Attribute-based Risk Model for Assessing Risk to Industrial Construction Tasks

by

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B.S./M.S, Universitat Politècnica de Catalunya, 2013

A thesis submitted to the

Faculty of the Graduate School of the

University of Colorado in partial fulfillment

of the requirements for the degree of

Master of Science

Department of Civil, Environmental, and Architectural Engineering

2014

This thesis entitled:

Attribute-based Risk Model for Assessing
Risk to Industrial Construction Tasks

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has been approved for the

Department of Civil, Environmental, and Architectural Engineering

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Date: November 14, 2014

The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline.

IRB protocol #: 14-0051

Prades Villanova, Marc. (M.S., Civil Engineering)

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Thesis directed by Prof. Matthew R. Hallowell

Due the saturation of the traditional injury prevention strategies in the industry, risk-based safety innovations are emerging. However, application of risk-based strategies is very limited because: (1) there is a dearth of robust empirical databases; (2) the granularity of risk analysis methods is limited to trade/task-level risks; and (3) interactions among risk factors is not considered. In order to address these limitations, this thesis focuses on quantifying attribute-level risks for industrial construction projects using empirical data contained in 1,611 injury reports. An iterative content analysis was employed with a team of analysts in order to identify attributes, outcomes, and energy sources. The resulting data were analyzed, along with an exposure database provided from industry, in order to quantify relative risks. Finally, a Monte Carlo simulation was performed in order to interpret the risk of new safety scenarios.

Acknowledgements

The authors of this paper would like to acknowledge the work of all the members that collaborate in this research. Dean Bowman and Adam Klatzkin from Bentley Systems and John Barry from SABIC Plastic, as well as all the researchers from the academia as Alex Albert from North Carolina State University, and Antoine Tixier (PhD), Dillon Alexander (MS), Daniel Hansen (MS), Siddharth Bhandari (BS), Spencer Lacy (BS), Zachary Noonan (BS) and Alexander Aguilar (BS) from the University of Colorado at Boulder

Table of Contents

Tables

Figures

Equations

CHAPTER 1 INTRODUCTION

The construction industry has long been considered extremely hazardous (Ringen and Englund, 2006). Despite the numerous attempts of improvements that followed the inception of the Occupational Safety and Health Act of 1970 (OSHA) the construction industry still accounts for a disproportionate injury rate (Mitropoulos and Cupido 2009). In fact, the US construction industry is responsible of 16% of all occupational injuries but only employs 4% of the national workforce (Bureau of Labor Statistics, 2014). The case of the UK is even more dramatic where construction workers account for roughly 27% of all known work-related mortality even though they account for only 5% of all employment (Health and Safety Executive 2013). The specific construction fatality rate in the US is 9.4 per 100,000 workers, meaning that an average of three construction workers are killed every day (Bureau of Labor Statistics 2013). The high and disproportionate rate of injuries and fatalities is a compelling reason for construction safety research.

In addition to the suffering experienced by the victims and their families following a construction injury, the events also have a strong negative impact on the financial performance of the industry (Everett and Jr. 1996). In fact, injury costs totaled over $10.5 billion in US between 1992 and 2002 and have increased due the rising medical costs (National Institute for Occupational Safety and Health 2011). Further, Waehrer et al. (2007) fount that the costs of construction injuries are almost double the all-industry average because of their relative severity and the associated lost work time.

In order to reduce the frequency and severity of construction injuries, many researchers have focused on identifying and prioritizing effective injury prevention practices (Silva et al. 2004). Many safety programme elements have been commonly implemented by most of the construction companies. According to Hallowell (2010), the implementation of programme elements such as upper management support, written plan, frequent worksite inspections, emergency response planning, or safety and health committees resulted into a reduction in recordable injury rates. However, even being able to identify and implement the most effective safety programmes, Hallowell and Gambatese (2007) pointed that traditional injury prevention strategies such accident investigation or inspections are limited due to their reactive and regulatory-based nature. Despite the positive implementation of prevention strategies, in 2005 the construction industry has reached saturation with respect to administrative safety innovations (Esmaeili and Hallowell 2011a). In response to this lack of plans to implement safety innovations new injury prevention strategies such as risk analysis techniques are emerging.

