2). In order to optimize safety performance, residual risk must be minimized

$$\sum_{Act.=A}^{Z}\left[\sum_{R_1}^{R_n}(\text{safety risk})\right] = S_u = \text{demand} \tag{3}$$

$$\sum_{El.\alpha}^{\zeta}\left[\sum_{R_1}^{R_n}(\text{safety risk mitigation})\right] = S_n = \text{capacity} \tag{4}$$

In order to populate the risk model illustrated in Fig. 1, the risks associated with the activities required to conduct a specific construction process must be known. Additionally, the risk capacity of the available safety program elements must also be known. In recent research, Hallowell and Gambatese (2009a) quantified the risk demand for the process of constructing concrete formwork and the risk mitigation capacity associated with 13 safety program elements. The demand and capacity data are reproduced in Tables 1 and 2, respectively, as the values in these tables are directly related to the study described in this paper. One should note that the risk demand values presented in Table 1 represent the expected risk values associated with the construction of concrete

J. Constr. Eng. Manage., 2010, 136(9): 981-990

Table 2. Risk Reduction Ratings Associated with Essential Safety Program Elements (Hallowell 2008)

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	JHAs	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}

formwork. The values in Table 3, however, represent the risk mitigation resulting from the independent implementation of each safety program element for *the construction industry in general* and are robust for all processes and project types. Risk demand is reported in terms of units of severity per worker hour (S/w h) and capacity is defined in terms of a reduction in severity per worker hour (−S/w h). The data were quantified using the risk scales illustrated in Table 3. The writers encourage the reader to refer to Table 3 when interpreting the risk values in Tables 1 and 2.

Methodology

In order to validate the application of the equilibrium concept to safety and health management, the research team considered several methodologies. For example, field testing of the model and correlations of residual risk with incident rates was considered. However, this approach posed two significant problems. First, field testing of a theoretical model would be unethical because of the potential for increasing safety and health risk if the model could not be validated or was improperly implemented. Second, the method of correlating residual risk with incident rates was not possible because of the significant time between incidents and the lack of available data.

To address these limitations, alternative subjective research methodologies were implemented. Rather than validate the model as a whole, the research team chose to independently validate each of the three components of the model: demand data, capacity data, and the concept of equilibrium. Specifically, the validation effort for this study involves the following three efforts:

1. Validation of the risk data collected and described by Hallowell and Gambatese (2009a) and summarized in Table 1;
2. Validation of the risk mitigation data collected and described by Hallowell and Gambatese (2009b) and summarized in Table 2; and
3. Validation of the equilibrium model and its application to construction safety management.

Studies that may have an impact on the health, economy, political climate, or environment should be validated before the results are used to make influential decisions (Thorne and Giesen 2002). This is especially true for research that may have a direct impact on the welfare of the public. Since this study focuses on construction safety and health, the validation of the results is extremely important. In an academic study, validation may be conducted through the process of collecting similar data in an effort to confirm or deny values obtained through original research efforts. As with most research, validation can be conducted in many ways. Due to the diversity of the data used to populate the risk equilibrium model, two distinct methods of validation were implemented to confirm the accuracy and reliability of the data in Tables 1 and 2.

Typically, validation research is conducted in one of the five ways: retrospective project analyses, use of archival data, alternative methods of collecting similar data, replication of the study, or experimental implementation. While objective experimental research studies are ideal methods of validation, it is well known that such research methods are impractical and unethical for safety and health research. Perhaps the second best method is the use of objective archival data. Unfortunately, archival data published by agencies such as the BLS and the National Safety Council only include data for high severity injuries. Therefore, the validation efforts for the study used retrospective project analyses, replication, and an alternative method of collecting similar data.

Demand Validation

Since objective data collection methodologies were unrealistic, an alternative subjective research methodology was selected. Hallowell and Gambatese (2009a) used a rigorous application of the Delphi method to collect the original demand data. In order to validate these values, risk perceptions of construction laborers were used to define risk levels for various work periods using simple but intensive questionnaires. According to Starr (1969), risk perception is the subjective judgment that people make about the characteristics and severity of a risk event. While individuals may rate the same environment differently, the statistical aggregation of risk perceptions may represent actual conditions when the major sources of bias have been minimized. In the past 30 years, several theories have been developed that explain why people make different estimates of risks.

