Construction Industry Institute®

Precursors of High-impact, Low-frequency Events, Including Fatalities

Research Summary 321-1

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Precursors of High-impact, Low-frequency Events, Including Fatalities

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Contents

Executive Summary

Annual total recordable injury rates have shown great improvement over the past few decades, yet the rate of fatalities appears to have plateaued. Studies of catastrophic incidents in other industries have revealed that high-impact, low-frequency (HILF) events are preceded by events or conditions that can be detected and, if acted upon, can prevent the HILF incident. Although the precursors are often unique to each industry, the methods implemented to identify and analyze precursors are consistent. Using existing precursor analysis programs as guidance, CII Research Team 321 (RT-321) defined HILF events as *high-energy events that result in or have the potential to result in a fatality or life-altering injury or illnesses* and precursors as *reasonably detectable events, conditions, or actions that serve as warning signs of an event.*

The ultimate goal of the research project was to conduct rigorous scientific research that yielded a precursor analysis protocol for construction that would enable practitioners to pursue the following series of steps:

1. Assess conditions in a leading fashion.
2. Identify the presence of precursors, and quantify their extent, in a structured and methodical fashion.
3. Predict and prevent the potential for a HILF event.

In pursuit of this goal, RT-321 addressed the following essential questions:

- Are there precursors to HILF construction events?
- If so, what are they, and how can they be identified, analyzed, and used in a predictive fashion to prevent HILF events?

Addressing these research questions will help to address the fact that fatality rates have recently plateaued or even increased.

By using a combination of literature review, input from industry experts, empirical data collection, a series of randomized and blinded experiments, and objective multivariate statistical analyses, RT-321 was able to achieve the aforementioned goal and exceed original expectations. This project yielded the construction industry's first valid and reliable method for identifying the leading conditions that predict HILF events.

The RT-321 research process delivered the following key findings:

1. The process for predicting a HILF event is far more difficult than conducting a retrospective root cause analysis.
2. Precursors are different from leading indicators, and precursor analysis is different from monitoring and evaluating leading indicators.
3. The quantity of energy that is present in a work operation or condition before an incident occurs is a direct predictor of the severity of an injury.
4. Professionals are able to use the precursor analysis protocol developed in this research and their intuition to correctly predict the occurrence of HILF events with significantly better than random frequency.
5. The errors made in prediction were most often conservative.
6. Mathematical models provide a valid, reliable, and objective method for predicting the occurrence of HILF events.
7. The precursors for fatalities and severe injuries are indistinguishable from those that were involved in high-energy near misses.

RT-321's detailed research findings are presented in Chapter 4. The user-friendly predictive scorecard that RT-321 developed from these findings is the focus of Implementation Resource 321-2, *Guide to Precursor Analysis for Construction Fatalities*.

1

Introduction

In 2015, the U.S. Bureau of Labor Statistics (BLS) released its 2013 census data for work-related fatalities, injuries, and illnesses (BLS 2015). Construction recorded the highest number of fatalities of any industry, with a total of 856. Tragically, this marks the highest number of fatalities in the construction industry since 2009 and, more importantly, highlights the growing concern that the once-declining fatality rate in construction has recently plateaued. As shown in Figure 1, CII data show similar trends.

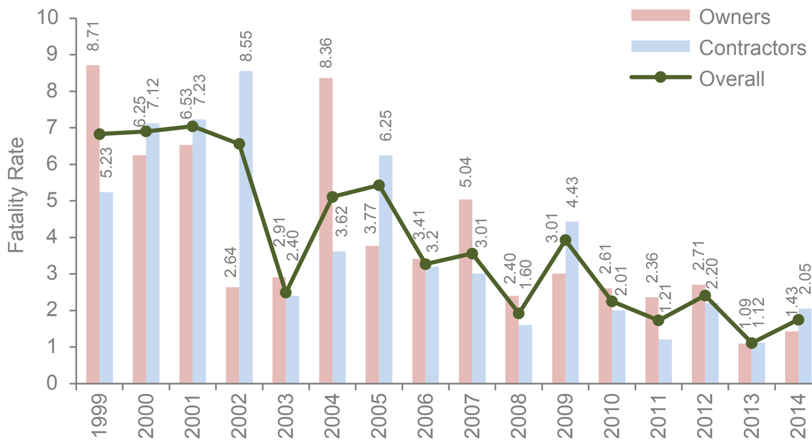

Figure 1. CII-reported Fatality Statistics
(Source: PAC2015-2, *2015 Safety Report*)

As these data suggest, there is a need for new injury-prevention methods that focus purely on the fatalities that continue to plague the industry. Enhancing traditional safety methods and using leading information to predict and prevent catastrophic fatalities are logical next steps for the industry. Research Team 321 (RT-321) addressed the observed problem by tackling the following research questions: *Are there precursors to HILF construction events? If so, what are they, and how can they be identified, analyzed, and used in a predictive fashion in order to prevent the occurrence of HILF events?*

In designing the research process, RT-321 relied heavily on other industries' successfully designed and implemented precursor analysis programs. In particular, NASA's Accident Precursor Analysis (APA) program, the aviation industry's Aviation Safety Action Program (ASAP), and the nuclear industry's Accident Sequence Precursor (ASP) program provided guidance.

Each industry has a unique set of precursors that relates to its distinct tasks, environments, and risks; however, despite the differences in precursors among industries, the underlying logic and structure of the precursor analysis processes are surprisingly similar. In fact, the protocols used to create the precursor analysis processes can all be segmented into three fundamental steps:

1. an in-depth deterministic analysis of past incidents to identify precursors
2. development of a system for incident investigation with specific information criteria to support data collection *in a leading fashion*
3. a probabilistic risk assessment based on continuously updated information regarding operations.

All industries place emphasis on the leading and predictive nature of their programs, and RT-321 followed this same general method.

2

Research Overview

The RT-321 research process was both complex and extensive. To enhance the readability of this report, the team organized the summary as a series of phases, with each involving a specific theme. These phases are illustrated in Figure 2, which can be used as the map for this research summary. Because this research process involved many interdependent phases, each section follows the same format: objectives and summary, methods, and results. Each phase also includes a figure that follows the format in Figure 3.