Risk analysis applied to safety management in construction has shown to be an effective method to improve proactive safety management. For example, Hallowell and Gambatese (2009a) used risk to compare and select design alternatives based on their potential safety impacts and Navon and Kolton (2006) integrated risk data into project schedules to produce safety forecasts during project planning. The traditional approach to safety risk quantification involves estimating the relative risk of tasks, trades, or industry sectors (Hallowell et al., 2010; Baradan and Usmen 2006). The limitation of this traditional approach is that it the risk values are not context-dependent nor are they stable as work processes change. Furthermore, due the large number of tasks in the construction industry it is impractical to independently quantify the risk of each individual and task context. To address these challenges, we have adopted an attribute-based approach to safety risk analysis that has the potential for a wide array of applications to virtually any construction context.

CHAPTER 2 LITERATURE REVIEW

To develop a point of departure and define our intellectual contribution the relatively small body of literature available in the area of safety risk analysis was reviewed. Although literature on general risk analysis abounds, risk analysis methods for safety are limited in terms of their data sources and levels of granularity. As will be discussed, the sources of construction safety risk data tend to be derived from opinions and the granularity of empirical data tend to be limited to trade/task-level risks. (e.g. comparison of the risk of carpentry to other trades). The implication of these limitations is that robust and empirical safety risk data do not yet exist and the potential of risk-based safety management has not been tested.

2.1 Data Sources

According to literature, there are three main sources of data used to quantify safety risks: opinion-based, government statistics, and empirical data from construction companies and owner organizations. Opinion-based methods usually rely on the ability of experts to rate the relative magnitude of risk based on their professional experience. Often, qualitative ranges are provided by researchers to bound risk values. On the other hand, empirical methods are performed by mining data from injury databases and modeling probability as long-run frequency (Clemen and Reilly 2003). Data sources for safety risk analysis vary widely among studies. The US Bureau of Labor Statistics (BLS) data has been used in many occasions.

The various data sources used in safety risk studies is provided in Table 1. As one can see, empirical data sources were, for the most part, limited to BLS data. One notable exception was Jannadi and Almishari (2003) estimated a safety risk analysis on worksites by considering risks from 3700 injured workers database based on different construction trades. Such trade-level risk has limitations; however, this was the first study to use data with sufficient detail to compare trade-level risks. The vast majority of safety risk studies use expert opinion data, which are unfortunately severely limited due to psychological factors that confound judgments of uncertainty.

Opinion-based data is limited to the reliability of human perception to quantify risk. Capen (1976) pointed that even technical experts perform poorly when dealing with uncertainty. Subjective probability is always ruled under the influence of biases that affects people's decisions. Many experts has explored cognitive psychology field determining different biases affecting judgments under uncertainty such as overconfidence, anchoring, availability, representativeness, unrecognized limits, motivation, and conservatism (Tversky and Kahneman 1981; Capen 1976; Rose 1987). Alternatively, Sjöberg (2000) studied different factors beyond heuristics and biases that affects risk perception. Even women and men perceive risk differently (Gustafsod 1998). As indicated, an extended literature shows that humans are not good at perceiving risks and also that variations on risk assessments within different people are noticeable. As a consequence, data obtained from expert's opinion is strongly biased and potentially inaccurate. Although there are controls that minimize the effects of bias (Hallowell and Gambatese 2009b), empirical data are far more reliable.

2.2 Risk Scales for Opinion-Based Data

Risk assessment for safety in construction has typically been performed by qualitative risk ratings on numerical or linguistic scale (Table 1). For example, Likert scales with 5 subjective levels from frequent to improbable have been used to classify the frequency for safety risk quantification by both Brauer (2005) and Sun et al. (2008). Alternatively, Everett (1999) used a 1-3 scoring system; however this may simply considered as an alternative to the Likert scale. Other researchers have adopted linguistic scales and absolute scales to elicit expert opinions of risks. For example, Hallowell and Gambatese (2009a) used continuous but bounded scales when collecting both frequency and severity data. The various scales adopted in past studies are summarized in Table 1. One can see that there has been a transition away from Likert to more practical scales but that the inherent limitations of expert ratings persist.

2.3 Data Granularity

Construction projects are very complex from both technological and organizational perspectives. Due this complexity most safety risk studies assume that construction processes can be “decomposed” into smaller parts (Lingard 2013). Such decomposition allows researchers to model risk for a variety of units of analysis. For example, Baradan and Usmen (2006) building trades, Hallowell and Gambatese (2009a) focused on specific worker motions and activities needed for formwork construction, Navon and Kolton (2006) analyzing interactions among planed tasks at height including site layouts, and Huang and Hinze (2003) modeled task, location, time, human error, and age as risk factors. Most commonly, trade-level risk analysis has been adopted (Everett 1999; Jannadi and Almishari 2003; Huang and Hinze 2003; Gürcanli and Müngen 2009). The major limitation is trade-level risk analysis is that there is a virtually infinite number of tasks that must be modeled in order to be comprehensive. To date, risks have been quantified for fewer than 100 tasks.