Two major families of theory have been developed by social scientists: the psychometric paradigm and cultural theory (Thompson et al. 1990). Tversky and Kahneman conducted the original psychometric research when they performed a series of gambling experiments to see how people evaluated probabilities (Tversky and Kahneman 1973; Kahneman et al. 1982). These researchers found that people use a number of cognitive shortcuts to evaluate risks. However, these theories support the assumption

Table 3. Frequency and Severity Scales

Subjective score	Scaled frequency (w-h/incident)	Severity level	Scaled severity (relative impact)
1	Negligible or 0	Temporary discomfort	2
2	10–100 million	Persistent discomfort	4
3	1–10 million	Temporary pain	8
4	100,000–1 million	Persistent pain	16
5	10,000–100,000	Minor first aid	32
6	1,000–10, 000	Major first aid	64
7	100–1,000	Lost work time	128
8	10–100	Medical case	256
9	1–10	Permanent disablement	1024
10	<1	Fatality	26,214

J. Constr. Eng. Manage., 2010, 136(9): 981-990

that, when biases are controlled and the impacts of cognitive shortcuts are minimized, risk perceptions can be an accurate measure of actual risk.

The goal of this validation effort was to determine whether the results published by Hallowell and Gambatese (2009a) accurately represent the risk levels that the workers experience on site. For this effort, the validating data consist of risk perceptions collected on active worksites where workers were actively constructing concrete formwork. This validation effort involved two major research tasks. First, the durations of specific work tasks performed by each of the workers were recorded by direct observation. Observations were made in 4-h work periods. Following these observations, workers were interviewed, one on one, during their lunch breaks and at the end of the work day. These times were selected because they typically marked the end of a 4-h work period.

During the interviews, workers were asked to approximate the expected incident frequency for various severity levels if the work conditions were to continue in perpetuity. For example, workers were asked "If your work continued exactly like the last 4-h work period, how often would you expect to experience a first-aid injury?" In this scenario, the worker was provided with a definition of a first-aid injury to maintain consistency and was encouraged to express frequency in easily defined time periods such as days, weeks, months, or years. For example, a sample response to the question posed above was "I would expect a first-aid accident once every three weeks." Similar questions were asked of the workers for several injury severity levels. Responses were recorded on survey forms by the interviewer.

In order to validate the demand data the unit risk values in Table 1 (S/w h) were multiplied by the exposure durations recorded during observations (w h) to predict risk cumulative risk values (S). These risk values were then compared to the risk perceptions of the workers. Worker risk perceptions (S) were calculated by multiplying the frequency values obtained during interviews (converted to units of incidents/w h) by the associated severity score in Table 3 (S) and the exposure durations observed (w h). The median value for each worker represented the worker's risk perception and the median perception value for the crew was taken to represent the crew's risk perception for the 4-h work period. The crew risk perceptions were then correlated to the predicted demand for the work period to determine the level of validation.

In order to minimize the potential effects of cognitive biases, redundancy and medians (rather than means) were used to represent the perceptions of the work crews. This methodology was implemented to reduce the potential impact of biases such as recency, primacy, and contrast (Heath and Tindale 1994). The use of means for such a study would allow a biased individual to adversely affect the quality of the results. While means may compromise the influence of outlying responses, the writers held the reduction of judgment-based bias paramount.

One will note that detailed data were to be collected a small sample of projects completed by a single contractor in one geographic region. Specifically, four distinct work crews employed by one contractor that were actively constructing concrete formwork in the Pacific Northwest were selected for participation in this study. This methodology was selected over the involvement of a diverse population of contractors because researchers have found that factors such as crew competency, time of day, weather, and project scope influence safety performance on site (Hinze 1997). This methodology allowed the research team to control for most project-specific and regional factors; however, the effects of personal characteristics such as individual behavior, risk tolerance, and field experience were not controlled for this study. Rather, medians and redundancy were used to limit the influence of any extreme personal experiences, characteristics, or behaviors.

Capacity Validation

The second form of validation for this study involved the confirmation of the risk mitigation values associated with the implementation of safety program elements. As indicated previously, the use of experimental techniques to validate these data is both impractical and unethical. Additionally, the complex and abstract nature of the capacity data makes the use of project data impractical. Therefore, a qualitative data collection methodology was most appropriate. To validate the capacity data a second independent Delphi panel was selected. A Delphi panel consisting of experts with significant experience in the construction industry was desired as the capacity data are ultimately used to evaluate the relative effectiveness of the elements. The team believed that, if the second independent Delphi panel confirmed the relative effectiveness of the program elements, the risk reduction values would be sufficiently validated.