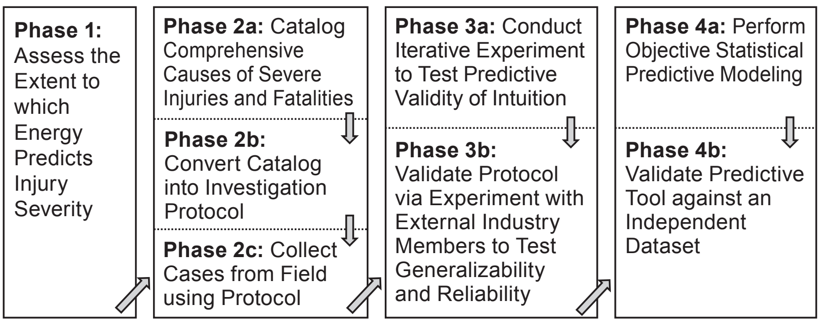

Figure 2. Overarching Research Process and Organization of this Summary

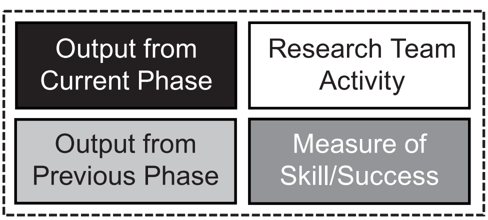

Figure 3. Figure Key Showing the Color Scheme Used in Each Figure

Phase 1: Assess the Extent to which Energy Magnitude Predicts Injury Severity

> **Objective 1:** *Define the "high-energy" threshold by testing the hypothesis that the quantity of energy in an environment is a direct predictor of the potential severity of an event.*

Because precursor analysis is resource-intensive, it is not realistic to implement it before every work period. Thus, the research process began by addressing a core question: *When do conditions exist that have the potential to cause a HILF event?* Suppose a painter is working in isolation, in a well-ventilated space, with low volatile organic compound paint, on a level ground surface clear of debris, and away from all other activities and equipment. It is reasonable to assume, under these benign conditions, that a HILF event is very unlikely if not impossible, simply because there is not enough danger in the environment. Conversely, suppose a crew of workers is installing a large pipe spool 40 feet from other active crews. Obviously, this situation possesses the characteristics that could possibly lead to a HILF event. Based on these types of observations, RT-321 offered the following hypothesis: *The quantity of energy in an environment before an incident occurs directly predicts the severity of an injury.* If this hypothesis is correct, then the team could obtain empirical evidence for a specific energy threshold that defines the HILF boundary.

The team felt that it was critical to test this hypothesis, because it provides scientific justification for when to initiate a precursor analysis process. Unlike NASA launches, commercial flights, and nuclear power plant operation—where conditions are highly controlled, vary minimally, and continuously involve extreme amounts of energy—construction activities are diverse and range greatly in the amount of energy present at any given time. Thus, the industry needs some form of a gateway to initiate a precursor analysis process. The team postulated that the quantity of energy could serve as such a gateway. Although it was deeply rooted in logic and intuition, this theory had never been formally tested in the construction industry.

Phase 1 Methods

Testing the team's hypothesis required an objective analysis to investigate the relationship between the severity of worker injury and the characteristics of a hazard energy that existed *before* the injury occurred. To achieve this, the team analyzed 505 injury cases using the process shown in Figure 4.

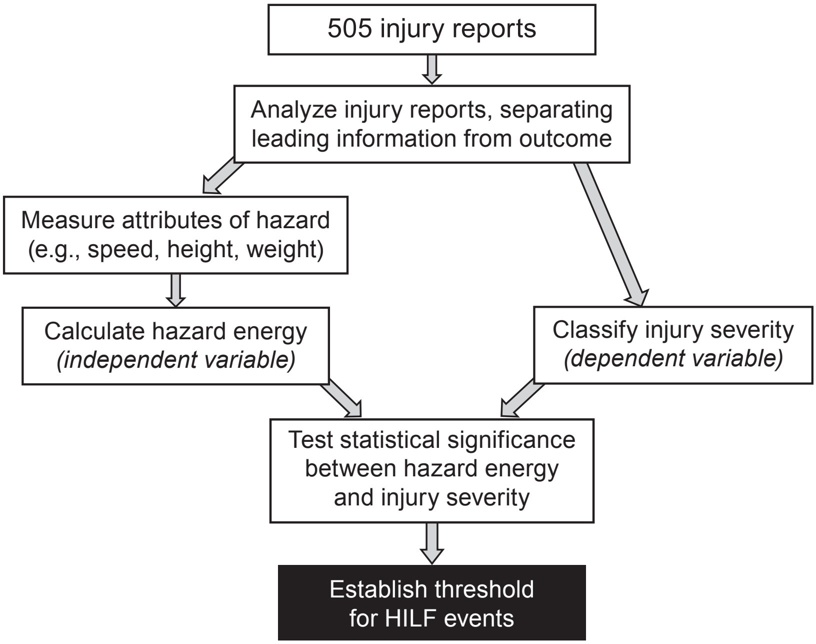

Figure 4. Research Process Implemented to Define the High-energy Threshold for HILF Events

Processing the injury report data first involved separating the independent predicting variable, *hazard energy magnitude*, from the dependent variable, *injury severity*. Using only descriptions of conditions contained within each written injury report, RT-321 researchers estimated the magnitude of energy preceding each injury by estimating height, weight, speed, and other physical characteristics of the equipment, tools, material, and workers. Once the team had obtained energy values for each report, these values were statistically compared to the actual severity of the injuries sustained. The sample included first aid (n=55), medical case (n=113), lost work time (n=280), and fatality (n=57) cases.

Phase 1 Results

The distribution of hazard energy magnitude within each severity classification was visualized with box plots showing the minimum, 25th percentile, 50th percentile, and 75th percentile, and maximum values. As Figure 5 shows, the distribution of energy magnitude is starkly different across severity levels. The red dashed line illustrates the selected high-energy threshold of 1,500 ft-lbs. Although very few fatal or near-fatal events occurred with energy levels lower than 1,500 ft-lbs, this value still involves a highly conservative choice. For reference, 1,500 ft-lbs is equivalent to an average-sized male worker at an elevation of eight feet.