Further compounding this issue is the fact that new tasks are analyzed using expert opinion data, which is cumbersome and time-consuming to obtain. Two studies have employed methods to address these limitations. First, Shapira and Lyachin (2009) quantified risks for very specific factors related to tower cranes such as type of load or visibility affecting safety, thereby allowing them to model risk for any crane activities and scenarios. Similarly, Esmaeili and Hallowell (2011b; 2012a) used an attribute-based model for measuring safety risk focused on struck-by accidents. Since this study was limited to struck-by injuries in infrastructure projects, the application is very limited. In this study we have adopted the attribute-based risk analysis methodology and have attempted to quantify risks for all salient attributes and for all potential outcomes.

Table 1. Literature Review on Risk Type and Collection Data Methods

Author	Risk Type/Level	Method to collect Data	Scale
Brauer, 1994	Items or events	Expert opinion	Likert (1-5)
Everett, 1999	Ergonomic risks associated with construction processes or tasks	Expert opinion	Likert (1-3)
Jannadi and Almishari, 2003	Activities at the moment of the injury	Expert opinion	Absolute ratings
Huang and Hinze, 2003	Fall accidents in different types of projects	OSHA construction worker accidents involving falls	Absolute values
El-Rayes and Khalafallah, 2005	Sensitivity categories for falling objects from crane operations	Bureau Labor Statistics	Performance scale 0 to 100%
Hinze et al. 2005	Frequency of struck-by accidents by material involved, equipment involved, human factors, and environmental factors	OSHA construction worker accidents	Absolute values
Navon and Kolton, 2006	Dangerous activities Dangerous areas Fall hazards	Safety Regulations Activity Characteristics PM / Risk Factors Risk Assessment	-
Baradan and Usmen, 2006	Construction trades	Bureau Labor Statistics	Likert (1-7)
Sun et al., 2008	Analytic hierarchy process to assess the status of risk	Expert opinion	Likert (1-5)
Gürcanli and Müngen, 2009	Occupational accidents according to the type of work in the Turkish construction industry	Expert opinion Occupational accidents	Fuzzy linguistic parameters
Hallowell and Gambatese 2009a	Activity based risk for concrete formwork construction	Expert opinion (Delphi method) Worker-hours observation	Absolute Ratings
Saphira and Lyachin, 2009	Factors affecting safety in tower-crane environments	Expert opinion	Likert (0-5)
Hallowell, 2010	Safety risk perceived by construction workers in Northwest USA	Experts opinion	Absolute values
Hallowell et al. 2011	Highway construction work tasks	Expert opinion (Delphi method)	Absolute values
Esmaeili and Hallowell, 2011b	Attribute-based risk model for measuring safety risk of fall accidents	NIOSH	Absolute values
Esmaeili and Hallowell, 2012a	Attribute-based risk model for measuring safety risk of struck-by accidents	FACE database IMIS database	Absolute values
Esmaeili and Hallowell, 2012b	Highway construction work tasks	Expert opinion (Delphi method)	Absolute values
Wu et al. 2013	Objects in Struck-by-falling-object accidents.	OSHA construction worker accidents	Absolute values

2.4 Integration and Implementation of Safety Risk Data

As indicated in Table 1, researchers have modeled safety risk using a variety of perspectives, data sources, and measurement techniques. Similarly, the application of safety risk data also varies widely. Table 2 shows that various applications of safety risk data in construction. Examples of applications include El-Rayes and Khalafallah (2005) who integrated algorithms with decision variables to model falling objects from crane operations. Wu et al. (2013) who used risk data to create a ZigBee RFID sensor network to prevent struck-by-falling-object accidents, and alternatively, Esmaeili and Hallowell (2012b) crated a scheduled-based safety risk assessment and management system. As one can see in Table 2, some risk applications are more focused to the design phase (El-Rayes and Khalafallah 2005; Navon and Kolton 2006), while others (Wu et al. 2013), are more oriented to real time safety strategies. Risk integration models are scarce and most are not supported by a robust database. They are also quite limited in their scope of application and serve more of a proof of concept rather than a robust solution to safety management needs.