The specific methodology suggested for effective implementation of the Delphi process is well documented. The research team followed the typical conventional procedures outlined by Linstone and Turoff (1975). Some specific characteristics of this Delphi study are as follows:

1. Target panel size of 15 participants;
2. Three rounds of surveys;
3. Feedback reported in terms of median results from the previous round;
4. Feedback including reasons for outlying responses in Round 3;
5. Consensus measured in terms of absolute deviation; and
6. Expert panelists were required to meet at least four of the following eight characteristics *related to the field under examination*:
    a. Primary or secondary author of at least three peer-reviewed journal articles on the topic of construction safety or health;
    b. Invited to present at a conference focused on construction safety or health;
    c. Member or chair of a construction safety and health-related committee in a nationally recognized organization;
    d. At least five years of professional experience in the construction industry;
    e. Faculty member at an accredited institution of higher learning with a research or teaching focus on construction safety and health or risk management;
    f. Author or editor of a book or book chapter on the topic of construction safety and health or risk management;
    g. 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 Bachelor of Science (BS)]; and
    h. Designation as a professional engineer (PE), certified safety professional (CSP), associated risk manager, or a licensed architect (American Institute of Architects).

Potential experts were identified by searching the rosters of national safety-related committees such as the ASSE Construction

J. Constr. Eng. Manage., 2010, 136(9): 981-990

Safety Specialty, obtaining contact information from relevant publications, and by identifying industry experts with many years of construction experience. In total, 22 potential experts were identified and invited to participate in the study. Of the 22 invitees, 17 panelists agreed to participate resulting in a participation rate of 73%.

Delphi participants were asked to begin the process by completing an introductory survey that solicited information about their background, experience, education, and qualifications. Potential experts were required to meet at least four of the seven predefined requirements previously discussed. Sixteen of the 17 potential panelists qualified for participation. The final panel includes members from 10 different states and every major geographical region of the United States. The most important attribute of the panel is its collective expertise as the results represent consensus of group opinion. The collective qualifications of this Delphi panel are as follows:

- Three individuals possess a Ph.D., four possess a MS, and two posses a BS as their terminal degree in a related field of study;
- One individual is employed at the associate professor rank and one is employed as at the assistant professor rank at an accredited academic institution;
- The panel has produced a total of 305 peer-reviewed publications on the topic of construction safety and health or risk management;
- The panel has produced 13 books or book chapters on the topic of construction safety and health or risk management;
- The panel has over 331 years of field experience in the construction industry; and
- The panelists have obtained six CSP licenses and two PE licenses.

For each round, the expert panelists were asked to rate the relative effectiveness of the 13 safety program elements in Table 2 on a 1–10 scale. For this scale, a value of 1 represents an element that is completely ineffective and a value of 10 indicates that the element is exceptionally effective. The validation panel was not provided with any information regarding data that were previously collected and the process was conducted *before* the capacity data were released for publication. Furthermore, individuals that participated in the study of Hallowell and Gambatese (2009b) were precluded from participating in this study. In subsequent rounds, panelists were provided with the panel's median response from the previous round. In Round 2, the panelists were asked to provide reasons with their ratings if they believed that the true effectiveness was two or more units from the median on a 1–10 scale.

During the Delphi process several controls were implemented to minimize the potential effects of judgment-based bias. Because the Delphi surveys involved rating the effectiveness of program elements, there was potential for several biases such as contrast, primacy, myside, the Von Restorff effect, and dominance. In order to control for these biases the order of the safety program elements on the Delphi surveys was randomized for each panel member, the definitions associated with each safety program element were provided on the Round 1 survey, anonymity of the panelists was maintained throughout the process, and median responses were taken to represent the collective group opinion.

Equilibrium Validation

The final validation effort for this research involves verifying the concept of equilibrium. While Newton's third law and the concept of equilibrium have been accepted in the scientific community, the application of this concept to safety and health risk management was explored. The methodology implemented to evaluate equilibrium was similar to the demand validation procedure in that it involved the collection of durations of time spent on formwork activities (exposure) and risk perceptions for a particular project. This process was different from the demand validation because a sample of projects that was diverse with respect to scope, funding source, geographic region, and delivery type was targeted. Furthermore, safety managers were asked to estimate the number of worker hours spent on formwork activities *for an entire project*. Additionally, safety managers were asked to indicate the incident rate for formwork construction for the case project. If no incidents were experienced, the safety managers were asked to rate the expected durations between incidents of various severity levels (i.e., frequency) if the project was to continue in perpetuity.

One should note that there are several limitations associated with this validation effort. First, this partial validation method limits the identification of internal perturbations within the model. In other words, the independent validation of the demand and capacity data does not necessarily validate the relationship between these two components. The partial validation method was employed because the model has been populated with data from two separate and distinct studies. To compensate for the shortcomings of this partial validation, the writers attempt to validate the concept of equilibrium and the final output of the model by presenting a case scenario. Finally, it should be noted that the external validity of the demand validation effort is limited due to a small case sample.