Phase 2: Identify Potential Precursors, Build a Precursor Questionnaire, and Collect Cases

Objective 2a: *Create a comprehensive catalog of potential precursors to HILF events.*

Objective 2b: *Convert the comprehensive catalog of potential precursors into a questionnaire that can be used to determine the presence or absence of each precursor before a work operation begins.*

Objective 2c: *Deploy the questionnaire in the field to collect data for cases where high energy was successfully managed, there was a high-energy near miss, or a severe injury or fatality occurred.*

The team needed a starting point from which a precursor analysis process could be developed. The team decided that a list of potential precursors could be developed based on current literature and team experience, and then used as a means to craft a precursor analysis protocol. Additionally, the potential precursors were to come from actual construction work and incidents, in order to be representative of and generalizable to the construction industry. This list was intentionally comprehensive to begin with, and then refined to create an accurate process that could be realistically implemented.

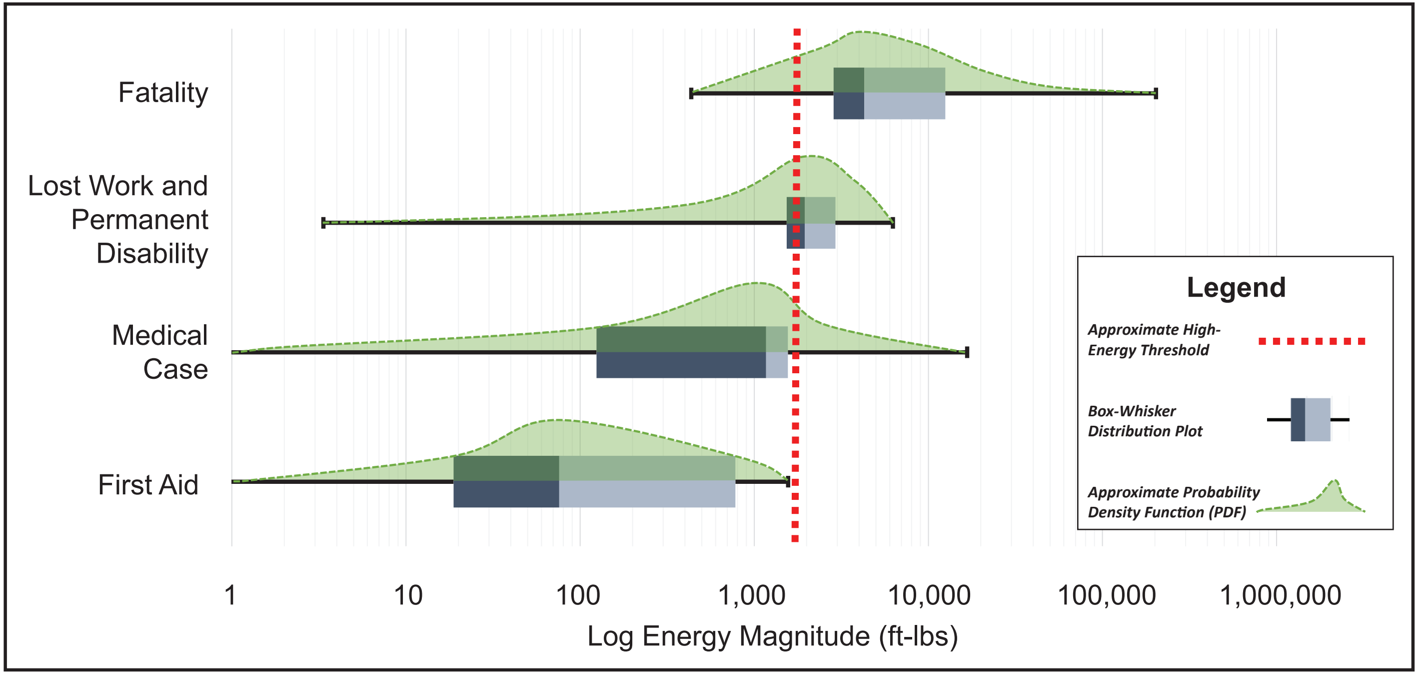

Figure 5. Box Plots Showing the Distribution of Energy for Each Injury Severity Level

In order to conduct the iterative experiment, the team needed examples of work operations from past or ongoing construction projects (cases). To assess the value of the potential precursors and ability of personnel to use the precursors to predict a HILF, cases with different outcomes were needed. In order to generalize the results to the entire industry, the team desired cases that involved different types of work, and different types and levels of energy present.

Phase 2 Methods

Identifying Potential Precursors

Potential precursors were identified through the four-step process shown in Figure 6.

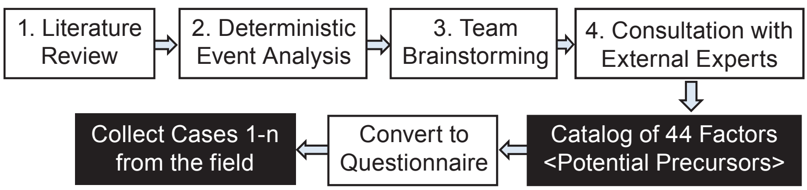

Figure 6. Process Used to Create a Comprehensive List of Potential Precursors of HILF Events

1. Literature Review

The team reviewed all available literature pertaining to precursor analysis, focusing primarily on the most successful precursor programs and the limited research in construction. Fortunately, NASA, the nuclear industry, and aviation industry all have publicly available handbooks providing lists of immensely detailed precursors (DOT_FAA_AFS-230, 2002; IAEA, 2004; NASA/Sp-2011-3423, 2011; Wiegmann and Shappell, 2001). In addition to these resources, the body of literature related to the causes of construction fatalities was reviewed and catalogued. Forty-four potential precursors were identified through the various means described below, and then cross-referenced with literature.

2. Deterministic Event Analysis

In order to supplement the literature review with empirical data, the team performed a deterministic event analysis of past construction fatalities and disabling injuries. The deterministic event analysis involved uncovering the immediate causes of each injury by considering human error, management, social climate, worker demographics, work conditions, and organizational influences. Once the immediate causes were uncovered, the team examined the reasons why the conditions existed, to uncover latent precursors (e.g., lack of training specific to work, inexperience). A strength of the deterministic analysis process in this research was the team's collective 308 years of industry experience and the fact that all members had been professionally trained and educated in accident causation and investigation techniques.