Table 2. Literature Review on Risk Applications

Author	Data Content	Risk Application
El-Rayes and Khalafallah, 2005	Hazard degrees among facilities	Multiobjective genetic algorithm with decision variables and optimization objectives in worksites. Integrated for falling objects from crane operations
Navon and Kolton, 2006	Dangerous activities Identification of risky areas Proposed protective action	Monitoring fall hazards in building construction by analyzing the interactions among planed tasks and site layouts
Gürcanli and Müngen, 2009	Defuzzified values for each cause of accident and corresponding hazard levels	Accident likehood, safety level and severity used as inputs for a fuzzy rule-based system
Hallowell et al. 2011	Safety risk interactions	Pair-wise spatial and temporal interactions on base-level risk of common highway construction work tasks
Esmaeili and Hallowell, 2012b	Unit risk scores for highway reconstruction work tasks	Scheduled-based safety risk assessment and management (SSRAM)
Wu et al. 2013	Real-time location info. of workers and materials	ZigBee RFID sensor network to prevent struck-by-falling-object accidents

This literature review has revealed that safety risk data and risk-based integration with safety planning tools is feasible and potentially impactful. However, the current body of knowledge is severely limited in terms of data quality, quantity, and granularity, which has also stunted implementation and integration with project planning tools

Specifically, the current body of knowledge suffers from: (1) Lack of robust and empirical databases; (2) data sources that are mostly obtained from expert opinions, which are strongly limited to the reliability of human perception to quantify risk; (3) empirical data sources that have insufficient levels of detail; (4) a lack of focus on interactions among risk factors; and (5) integration of safety risk data that is limited to tools with small scopes of application due to data limitations.

CHAPTER 3 POINT OF DEPARTURE

To address the limitations of the current body of knowledge, our goal was to analyze risk at the attribute-level for industrial construction work using empirical data and modeling risk for all types of outcomes in this very large industry sector. The ultimate goal was to quantify risks with reliable data at a level that could be used to characterize risk in any new industrial construction environment. Such knowledge would build on the work of Esmaeili and Hallowell (2012a) who created an attribute-based model for measuring safety risk for struck-by injuries but would deviate by considering the plethora of potential outcomes in a very large sector.

CHAPTER 4 OBJECTIVES

From this point of departure the specific research objectives are to:

1. Identify the safety risk attributes that lead to any injury in industrial construction projects.
2. Conduct a content analysis to identify the attributes present for 1,611 industrial construction injuries
3. Quantify the relative safety risk for each attribute
4. Perform a simulation in order to determine the expected range of outcomes and interpret the risk values obtained in new scenarios.

CHAPTER 5 RESEARCH METHODS

In order to achieve our research objectives, we obtained and analyzed 1611 injury reports from 233 different organizations engaged in industrial construction projects throughout the world. The reports were provided by one large contractor who supervised and managed projects completed by these 233 organizations. All injury reports included the salient facts about the injury circumstances including conditions and environments that contributed to an injury. The data were originally entered by an individual who was actively working at the jobsite and was supplemented and confirmed by at least two members of the project management team to ensure completeness and consistency in the data reporting. The database contains cases from 2011 when the injury reporting system was originally established to the end of 2013. The database also contains cases from 16 different countries; however, the work was predominantly performed in the United States.

Although the reports are not lengthy, they are detailed and include salient information of the work conditions and causal factors. The reports of recordable injuries (i.e. medical-case, lost-work-time, disabling, and fatal injuries) are abstracts of root cause analysis. Although the reports are detailed, no information is provided on the emotional or psychological state of the worker, upstream, failures in the safety system, or latent forms of human error. Thus, the generalizability of our results is limited to the physical attributes of the worksite, equipment, materials, design features, and conditions of the work environment.

An example of an injury report is provided below:

> "The experienced iron worker was engaged in grinding truss segments to be lifted on the school structure when the grinding wheel broke. The tool came off the work and contacted his lower right arm, making a deep cut. 911 was called and he was transported to a nearby Hospital. The worker received 29 stitches to close the wound. The worker reported to work the next day. Preliminary investigation revealed that there was no guard on the grinder."

This example will be used to illustrate the methods used to extract and analyze the attribute risk data.