Results

Demand Validation Results

The project selected for this validation effort was chosen because it included a site layout that involved multiple, nearly identical, multistory housing units simultaneously under different phases of construction. The case project was a four-story apartment structure located in the Pacific Northwest that consisted of three distinct but similar wings. When observed, each of the three segments of the building was in a different stage of construction. In section one, the foundation walls were being poured, in section two the walls were being formed, and in section three, an elevated (second story) floor slab was being formed. All three sections of the building, while at different stages of production, were being constructed simultaneously when data were collected for this study. Sections two and three, the construction of the formwork for the walls and the elevated slab, were the focus of this validation effort. Section one was omitted because the workers were pouring concrete at the time of observation.

The construction manager had divided the formwork carpenters into two work crews with four workers each. One crew was responsible for constructing the formwork for the walls and the second crew was responsible for the construction of the elevated slab. The observations for this study were divided into four units over the course of two days, each consisting of a 4-h work period. That is, observations were conducted over the course of two work days and were divided into ante meridiem (a.m.) and post meridiem (p.m.) for one crew and a.m. and p.m. for the second crew.

As previously indicated, the research was conducted in two major phases: the observation and documentation of work activities and their durations and the collection of risk perceptions. The results of the observational phase are summarized in Table 4. The

J. Constr. Eng. Manage., 2010, 136(9): 981-990

Table 4. Predicted Cumulative Safety Risk Levels

Activity	Wall a.m. Exposure (w-h)	Wall a.m. Cumulative risk (severity)	Wall p.m. Exposure (w-h)	Wall p.m. Cumulative risk (severity)	Slab a.m. Exposure (w-h)	Slab a.m. Cumulative risk (severity)	Slab p.m. Exposure	Slab p.m. Cumulative risk (severity)
Manual transport	2.50	0.09	2.50	0.09	2.50	0.09	3.75	0.14
Motorized transport	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lift/lower materials	3.75	0.73	2.50	0.49	3.75	0.73	3.75	0.74
Static lift	1.25	0.03	1.25	0.03	1.25	0.03	3.75	0.10
Crane materials	3.75	1.93	3.75	1.93	1.25	0.64	1.50	0.77
Cut materials	0.00	0.00	0.00	0.00	1.00	0.05	0.00	0.00
Nail/screw/drill	0.00	0.00	0.00	0.00	0.25	0.01	0.00	0.00
Hammer	1.25	0.31	1.50	0.37	0.75	0.19	0.75	0.19
Plumb/level forms	2.50	0.27	2.50	0.27	0.25	0.03	0.00	0.00
A/D ladder	1.00	1.86	1.25	2.33	3.75	6.98	1.25	2.33
Inspect/plan	2.50	0.02	4.00	0.03	6.25	0.04	6.25	0.04
Excavation	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Lubrication/preparation	2.00	37.34	2.00	37.34	0.00	0.00	0.00	0.00
Total		42.57		42.89		8.79		4.29

duration of time spent on each of the formwork construction activities represented the exposure of the workers to the construction activities summarized in Table 1. These exposure values were multiplied by the risk values in Table 1 to obtain the cumulative risk experienced for each work period [cumulative risk (S) = unit risk (S/w h) × exposure (h)]. These cumulative risk values are defined in terms of units of severity and represent the predicted risk levels generated by using the risk model.

The risk perceptions collected during the interview phase are presented in Table 5. These values are also defined in terms of severity because the unit risk obtained during the interviews was multiplied by 4 h (i.e., the duration of exposure). It has been noted that this method of data collection was selected is most closely represented by minicase studies where the unit of analysis was an independent work crew of four individuals because the risk perceptions were obtained individually, aggregated by crew, and pattern matched using linear regression (Fig. 2). The writers selected this method of data collection over a large survey population to minimize the potential impacts of confounding factors such as management style, weather, and site conditions. It should be noted, however, that the scope of inference is limited because of the small validation population. Thus, the writers suggest further validation.