3. Team Brainstorming

One of the team's concerns with identifying precursors from the literature review and deterministic event analysis alone was that some precursors would remain latent, because they had not been documented by an incident investigator. Thus, the team used its experience to document other precursors that they had witnessed over their careers. The group brainstorming took place during the first day of a two-day, face-to-face meeting. Because the team was comprised solely of construction safety experts, the team aimed to involve experts from other fields to broaden the scope.

4. Consultation with External Experts

On the second day of the face-to-face meeting, five outside experts were consulted: an attorney, a risk consultant, an OSHA inspector, an applied psychologist, and a human factors engineer. The experience of these consulted individuals ranged from 10 to 35 years in their respective professions. The interaction between 14 construction industry experts and five external consultants offered a rare opportunity to uncover precursors that might not have been easily recognized without interdisciplinary training. In total, 13 new precursors were identified through this process.

Building a Precursor Questionnaire

Once RT-321 had identified a comprehensive list of potential precursors, its next goal was to design a question or series of questions that could be asked in the field in order to identify and quantify the presence of a potential precursor. For example, one potential precursor was *working alone*. To collect information in a leading fashion in the field, the following questions were designed: "*Where will everyone be working?*" and *"Will anyone be working out of sight or earshot of others for any period of time?"* As one might imagine, the result was a long questionnaire that took over an hour to administer. Fortunately, in later phases the team reduced this time burden to approximately 20 minutes.

Collecting Cases from the Field

Once the team had created the precursor questionnaire, its next step was to collect as many cases from the field as possible, in order to test a person's ability to use the questionnaire to predict a HILF. Since implementing the questionnaire was time-intensive, each case was crucial to the effort. The goal was to establish a sample of cases with a relative distribution of: three cases where high energy was present but no energy was released (success); one case where high energy was present and released but, due to luck, no one was injured (near miss); and another case where high energy was present and, unfortunately, one or more workers was severely injured or killed (fatality or disabling injury).

Phase 2 Results

In all, 44 potential precursors were identified. (The entire catalog is available in Research Report (RR) 321-11, *Precursor Analysis for the Construction Industry: A Systematic Method for Predicting and Preventing Fatal and Disabling Injuries*.) Once the precursors were translated into a questionnaire, 26 cases were collected from the field, representing work from 10 trades in six countries, and from projects that varied in size, complexity, and industry sector. Given such a distribution, the researchers believe that the dataset was representative of the construction industry as a whole.

Phase 3: Assess Predictive Validity of Potential Precursors through a Series of Randomized Experiments

> **Objective 3a:** *Conduct a controlled, randomized experiment to measure the extent to which the expert team could distinguish between successful energy management and HILF events by using only the leading information captured in the precursor analysis questionnaire.*
>
> **Objective 3b:** *Conduct the same controlled, randomized experiments with external industry members with modest experience and with individuals with little to no safety experience.*

The utility of a precursor analysis process is the minimization of bias and subjectivity in its development. A randomized, controlled experimental process provides a means by which bias and subjectivity can be eliminated, and effectiveness can be quantified with confidence. For safety research, it is unethical to expose workers to new hazards or allow workers to be exposed to existing conditions that are known to contribute to HILF events. Therefore, RT-321 chose an experimental process that used descriptions of actual work operations and conditions, along with an evaluation of skill in predicting outcomes. The experiment permitted reliable validation of the precursors and precursor analysis process without subjectivity or exposing workers to safety risks.

Recognizing that skill at predicting outcomes is dependent on personal background and experiences, the team sought to control for this variable by using subjects with different backgrounds and levels of experience. To do so, the team relied upon experts within the research team, along with others who had modest levels of experience. In addition, participants external to the research team were targeted. Since team members were knowledgeable about and intimately involved with the research topic, premises, and activities, their involvement in the experiment could have been a factor that influenced their skill at predicting case outcomes correctly.

Phase 3 Methods

This phase involved two efforts: a primary experiment and a series of validation experiments. Although the protocol was essentially the same, there were subtleties that are important to distinguish.

Primary Experiment

The core activity of this research team, which consumed nearly a year of the process, involved a randomized, controlled, iterative experiment. The goal of the experiment was to measure the extent to which experts could use *only the leading information* captured by the precursor questionnaire and their intuition to correctly predict the outcome of a series of cases. This research process is depicted as Figure 7.

In total, 19 original cases, all involving high energy, were used in the primary experiment with the following distribution: nine successes, seven high-energy near misses, and three fatal or disabling events. Cases were randomly assigned for inclusion in four rounds of an experiment in a stratified fashion. That is, in each round, five cases were randomly selected from the general pool, where at least one case was fatal or disabling, one case was a near miss, and at least two cases were successful. The stratified sampling procedure is illustrated as Figure 8. The goal of such stratification was to focus team attention on distinguishing between success and failure, with failure defined as either a near-miss event or a disabling/fatal event occurring.

The information gathered from each questionnaire was scrubbed by the academic members of the team to ensure that only leading information was present. This involved changing tense and subtleties in the wording but not the essence of the response. Only the academic team members and one other member of the team who collected the case from the field were aware of the actual outcome. The remaining team members (at least seven for each case) were charged with:

1. reviewing the responses to the case
2. identifying whether each factor was present, might have been present, or was not present for each case
3. predicting the outcome of each case.