5.1 Content Analysis

In order to identify attributes from the reports, a manual content analysis procedure was implemented using a team of nine researchers. A large team war required because of the volume of the data, the lack of prior attributes from which to build, and the need for peer-review to determine inter-rater reliability. Different perspectives were required to minimize the potential effects of the researchers' personal biases. Our team consisted of six researchers, one coordinator and reviewer, one academic reviewer, and an industry expert reviewer. The team went through an iterative process to identify the attributes from each report. Figure 1 shows the basic steps of the process.

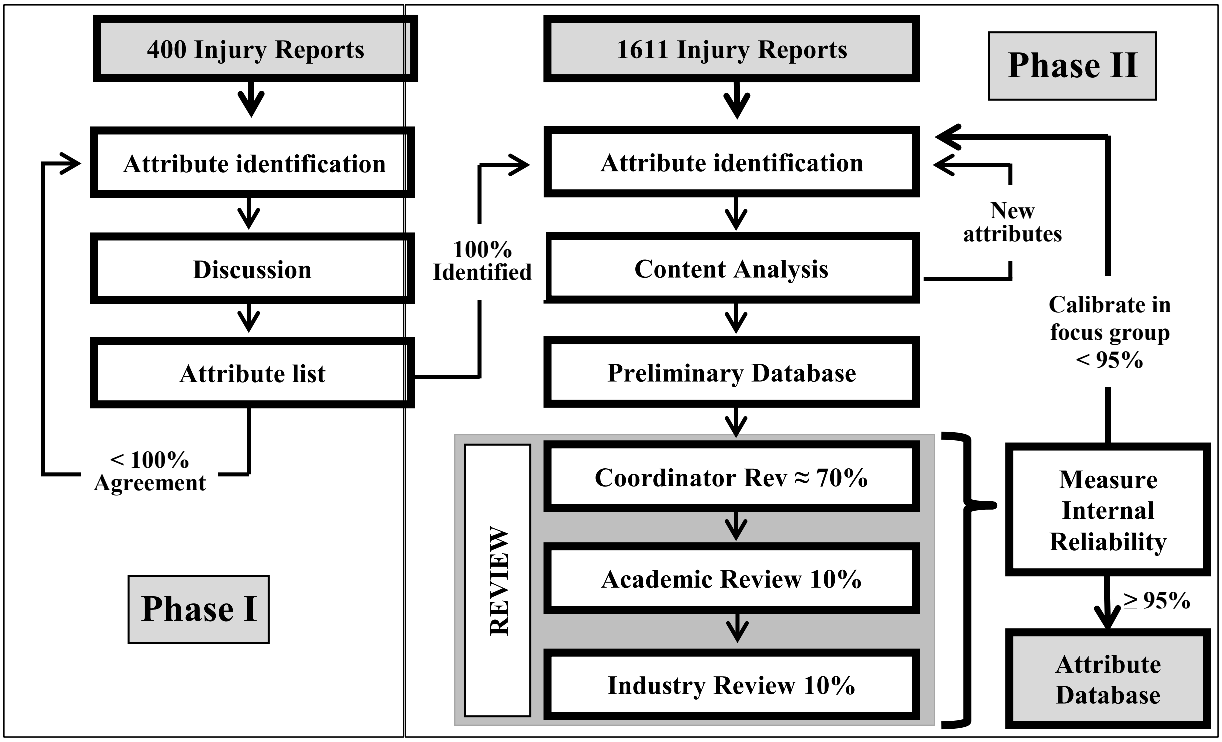

Figure 1. Identification and Attribute Database Creation Process

Our process of extracting attribute-level risk data from injury reports was inspired by the rigorous and often cited content analysis methodology established by Neuendorf (2002) and Krippendorff (2004) (Figure 1). Content analysis was employed because it helps researchers to quantify the distribution and frequency of content in texts. Since our end goal was to identify attributes in a large volume of injury reports, content analysis was preferred. Because we also were the first to establish and define attributes for industrial construction we performed a manual content analysis without the aid of computing or machine learning. Hence, our large and diverse team.

Our manual content analysis involved sampling, coding, and reliability testing (Neuendorf 2002; Krippendorff 2004). For sampling, we initiated the process with Phase I using a randomly selected subset of 400 injury reports in order to establish clear definitions and consistency within the team. Once attributes were identified and defined and our team reached consensus on the content of the initial 400 reports we initiated Phase II in order to complete the remaining 1,211 reports. All of the injury reports were coded in data sheets that including the identified attributes, the injury outcome, the energy source, the injury code, and the part of the body affected.

5.1.1 Phase I: Attribute Identification

Before identifying the attributes and analyzing the reports our research team needed to create a clear operational definition for an attribute. Thus, the team agreed on the following definition of the attribute.