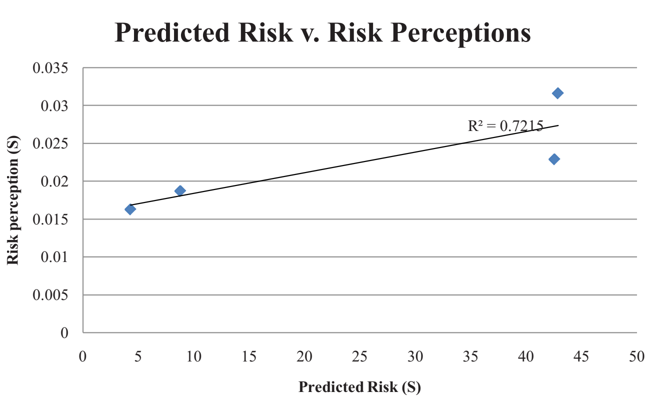

Fig. 2. Predicted risk versus safety risk perception

Capacity Validation Results

During the Delphi process the participation was extremely strong. Fifteen of the original 16 panelists completed the Round 1 survey resulting in a response rate of 94%.

The results of the three rounds of surveys indicated that, similar to the original capacity data, the safety program elements could be classified in multiple tiers of effectiveness. The results of all three rounds of Delphi process are summarized in Table 6. As one can see in the table, the most effective program elements were upper management support, project-specific training and safety meetings, safety and health orientation and training, and job hazard analyses (JHAs).

One of the goals of the Delphi process was to achieve consensus among the expert panelists. After the initial round of surveys, the absolute deviation was 1.41 units on a 1–10 scale. In other words, the absolute deviation from the median for all ratings is 1.41 units. Since group consensus of the experts is vital to the quality and precision of the results, Rounds 2 and 3 focused on reducing the variation in the expert responses and obtaining the true probability and severity values.

As a result of the multiple rounds, the absolute deviations from the median were reduced to 1.23 and 1.02 units for Rounds 2 and 3, respectively. Therefore, after Round 3 the targeted consensus of

Table 5. Worker Risk Perceptions (S)

Worker ID	Project unit	Risk perception a.m.	Risk perception p.m.
W1	Elevated slab	0.017	0.060
W2	Elevated slab	0.010	0.032
W3	Elevated slab	0.015	0.002
W4	Elevated slab	0.032	0.006
W5	Wall	0.014	0.043
W6	Wall	0.010	0.032
W7	Wall	0.102	0.003
W8	Wall	0.032	—

J. Constr. Eng. Manage., 2010, 136(9): 981-990

Table 6. Delphi Results and Comparison to Capacity Data

Safety program element	Effectiveness original capacity Rating	$(-S/w\,h\times 10{,}000)$
Upper management support	10	144.2
Project-specific training/meetings	9.5	27.2
S&H orientation/training	9	4.3
JHAs	8.5	35.3
Frequent worksite inspections	8	15.8
Substance abuse programs	8	6.4
Subcontractor selection and management	8	133.0
Written safety and health plan	8	4.0
Employee involvement and evaluation	8	43.4
Safety manager on site	7	15.3
Emergency response planning	5.5	0.01
Safety and health committees	5.5	5.0
Record keeping/analyses	5	0.04

approximately one unit was achieved. During the multiple rounds of surveys no expert panelists failed to respond.

Equilibrium Validation Results

Unlike the demand and capacity validation, validating the concept of equilibrium proved to be challenging. In total, six safety managers participated in the study; however none of the safety managers had experienced incidents on their projects. When analyzed, it was found that the residual risk on these projects was expected to be zero due to the extensive safety programs. Therefore, the desired correlations could not be made. To illustrate the applicability of the tool a case scenario will be discussed in the applications section of this paper.

Analysis

Demand Data Comparison

As previously indicated, the demand risk data were to be validated by comparing the expected risk resulting from the use of the safety equilibrium model and the risk perceptions obtained on site. The predicted risk values were obtained by multiplying the unit risk values in Table 1 by the exposure durations observed on site. The resulting risk demand is summarized in Table 4 and the risk perceptions are summarized in Table 5. When the predicted risk for the work period was plotted against the crew members' median risk perception for the time period observed, an r-squared value of 0.72 was obtained. The r-squared value represents the degree of fit of the data by finding the square of the residuals of the data when fit to a linear regression of the two data sets. An r-squared value close to 1 indicates a very strong statistical correlation of the data. The R-squared value is recommended for such comparisons by Ramsey and Schaefer (2001). The resulting r value was 0.72 indicating a strong correlation for a study that involves a social science research component. While the sample size was small, the data were rich and the correlation was fairly strong.

The strength of fit leads the writer to believe that the demand data are indeed an accurate representation of the actual conditions on site. As an interesting aside, the strength of this correlation also indicated that these crew members are well aware of the risk climate on site. One should note that the risk perceptions are significantly lower than the risk demand values because the original risk demand values are defined for the industry as a whole and do not incorporate factors such as safety programs, culture, and project type.