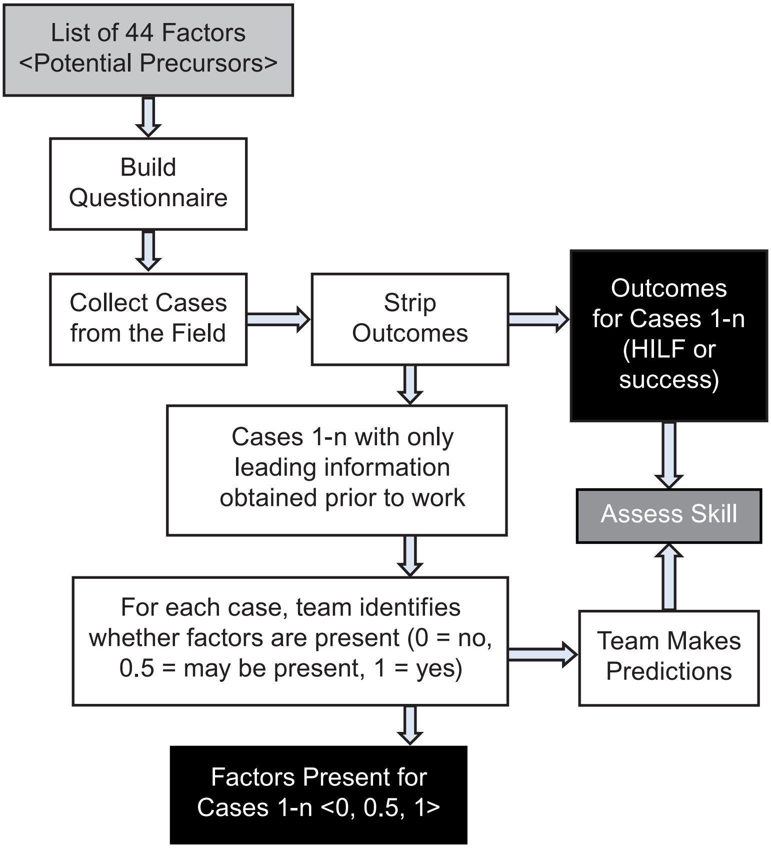

Figure 7. Overarching Research Process for the Iterative Experiment

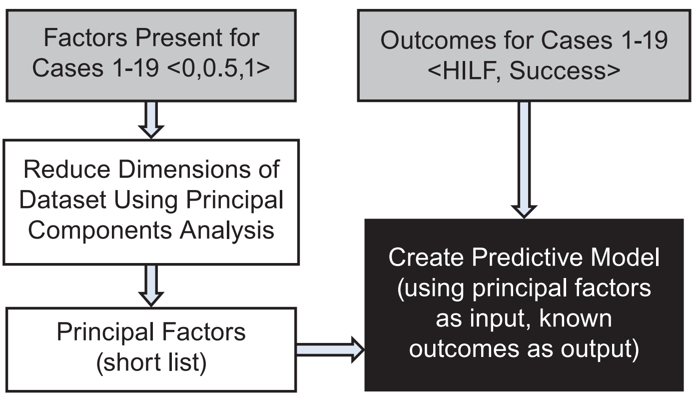

Figure 8. Statistical Modeling Techniques to Create a Predictive Model

As the team reviewed and made predictions on each case, two forms of output were provided. First, the team assessed the extent to which each factor was present, where 1 represents that the factor definitely was present, 0.5 represents that the factor may have been present, and 0 represents that the factor definitely was not present. Such an assessment was made for all factors in each case, and for all cases, resulting in a dataset of 44 factors by 19 cases. Second, the team made predictions of the outcomes of the cases. Only at the end of each round were the results from the round revealed. At no time did the team know the distribution of cases in the pool from which the cases were drawn, to prevent compromising the validity of future rounds. The team initially provided their prediction based on their own evaluation of the case without any consultation with other team members. After each team member recorded his or her prediction, the team was permitted to collectively discuss the case.

Validation Experiment

Although the primary experiment was rigorous and valid, its participants were the experts from RT-321—the same experts who designed the protocol. Thus, to improve the generalizability of the results, the team aimed to validate the experimental results with a group of industry professionals with modest experience who were not involved in the creation of the protocol, and a group of students who represent novice professionals. In total, 13 professionals and 23 students participated in the validation experiments following the same general protocol.

Phase 3 Results

Primary Experiment

The results of the experiment were surprisingly strong, with 84 percent of cases correctly predicted by the team; that is, in 84 percent of the cases, the majority of the team members correctly predicted the outcome of the case, whether a near-miss or a disabling or fatal injury. Such skill is significantly better than random (p-value = 1.6×10^{-5}). The stop criterion (a minimum of four out of five cases, or 80 percent, in two consecutive rounds of five) was met after the third iteration. However, the team continued with a fourth round to obtain enough data for subsequent statistical modeling. The results of the primary experiment are shown in the experiment/intuition column of Table 1, in Chapter 3. It is important to reiterate that this primary experiment only involved the precursor questionnaire and the expert panelists' intuition. Subsequent statistical predictive models returned even better results.

As the team quickly learned, the precursors were indistinguishable between fatalities or disabling injuries and high-energy near misses. Thus, the team considered the selection of near miss for a fatal or disabling event to be correct and vice versa. Incorrectly identifying a success case as a HILF event (false negative error) was preferred over incorrectly identifying a HILF case as success (false positive error), but both were reported as incorrect predictions in the results.

Validation Experiment

The precursor analysis process was also externally tested with individuals not involved in the research using the same experimental procedure previously described. Participants with industry experience ranging from one to 44 years reviewed 16 randomly-selected cases. In total, they correctly predicted 12 of 16 cases (75 percent). Although the research team proved to be more accurate, a prediction skill of 75 percent was still far better than random (p-value: 0.016). These results provide evidence of external validation of the tool and confirm the participants' need for practice and expertise to achieve the highest levels of skill.

Phase 4: Assess Predictive Validity with Statistical Modeling

Objective 4a: *Build an objective statistical model that can reliably predict the correct outcome of a case using only leading information as an input.*

Objective 4b: *Measure the extent to which the model predicts the outcome of new cases that were not used to build the original model.*

Ultimately, the goal was to produce a valid, reliable, and efficient resource for precursor analysis and HILF event prediction. If successful, an objective statistical model could reduce variability and bias in the process and provide scientific backing for important and sometimes resource-intensive decisions. Possessing such a resource would enable the construction industry to predict and prevent disabling injuries and fatalities on construction sites—the overall goal of the research. The goal would be achieved if the model were able to predict the outcomes of the new cases better than random, and better than an individual could do without the model.