> "Attributes are independent elements identifiable in the design phase or in the worksite before a task is initiated. Attributes can be physical elements of the worksite, equipment, tools, materials, design features, but also conditions of the work environment or weather conditions."

To build the initial attribute list an initial subset of the injury reports (n=400) was content analyzed through an iterative process with the research team of eight. The team randomly and evenly distributed the reports (e.g., 50 reports to each coder) and the research team was tasked with reading and identifying the attributes present in each of their 50 reports.

Once the manual content analysis was performed, the team met to discuss the definitions of the attributes, grouping or division of attributes (e.g. "hammer" and “screw driver” grouped as “unpowered hand tools”), and to obtain alignment for attributes that were particularly vague or difficult to extract from text.

Following the group meeting, the same set of 400 reports was randomly divided and distributed in a way that each researcher received a new subset of 50 reports with no overlap in their set from the first phase. In this way, our team could measure internal consistency among researcher coding after each iteration.

As reports were content analyzed the researchers noted that more than one attribute was often identified in a single injury report. For example, worker welding a pipe who twisted his ankle due a hammer on the floor – would have 4 attributes identified (“*welding*”, “*piping*”, “*object on the floor*”, and “*unpowered hand tool*”).

The presence of multiple coders is was crucial to ensure that the results are not subject subject to one individual’s judgment (Tinsley and Weiss 1975). The coordinator reviewer compared the results and provided examples of disagreement or inconsistency to the group in order to align the researchers throughout the identification process. This iterative process was constantly repeated in order to achieve the most reliable dataset. Iterations were performed until consensus on the identifiable attributes list was achieved. In other words, this means that Phase I was finished when 100% of the attributes were identified for the 400 injury reports initial sample.

Once the attributes were identified and defined, they were categorized based on the project phase in which they appear and can be managed. The three main phases of interest are described below:

Upstream - An upstream attribute is an attribute that can be reasonably identified during the design phase of a project, before construction begins and that is independent of human behavior. Incidents with identifiable upstream attributes can theoretically be foreseen and prevented by adopting new design solutions. Upstream attributes can be divided into three main categories: materials, equipment, and site-design. Each category is composed of several attributes.

Transitional - A transitional attribute is an attribute that can be reasonably identified before construction begins but that requires some research and/or projections of environmental conditions and construction means/methods. Transitional attributes are generally the responsibility of the contractor, who is required to provide a safe workspace according to OSHA regulations. Transitional attributes can be divided into four categories: equipment & tools, materials & substances, site quality, and weather & environment.

Downstream - A downstream attribute is an attribute that could not be observed and identified until construction actually begins. Downstream attributes can be divided into three main categories: human behavior, site characteristics, and other.

5.1.2 Phase II: Complete Database Analysis

Based on the attribute list created in Phase I, a second phase was performed in order to create a complete database from complete set of 1,611 reports. Similar to Phase I, each researcher was given the task to manually content analyze 50 reports per round until the entire database was analyzed with 95% inter-coder reliability. Again, injury outcomes, energy sources, injury codes, and the part of the body affected where identified for each injury report. Differently from the first phase, attributes were classified as upstream, transitional, and downstream. Furthermore, in order to ensure the quality of the results, injury reports with poor descriptions were not included. Fortunately, less than 15% of the reports needed to be deleted.

Internal reliability (i.e., inter-coder reliability) was the primary metric of data quality from the content analysis. According to Carmines and Zeller (1979), the content analysis reliability is the capacity to achieve the same results in repeated trails by following the established procedures. In this current study internal and external reliability is measured as typically by a simple percent agreement (Neuendorf 2002).

In order to ensure external reliability from these six researchers, each reviewer's data were reviewed by multiple reliability coders. Specifically, a randomly selected on 70% of the reports was independently analyzed by the lead researcher, 20% were reviewed by an academic expert, and 10% by an industry expert. As such, each report was reviewed by one primary reviewer and one secondary reviewer In each round, percent agreement was calculated and the process continued until 95% inter-coder reliability (i.e., less than 5% disagreement) in the entire dataset. According to Wimmer and Dominick (1994), the minimum acceptable proportion of a dataset to use for intercoder reliability is 10%. Our use of 100% review far exceeds this value.

After three months and eight iterations, all 1,611 injury reports were analyzed. In this analysis, 51 attributes were identified and classified (Table 3).