Capacity Data Comparison

The purpose of the Delphi process described in this paper was to validate the capacity data presented in Table 2 by obtaining similar data with a unique and independent Delphi panel. It was expected that, if the second Delphi process leads to similar results, the data were reliable and dependable. The results of the Delphi validation process are summarized in Table 6 where they are also compared to the expected risk capacity values. When compared to the original values, one can see that both panels resulted in ratings that placed safety program elements in three tiers of effectiveness. These data indicate that there is consistency among the two data sets with three exceptions. The safety and health orientation and training, subcontractor selection and management, and written safety and health plans are in conflict with the values from the capacity ratings from the capacity Delphi process.

While there are three of the 13 elements in conflict, the remainder of the validation data confirms the effectiveness values from the Delphi process. In fact, both independent data collection methodologies resulted in three tiers of effectiveness. The first-tier (i.e., most effective) program elements are upper management support, project-specific training and safety meetings, JHAs, and employee involvement and planning. These top-tier elements are represented by a rating of 8 or above for the validation rating and a rating of 0.0040 (S/w) or over from the Delphi capacity data. The second-tier elements, such as worksite inspections, substance abuse programs, site-specific safety manager, and safety and health committees, have both a validation rating of 5.5 or over and a capacity rating of $>0.0001\ S/w$. Finally, the third-tier elements, such as emergency response planning and record keeping and analysis, have a validation rating of ≥ 5.5 from the validation and a capacity rating of $<0.0001\ S/w$.

This level of validation may be described as moderately strong because the relative effectiveness of the safety program elements was confirmed for all but three elements. The conflicting evidence may exist because of the following factors:

- The validation panel may have considered interactions among the safety program elements.
- The two panels have different levels of qualification (i.e., the original Delphi panel's qualifications were more academic and those of the validation panel were more industry based).
- The validation panel may not think in terms of risk (frequency $\times$ severity).

Equilibrium Model Comparison

As previously indicated, none of the safety managers who responded to the equilibrium validation survey indicated that incidents had occurred on their work site. Due to the nature of these data, no correlations could be made. One should note, however, that the equilibrium model predicted an outcome of zero risk for each of these projects due to the number of safety program elements implemented. Therefore, the result of zero incidents on all

J. Constr. Eng. Manage., 2010, 136(9): 981-990

of these projects leads to moderate evidence. One should note that, theoretically, zero risk is unachievable unless the risk is transferred or avoided.

As one may recall, the safety managers were asked to rate the expected frequency of injuries of various severity levels if the project was to continue in perpetuity. Unfortunately, since the equilibrium model predicted zero risk for all projects, no correlations could be made. Therefore, only moderate evidence could be obtained to validate the concept of equilibrium. The application of Newton's third law to safety and health risk is still strong at a fundamental and theoretical level.

In summary, the three validation techniques provide moderate to strong evidence that the risk demand values, mitigation capacity values, and the concept of equilibrium presented in a previous study are indeed accurate. The strength of this support ranged from moderate in the case of the capacity validation to extremely strong for the demand validation. The validated data have strong application to the field of construction safety risk management.

Application

Evaluating Equilibrium for a Specific Process

The primary purpose of the data-driven equilibrium model is to allow safety managers to measure the expected risk and the resulting risk reductions that occur as a result of implementing safety program elements. This model can be used to direct the formal and objective selection of safety program elements when resources are limited for both small and large firms. For small firms, the system can be used to identify the most effective safety program elements based on expected activities. This, in turn, allows the firm to prioritize elements for selection when funding is limited. Likewise, large firms can use the system to evaluate the relative effectiveness of the elements and identify when risk has been minimized. In order to use the safety equilibrium model and the data presented in Tables 1 and 2, the following six steps must be carefully followed:

1. Determine the activities expected;
2. Select the expected safety program elements;
3. Reference the original demand data on the original 1–10 risk scale published by Hallowell (2008);
4. For each program element implemented, reduce the probability and severity levels accordingly through direct subtraction;
5. Multiply the resulting severity values by the corresponding frequency values to determine the resulting risk for each activity; and
6. Add the resulting risk values for each activity to determine the expected risk for the process.

One must note that this procedure must be performed on the *original* (unitless) values on a 1–10 scale because of the geometric nature of the severity scale. Hallowell (2008) specifically provided these data on the original scales and discussed the interpretation of these data in depth. The specific methodology listed in the six steps above must be implemented to ensure correct procedure. Once this process has been implemented, the resulting risk values can be converted to values with units of severity/worker hour (S/w h).