Phase 4 Methods

The statistical modeling took the form of a two-step process. First, the number of potential precursors was reduced to a set of principal factors by using principal components analysis (PCA). The number of potential precursors needed to be reduced because there was not enough statistical power with the limited sample of cases. Second, following data reduction through PCA, a predictive model was created using generalized linear modeling (GLM). This model was built using the cases from the experiment. The expert group's assessments whether factors were present served as the input (independent predictor variable), and the actual outcome of the case was used as the model output (dependent predictor variable). Thus, the input data were contained in a matrix of 19 cases by 16 principal factors, and the output variable was modeled as an array of 19 outcomes. These two statistical modeling steps were shown in Figure 8 (on page 13) and are explained in greater detail below.

Before any data reduction was implemented, RT-321 reviewed the precursor analysis questionnaire and the list of precursors to identify redundancy or any way by which several potential precursors could be combined into one more inclusive, higher-level variable. For example, *new workers to the site* and *new workers to the organization* were combined into the factor *new workers to the organization or site,* because these factors essentially captured the same fundamental vulnerability. Also, *payment system* (e.g., lump sum or cost plus) was removed because other factors captured the natural implications of the payment system (e.g., *productivity pressure*), and the manifestation of this potential precursor with the crew and the specific work was deemed to be more relevant. (A complete discussion of this process, including the specific reasoning for any omission or combination of potential precursors, is provided in RR321-11.) By employing this method, the team logically combined or removed 14 factors, yielding a set of 30 potential precursors. PCA was then applied to this new set of variables for further data reduction.

1. *Reduce the Dimensions of the Dataset Using Principal Components Analysis (PCA).*

A matrix of 19 cases by 30 potential precursors represented the independent variable at this stage. Each case represented a row and each item in that row corresponded to the presence or absence of one of the 30 potential precursors. PCA was used to find natural precursor themes within the dataset—termed *principal factors*—that captured the greatest amount of variability. For example, the potential precursors *crew members unaware of standard operating procedure*, *poor plan to address work changes*, and *poor pre-task plan* were found to define the thematic principal factor *poor work planning*. Although each of these variables is different, they shared a common theme and, statistically, could be modeled together as a single variable.

2. *Create a Mathematical Model to Predict Outcomes and Distinguish between HILF Cases and Success Cases.*

Using the principal factors from Step 1 as input, the team created an objective predictive model by using a Generalized Linear Model (GLM). The outcome of this step is a simple equation that uses the presence or absence of precursors as an input that yields a probability estimate for the occurrence of a HILF event. Since the mathematics and mechanics of creating a GLM are complex, the reader is referred to RR321-11 for the details of this process.

3. *Measure the Extent to which the Model Predicts the Outcome of New Cases that Were Not Used to Build the Original Model.*

The final step in the statistical process involved measuring the extent to which the GLM predicted the correct outcomes of new cases better than random. The team did not expect a perfect prediction for every case, in the same way that it is unreasonable to expect weather predictions to be correct every day. Instead, the team intended to measure the extent to which the model was better than random and, hopefully, better than intuition. In order to make this measurement, the team collected 10 new case questionnaires, stripped outcome information, reviewed the responses to assess the extent to which each factor was present, and used the resulting assessment as input to the model. Then, the output of the model was compared with the actual outcomes. Figure 9 depicts this process.

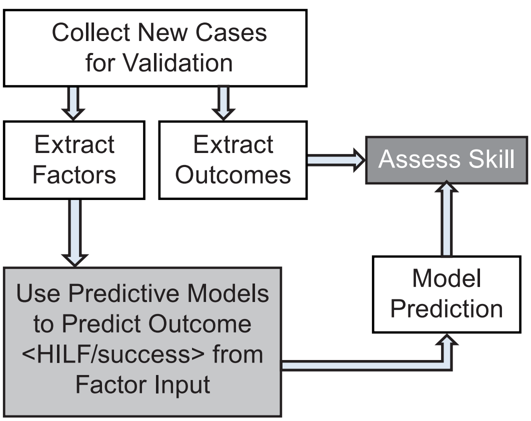

Figure 9. Statistical Validation Procedure

Phase 4 Results

The PCA returned four principal factors defined by a total of 16 constituent factors. These principal factors and their constituents are summarized in Figure 10 in the next chapter. By reducing the number of predictor variables from an original set of 44 to a set of 16 that still captures the vast majority of the data structure, the feasibility of the resulting tools increases substantially, because a prediction can be made with a third of the questions. It is important to note that the principal factors shown in Figure 10 were not determined by RT-321; rather, they were statistically derived, but then subsequently labeled by the research team. Thus, some constituent factors may seem logically “out of place” with a named theme (e.g., prior safety performance is poor as a part of productivity-dominated culture). The team did not attempt to make adjustments or correct these groupings; rather, the team aimed to measure the overall skill in predicting outcomes.

3

Precursor Analysis Tool

Because applying a GLM in practice would be cumbersome and burdensome, the team translated the GLM into a simple, easy-to-use scorecard for assessing an operation. The scorecard for making such an assessment is shown in Figure 10, and fully presented in Implementation Resource 321-2, *Guide to Precursor Analysis for Construction Fatalities*.

Mark the presence of each factor by using the numeric scale below:

1 = Precursor Is Present *½ = Precursor Is Partially Present* *0 = Precursor Is NOT Present*

Poor Work Planning	Factor Presence	Weight	Weighted Score
Crew Members Are Unaware of Standard Operating Procedures		×1	
No or Poor Plan to Address Work Changes		×1	
No or Poor Pre-task Plan or Discussion Specific to Work		×1	
Productivity Safety Stressors	**Factor Presence**	**Weight**	**Weighted Score**
Significant Overtime		×2	
Fatigue		×2	
Schedule/Productivity Pressure		×2	
Prior Safety Performance Is Poor		×2	
Crew Members Are NOT Active in Safety		×2	
Vulnerability to High Energy	**Factor Presence**	**Weight**	**Weighted Score**
Lack of Control Barrier and/or Visual Warning		×2	
Line of Fire Is Uncontrolled		×2	
Improvisation		×2	
Outside Safety Influences	**Factor Presence**	**Weight**	**Weighted Score**
Limited Safety Supervision		×1	
Poor Quality or Inexperienced Foreman		×1	
Distracted Workers		×1	
Working Alone		×1	
Congested Workspace/Crowding		×1	
Total Score *(if this score is equal to or greater than 4, a HILF is predicted)*			

Figure 10. Simplified Precursor Scorecard

In order to assess the ability of this simplified method to make correct predictions, it was applied to all cases. The result was that the simplified precursor analysis tool was able to correctly predict 90 percent of cases when a threshold of 4 was used. Table 1 compares the performance of experts who used intuition in the experiment for the first 19 cases with the complex generalized linear model and the simplified model. As one can see, the complex mathematical model was the best predictor, but also the most burdensome. Alternatively, the simplified method performs as well as the complex model while requiring less effort and time, and performs better than the panel of experts using intuition. In addition, for those cases that were not predicted correctly using the simplified method, the threshold of 4 provides a conservative assessment, i.e., the method predicts a HILF event when a success actually occurred (Type 1, false positive error), but not vice versa (Type 2, false negative error).