Table 3. Fundamental Identifiable Attributes List

Upstream Attributes
Materials
Concrete: construction/placement of any concrete section such as beams or girders
Heavy material: any kind of material with considerable weight (>40 lbs). Doesn't include "Lumber" "Pipe", "Steel beam" or "Concrete beam"
Lumber: any kind of dimensional lumber
Piping: any type of piping
Rebar: any type of steel reinforcement bar
Scaffold: any component of a scaffold
Stairs: any kind of step, including all kinds of static stairs
Steel Sections: any kind of steel section (i.e. beams, girders)
Valve: any type of valve
Wire: any wiring or conduit
Site-Design
Congested work space: any condition with limited egress or working space (< 5 ft. radius of open movement)
Door: anytime a doorway is present within a project
Object at height: potential falling object that is elevated more than 1 story (10ft) above lower level.
Object at height on same story: potential falling object located at a height less than 1 story (10ft) (i.e. material carried on shoulder)
Working at height: when work commences and the worker's feet are above ground level
Working below elevated workspace: work taking place below an elevated workspace
Equipment
Crane: anytime involving hoisting and maneuvering of materials with a crane
Formwork: anytime constructing or stripping concrete formwork is present on a project
Grinding: whenever metal grinding activities are present on a project (i.e. pipes)
Heat source: anytime that a worker has contact with unprotected heat (i.e. steam)
Heavy vehicle: large vehicles other than "machinery" and "light vehicles" (i.e. tandem trucks, trailers)
Machinery: any kind of machinery used by workers except for cranes and forklifts (i.e.. excavators, backhoe)
Manlift: either a motorized scaffold/platform or motorized bucket (i.e. "cherry picker")
Unpowered transporter: any equipment used to transport materials without a motor (i.e. wheelbarrow, dolly)
Welding: any welding activity taking place on the jobsite

Table 3. Continued

Transitional Attributes
<u>**Equipment & Tools**</u>
Forklift: any type of forklift
Powered hand tool: hand tools that require electricity, pressure, springs, etc. to operate
Unpowered hand tool: hand tools that do not require energy other than human power to operate (i.e. hammer)
Ladder: anytime involving the use of ladders to perform work
Light vehicle: any vehicle used in the worksite. (i.e. Vans, cars, small trucks, pick up truck)
Small machinery: any kind of machinery that can be operated and transported by a single worker
<u>**Materials & Substances**</u>
Electrical source: any type of electrical system, machinery, or tool
Hand size pieces: any material that is small enough to fit in human hand not including hand tools (i.e. nails)
Hazardous substance: any material known to have carcogenic, neurotoxins, etc. (i.e. primers, adhesives)
Small particles: any kind of airborne particle
<u>**Site Quality**</u>
Sharp edge: any kind of exposed sharp object or edge that could potentially cut or puncture
Slippery surface: any walking surface that doesn't ensure a normal grip (i.e. surface that is slippery when wet)
Unstable support / surface: temporary working surfaces other than a scaffold or a ladder. (i.e. scissor lift)
<u>**Weather & Environment**</u>
Ice / Snow: any time ice is present on a project site
Mud: any time in which mud is present
Poor visibility: any time visibility is limited. (i.e. smoke, steam, dust, darkness)
Wind: any substantial wind on a project (20 + mph)
Downstream Attributes
<u>**Site characteristics**</u>
No / Improper PPE: any time a laborer does not have necessary/required Personal Protective Equipment
Object on the floor: any kind of object/material on floor that prevents clear, flat, or even walking surface. (i.e. cords, tools).
Poor Housekeeping: when a work area is left cluttered with tools, material spoils, etc.
Uneven surface: surface that is not flat
<u>**Human behavior**</u>
Improper body position: when a worker uses improper body position (somehow restricted to poor position by the environment not choice)
Improper security of materials: when bundled or suspended materials are not properly secured or tied
Improper procedure: any time a laborer uses improper procedure (i.e. sticking flagger paddle out into traffic)
Safety equipment misuse: any time that a worker misuses safety equipment
<u>**Other**</u>
Insect: any time an insect is present on a project that may cause harm (i.e. bees, spider)

5.2 Content of the Attribute Database

As previously indicated, the coding of this content analysis included the identified attributes, the injury outcome, the energy source, the injury code, and the part of the body affected populated the Attribute Database (Table 4):

Table 4. Injury Outcome Database Sample

Description	The experienced iron worker was engaged in grinding truss segments to be lifted on the school structure when the grinding wheel broke. The tool came off the work and contacted his lower right arm, making a deep cut. 911 was called and he was transported to a nearby Hospital. The worker received 29 stitches to close the wound. The worker reported to work the next day. Preliminary investigation revealed that there was no guard on the grinder. The guard had been removed to facilitate grinding in congested areas where the guard would prohibit contact with truss right angles.
Upstream	Steel Sections
Transitional	Powered hand tool
Downstream	No/improper PPE
Outcome	Medical Case
Energy Source	Motion
Injury Code	Struck by
Body Part	Arm

The specific content obtained for each report (shown in Table 4) is described in detail below. These dimensions were critical for the subsequent analyses.