To aid with this process, the writers have developed software in MS Excel that automates this process. Using this software the user can enter the activities expected and the chosen safety program elements. The software automatically computes the original risk demand, the capacity, and the residual risk. The software can be used by managers to evaluate the effects of alternative means and methods by adjusting expected exposure values and changing activities. The software can also be used to strategically select safety program elements to maximize the effectiveness of the safety program given the specific activities expected on site. In order to optimize the effectiveness and facilitate implementation, the basic system is free of cost upon request, easily identifies scenarios where accidents are more likely and/or more severe, identifies optimal methods for risk reduction, and, with cost input from the user, identifies the most cost-effective safety program elements for unique scenarios.

Case Project

To illustrate the applicability of the tool the writers identified a scenario where a crew of seven workers employed by a small contractor was constructing formwork with a minimal safety program. The case contractor was in the process of performing the following activities: static lift; motorized transport of materials and equipment; cutting materials; inspecting and planning; lifting and lowering materials; manual transport of materials and equipment; hammering; plumbing and leveling; and excavation. The only safety management effort implemented on site was a written safety and health plan.

Using the model a baseline safety risk demand can be calculated for this formwork process by summing the unit risks for each activity listed above (see values in Table 1). This baseline value, 1.27 S/w h, represents the safety risk demand for this process when no safety efforts are implemented. This value can be practically interpreted to mean that, without any safety efforts, this contractor could expect to incur a major first-aid injury on average once every 50 worker hours, a medical case injury every 101 worker hours, or a lost work-time injury every 201 worker hours. The model can also be used to predict the risk that exists when the written safety plan has been developed and effectively communicated. Once the equilibrium calculations have been performed as described in this paper, one may calculate that the residual risk (0.000 038 S/w h). Practically, this value can be interpreted to mean that one could now expect to incur approximately one major first-aid injury every 2.1 million worker hours, a medical case injury once every 4.2 million worker hours, and a lost work-time injury once every 8.4 million worker hours.

The model can also be used to evaluate the relative effectiveness of alternative safety program elements. For example, upper management support and commitment, JHAs, and employee involvement would all have effectively reduced more risk than the written safety plan. Additionally, with cost estimate inputs from the user of the model, the cost effectiveness of alternative safety program elements can also be evaluated. A cost-effectiveness rating is simply calculated by dividing the unit cost of a given safety program element by the safety risk capacity of each safety program element. For example, if a manager expected that JHAs cost, on average, \$300 per million dollars of project scope for his company, the model would compute the cost-effectiveness rating to be 1.78×10^{-5}/dollar (3.53×10^{-4}/\$300). A similar calculation could be performed for any of the 13 elements in the model and the user could perform a comparative analysis to determine the most cost-effective program.

During the process of merging the demand and capacity data one may note that the safety efforts required to reduce the resulting risk to zero are minimal. In fact, according to the capacity data, it is possible to reduce the risk of forming concrete to zero by implementing just a few safety program elements. Unfortu-

J. Constr. Eng. Manage., 2010, 136(9): 981-990

nately this is contradictory to what the writers have observed in practice. In fact, many firms implement all safety program elements analyzed in this study and continue to have accidents on their sites.

The writer believes that the data presented in this paper are, indeed, accurate. However, since the effectiveness of the safety program elements (Table 2) was rated by the capacity panel independently by Hallowell and Gambatese (2009b), factors such as diminishing returns and interactions among safety program elements were not accounted for. Furthermore, the specific risk mitigation for specific risk levels was not identified as a part of the risk mitigation quantifications. In other words, the writers cannot determine whether the effectiveness of an element is constant throughout the spectrum of injury severity levels.

The writer cautions the reader when implementing the current model in practice as the resulting risk may be misleading. Further research is necessary to determine whether there are any interactions among safety program elements (e.g., the effectiveness of one element may be significantly influenced by the implementation of one or more elements) or diminishing returns (e.g., once several elements have been implemented, a given element may no longer be as effective as it would have been if it was the only element implemented).

Conclusions

The three objectives of this paper were to introduce the conceptual framework of a risk-based analytic model for construction safety management, validate the risk demand and risk capacity data obtained in a previous study, and discuss applications of the model in practice. In order to achieve these objectives, the framework of the risk model and the previous demand and capacity data was introduced. Subsequently, the three methods of validation were discussed for demand, capacity, and equilibrium validation. The results of these three methods of validation were presented and analyzed and, finally, the application of the validated data was discussed in terms of the original equilibrium model.