Table 1. Comparison of Predictive Skill for Experts, Regression Model, and Simplified Method

Case #	Actual Outcome	Experiment (Intuition) Skill	Regression Model HILF Event Probability (Percentage)	Regression Model Skill	Precursor Assessment Rubric Score	Precursor Assessment Rubric Skill
Cases Used for Experimentation and Initial Model Building						
4	Success	Correct	32.3	Correct	1	Correct
3	Near Miss	Correct	89.8	Correct	14	Correct
2	Success	Incorrect	49.6	Correct	4	Incorrect
5	Success	Incorrect	49.6	Correct	4	Incorrect
1	Fatal/Disabling	Correct	87.6	Correct	13	Correct
16	Near Miss	Correct	87.1	Correct	12	Correct
14	Success	Correct	49.6	Correct	3.8	Correct
6	Success	Correct	26.9	Correct	0	Correct
9	Fatal/Disabling	Correct	64.8	Correct	7	Correct
11	Near Miss	Correct	94.2	Correct	15	Correct
20	Near Miss	Correct	50.4	Correct	4	Correct
8	Success	Incorrect	40.9	Correct	3	Correct
15	Near Miss	Correct	81.7	Correct	9	Correct
13	Fatal/Disabling	Correct	50.4	Correct	5	Correct
12	Success	Correct	29.3	Correct	1	Correct
7	Near Miss	Correct	94.0	Correct	15	Correct
18	Success	Correct	38.7	Correct	2	Correct
17	Near Miss	Correct	85.9	Correct	11	Correct
24	Success	Correct	36.9	Correct	2	Correct

Table 1. Comparison of Predictive Skill for Experts, Regression Model, and Simplified Method *(continued)*

Case #	Actual Outcome	Experiment (Intuition) Skill	Regression Model HILF Event Probability (Percentage)	Regression Model Skill	Precursor Assessment Rubric Score	Precursor Assessment Rubric Skill
Cases Used for Statistical Validation						
22	Near Miss	NA	73.3	Correct	7.5	Correct
10	Near Miss	NA	54.3	Correct	5	Correct
19	Near Miss	NA	62.4	Correct	6	Correct
27	Success	NA	36.3	Correct	2	Correct
21	Near Miss	NA	58.1	Correct	5	Correct
23	Near Miss	NA	76.3	Correct	8	Correct
24	Near Miss	NA	71.6	Correct	8	Correct
25	Near Miss	NA	56.1	Correct	4.5	Correct
26	Near Miss	NA	78.4	Correct	8.5	Correct
28	Near Miss	NA	65.5	Correct	6	Correct

4

Findings

The ultimate goal of the Research Team 321 (RT-321) project was to conduct rigorous scientific research that yielded a precursor analysis protocol for construction that enables practitioners to pursue the following series of steps:

1. assess conditions in a leading fashion
2. identify the presence of precursors, and quantify their extent, in a structured and methodical fashion
3. predict and prevent the potential for a HILF event.

By using a combination of literature review, input from industry experts, empirical data collection, a series of randomized and blinded experiments, and objective multivariate statistical analyses, RT-321 was able to achieve the aforementioned goal and exceed original expectations. This project yielded the construction industry's first valid and reliable method for identifying leading conditions that predict HILF events. Figure 11 is the most elegant summary of the results.

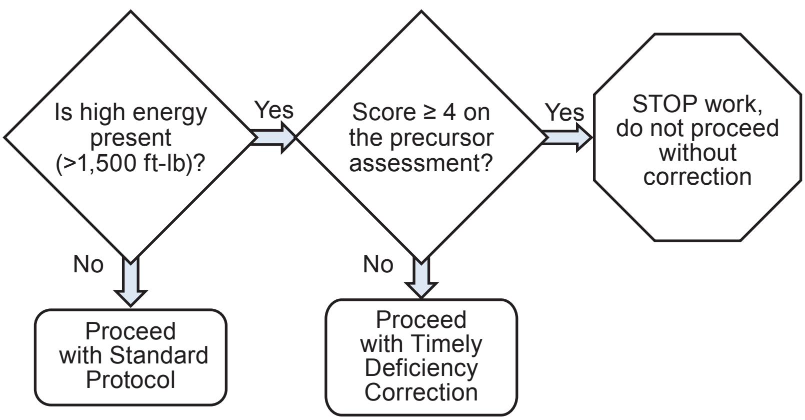

Figure 11. Recommended Precursor Analysis Process

As Figure 11 shows, first one must assess energy magnitude. If energy is high (greater than 1,500 ft-lb), the precursor analysis protocol should be deployed and the results should be assessed. If the results of the precursor analysis indicate that the workers are at high risk (i.e., score of 4 or greater on the protocol), the work should be stopped immediately and not released until corrective action has been taken. A precursor score of 4 or above in a high-energy situation indicates that there is high risk of a HILF event occurring *and* that key elements of vulnerability are present, which is an extremely disconcerting couplet. This guidance is based on empirical data, scientific experimentation, and conservative recommendations from experts in construction safety.