The risk-based model of construction safety management introduced and described in detail in this paper was based heavily on risk and safety management theory. The data-driven model can be used to evaluate risk values given specific activities, to aid with the selection of safety program elements by evaluating the relative effectiveness of available safety program elements, and to calculate residual risk. The data used to populate this model were obtained by Hallowell and Gambatese (2009a). Subsequent portions of this study focused on validating these data to ensure the highest level of effectiveness when the model is implemented in practice.

The results of the validation efforts suggest that the original data used to populate the model are reliable and can be used as a resource for safety managers in practice. Specifically, the validation of the demand data resulted in an r-squared value of 0.72 when the predicted risk values resulting from the use of the model were plotted versus worker risk perception. This result indicates that the demand data were indeed representative of site conditions and that formwork carpenters have a strong sense of the risk involved in their work.

The second validation effort for this project involved confirming the risk mitigation values associated with the implementation of the essential safety program elements obtained from a previous study. This research process involved forming an independent Delphi panel that was asked to rate the relative effectiveness of the safety program elements on a 1–10 scale. The Delphi panels reached consensus (absolute deviation of approximately 1) over the course of three rounds. The resulting ratings indicate that the relative effectiveness of the safety program elements was confirmed for 10 of the 13 program elements. The three exceptions of this validation were safety and health orientation and training, subcontractor selection and management, and written safety and health plans.

Finally, the writers attempted to validate the concept of equilibrium. Unfortunately, the findings were such that the resulting risk for each project, according to the data presented in this research, was zero. Furthermore, all formwork construction processes for these four projects were injury-free. The fact that the formwork processes were injury-free and the equilibrium model predicted zero resulting risk provides moderate evidence that the model is indeed effective. However, the writers believed that reducing risk on a construction site to zero is not possible because, according to risk management theory, it is impossible to reduce probability or severity to zero without avoiding or transferring the risk.

The results of this study indicate that the demand and capacity data are indeed accurate and appropriately used to populate the equilibrium model. It is expected that the model can be used in industry to improve the safety management strategies for all firm types. However, future research is needed to enhance the current model by defining any diminishing returns and interactions that exist when multiple safety program elements are implemented. Additionally, future research that involves the quantification of risk demand for other construction processes would help to enhance the range of applications of the model.

References

Bureau of Labor Statistics (BLS). (2006). "Career guide to industries: Construction." ⟨http://www.bls.gov/oco/cg/CGS003.htm⟩ (June 8, 2008).

Hallowell, M. R. (2008). "A formal model of construction safety and health risk management." Ph.D. thesis, Oregon State Univ., Corvallis, Ore.

Hallowell, M. R., and Gambatese, J. A. (2007). "A formal model of construction safety risk management." *2007 Construction and Building Research Conf. (COBRA)*, Royal Institution of Chartered Surveyors, London.

Hallowell, M. R., and Gambatese, J. A. (2009a). "Activity-based safety and health risk quantification for formwork construction." *J. Constr. Eng. Manage.*, 135(10), 990–998.

Hallowell, M. R., and Gambatese, J. A. (2009b). "Safety risk mitigation." *J. Constr. Eng. Manage.*, in press.

Heath, L., and Tindale, R. S. (1994). *Applications of heuristics and biases to social issues*, Plenum Press, New York.

Hill, D. C. (2004). *Construction safety management planning*, American Society of Safety Engineers, Des Plaines, Iowa.

Hinze, J. (1997). *Construction safety*, Prentice-Hall, Englewood Cliffs, N.J.

Kahneman, D., Slovic, P., and Tversky, A. (1982). *Judgment under uncertainty: Heuristics and biases*, Cambridge University Press, New York.

Linstone, H. A., and Turoff, M. (1975). *The Delphi method: Techniques and applications*, Addison-Wesley, Reading, Mass.

Mitropoulos, P., Abdelhamid, T. S., and Howell, G. A. (2005). "Systems-model of construction accident causation." *J. Constr. Eng. Manage.*, 131(7), 816–825.

J. Constr. Eng. Manage., 2010, 136(9): 981-990

Ramsey, F. L., and Schaefer, D. W. (2001). *The statistical sleuth*, Duxbury, Belmont, Calif.
Starr, C. (1969). "Social benefits versus technological risks." *Science*, 165(3899), 1232–1238.
Thompson, M., Ellis, R., and Wildavsky, A. (1990). *Cultural theory*, Westview Press, Boulder, Colo.
Thorne, M., and Giesen, J. M. (2002). *Statistics for the behavioral sciences*, McGraw-Hill, Boston.
Tversky, A., and Kahneman, D. (1973). "Availability: A heuristic for judging frequency and probability." *Cogn. Psychol.*, 5(2), 207–232.

J. Constr. Eng. Manage., 2010, 136(9): 981-990