The RT-321 research process delivered the following key findings:

1. **The process for predicting a HILF event is <u>far</u> more difficult than conducting a retrospective root cause analysis.** The construction industry is relatively adept at performing retrospective root cause analyses of safety events. However, the transition from a retrospective analysis to a predictive analysis proved to be extremely difficult, even for the industry-leading experts on this team. With the precursor analysis protocol, the approach became methodical, efficient and, most importantly, accurate—the predictions far outperformed the original goals.
2. **Precursors are different from leading indicators, and precursor analysis is different from monitoring and evaluating leading indicators.** Previous CII research by RT-284 exposed the importance of identifying and monitoring leading indicators of safety performance. Although leading indicators provide a means to assess overall safety performance on a project, precursors indicate the likelihood of an injury incident's occurring during a specific work operation. Precursor analysis is also designed to be conducted at the workface to assess planned or ongoing work operations at the worker and task levels. Both monitoring of leading indicators and precursor analysis are essential.

3. **The quantity of energy that is present in a work operation or condition before an incident occurs is a direct predictor of the severity of an injury.** It is not feasible to conduct a precursor analysis for all construction tasks on every project. The time and resources required are simply too burdensome. Thus, the industry needed guidance on when to initiate the precursor analysis process. The RT-321 philosophy was that a precursor analysis should be conducted any time the work situation had the potential to be fatal or life-altering. In order to assess this potential objectively, the team tested the hypothesis that the quantity of energy present before an incident occurs directly predicts the severity of an injury. An analysis of 505 cases showed that energy magnitude does, indeed, predict injury severity, and a threshold of 1,500 ft-lbs defines a boundary above which a HILF event is very likely.
4. **Professionals are able to use the precursor analysis protocol developed in this research and their intuition to correctly predict the occurrence of HILF events with significantly better than random frequency.** Not all high-energy situations involve injury. The core of this research involved a blind, randomized experiment designed to measure the extent to which professionals with varying levels of expertise could distinguish between HILF cases and success cases when presented only with leading information obtained through a conversation with workers prior to or during the work. The results showed that industry professionals with five or more years of safety experience were able to predict the correct outcomes and distinguish HILF cases from success cases far better than random (p-value < 0.01).
5. **The errors made in prediction were most often conservative.** When using intuition to distinguish between successful and HILF cases, all errors involved the prediction of HILF events when the scenario was actually successfully completed without an injury. Despite a limited sample size, there were no instances where the majority of participants incorrectly predicted success for an actual HILF event.

6. **Mathematical models provide a valid, reliable, and objective method for predicting the occurrence of HILF events.** The gold standard for this research was the creation of a data-driven objective method for predicting HILF events that complements intuition and experience. Using the data extracted during the iterative experiment and the known outcomes, RT-321 created a generalized linear model that was able to predict the outcomes of new cases with nearly perfect skill. This model was translated into a user-friendly scorecard, which is the focus of Implementation Resource 321-2, *Guide to Precursor Analysis for Construction Fatalities*.

7. **The precursors for fatalities and severe injuries are indistinguishable from those that were involved in high-energy near misses.** Many industry professionals are beginning to share the sentiment that near misses should be analyzed and treated as if they were events that resulted in actual injuries. This research revealed that there is no significant statistical distinction between the precursors for events that result in fatalities, disabling injuries, and the precursors of high-energy near misses (p-value = 0.21). This is empirical evidence that high-energy near misses are, in their essence, HILF events and should be treated the same as actual fatalities. They should trigger serious organizational investigations and be used as vital data for bolstering precursor analysis and other safety programs.

5

Conclusions and Recommendations

The drive to zero injuries and fatalities on construction jobsites continues to stimulate development of new ideas and resources for improving worker safety. Current rates of fatalities and disabling injuries in the construction industry highlight the need to focus safety efforts on high-impact, low-frequency (HILF) injury events. Precursor analysis programs present in other industries have proven to be successful in preventing HILF events. With the programs in other industries as inspiration, RT-321 felt that the construction industry could benefit from a precursor analysis process tailored to the unique aspects of construction operations. Using a rigorous, multi-phased, scientific approach, the research team successfully accomplished the task of developing a precursor analysis process for use on construction projects.

The research study revealed important insights into precursors to HILF events and the ability to predict HILF events, a skill that is far more difficult, yet more effective in preventing injuries and fatalities, than retrospective root cause analysis. The energy associated with a work operation provides an operational gateway to predicting HILF events; the release of a high level of energy correlates to high-severity injuries. When the level of energy is high, and considering the possibility of both near misses and disabling injuries or fatalities, the precursors to near-miss events and HILF events are indistinguishable. As a result, in the context of precursor analysis, near misses are in essence potential HILF events and should be treated in the same manner as HILF events.

When a high level of energy is present, the precursor analysis process developed by RT-321 increases the success with which a construction professional can predict a HILF event. Precursors are different from leading indicators, and precursor analysis is different from monitoring and evaluating leading indicators. The process, developed based on rigorous and reliable statistical analysis, consists of onsite observations and interviews to assess the presence of 16 highly effective precursors.

The 16 precursors are grouped into four principal components (i.e., Poor Work Planning, Productivity Safety Stressors, Vulnerability to High Energy, and Outside Safety Influences) that help organize the precursor analysis process and provide overarching guidance to safety management. Quantitative assessment of the precursors is then used to assign an operation an overall score that sheds light on the potential for a HILF event. Whether using the precursor analysis process or not, errors made in prediction are most often conservative, i.e., a HILF event is predicted when the operation is actually successfully completed without injury or near miss.

RT-321 recommends that construction firms use the precursor analysis process it has developed. The precursor analysis protocol produced by the research study provides construction professionals with a highly reliable means to positively affect worker safety. Implemented diligently and during critical operations, the process enables construction professionals to determine whether work should be stopped to prevent a potentially impending HILF event. This ability, when complemented by traditional safety best practices, greatly strengthens safety management capabilities on projects.

Each firm should carefully determine when and by whom the process should be implemented. Implementing the process for all activities is likely economically infeasible. Implementation by project staff who have a greater amount of construction site experience increases its accuracy. Importantly, the research undertaken to develop the precursor analysis process underscored the need to embrace active assessment of safety implications in the presence of the work operations, and assessment that includes input from and observation of those who are conducting or will conduct the work. Further research that targets active recognition and assessment of safety implications (e.g., work pressures, distractions, and human factors) would strengthen the precursor analysis process developed and take another step toward zero injuries.

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