Attributes- Selected upstream, transitional and downstream attributes from the 51 identified attributes list (Table 3). More than one attribute can be identified in each injury report.

Injury Outcome- Injury severity definitions based on the Occupational Safety and Health Administration (OSHA) definitions, which they could access at any time during the experiment via provided handouts:

- **Pain**: physical suffering or discomfort caused by illness or work-related injury but no treatment was needed or the worker did not seek for medical attention.
- **First aid**: any treatment of minor scratches, cuts, burns, splinters, etc., where the worker is able to return to work following the treatment.
- **Medical case**: any work-related injury or illness requiring medical care or treatment beyond first aid where the worker is able to return to their regular work and function in normal capacity.
- **Lost work time**: any work-related injury or illness that prevents the worker from returning to work the following day.
- **Permanent disablement**: any work-related injury or illness that results in permanent disablement.
- **Fatality**: any work-related injury or illness that results in death

Energy Source - Considering that all injuries are a result of exposure to different hazardous energy sources in the work environment, Albert et al. (2014) identified and listed 10 different and all-inclusive and mutually exclusive energy sources.

1. Motion;
2. Gravity;
3. Pressure;
4. Mechanical;
5. Electrical;
6. Thermal;
7. Chemical;
8. Radiation;
9. Biological; and
10. Sound

Injury Code - The OSHA's Occupational Illness and Injury Classification System contemplate 29 primary codes. Construction safety data reports are organized by the Bureau of Labor Statistics on 10 injury codes. However, all industries are included in both OSHA and Bureau of Labor safety data reports. Inspired by the construction-specific accident causation provided by Hinze (1997), Hallowell and Gambatese (2009a) selected 10 all-inclusive and mutually exclusive injury codes

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

Part of the body injured – The possible parts of the body were included in an all-inclusive but not mutually exclusive body part classification. Inspired by the most frequent parts of the body appearing in the descriptions this classification also includes reasonable safety prevention body divisions.

1. Finger;
2. Hand;
3. Arm;
4. Feet;
5. Ankle;
6. Knee;
7. Leg;
8. Eyes;
9. Face;
10. Head;
11. Neck;
12. Back
13. Shoulder;
14. Body; and
15. Wrist;

5.3 Phase III. Exposure database

As presented previously, to perform a safety risk analysis by finding the product of likelihood of occurrence and magnitude of impact it is necessary to know how often the attributes are present in the worksites from which the injury reports are obtained. Otherwise risk analysis is skewed toward attributes of a work space that are frequent. For example, an attribute that is rare yet is involved in many injury cases is higher risk than an attribute that is very frequent on site and is involved in the same number of injury cases. This site frequency is known as exposure in risk studies. These values can be also interpreted as the probability of presence for a particular attribute in a given task.

We obtained the exposure data empirically from the organization who collected the injury reports on their projects. Fortunately, for some of the attributes (e.g., "*crane*"), the total time the company and their subcontractors included the attribute on site was contained within the company's project controls data. However, for many other attributes (e.g., "*mud*") the exposure data were obtained from two project controls experts, each with over 25 years of managing the company's projects. The data collection process was very detailed and involved parsing the company's project controls data into levels of granularity where the attribute exposure estimates were reliable.

Specifically, the company's records for proportion of work in their major disciples were obtained, which included the major disciples listed in Figure 2 (e.g., civil and structural). For each of those major disciples, the proportion of time spent on each specific sub-disciplines was obtained (e.g., civil). Finally, the proportion of company time spent on specific activities (e.g., underground piping) was obtained. Within each of these tasks the experts provided their estimates of the exposure values for the attributes. In this process, we combined empirical project controls data with expert ratings in order to quantify exposure in very specific contexts. As such, we believe the reliability to be much higher than gross estimates of exposure that could be provided for the company's work as a whole.

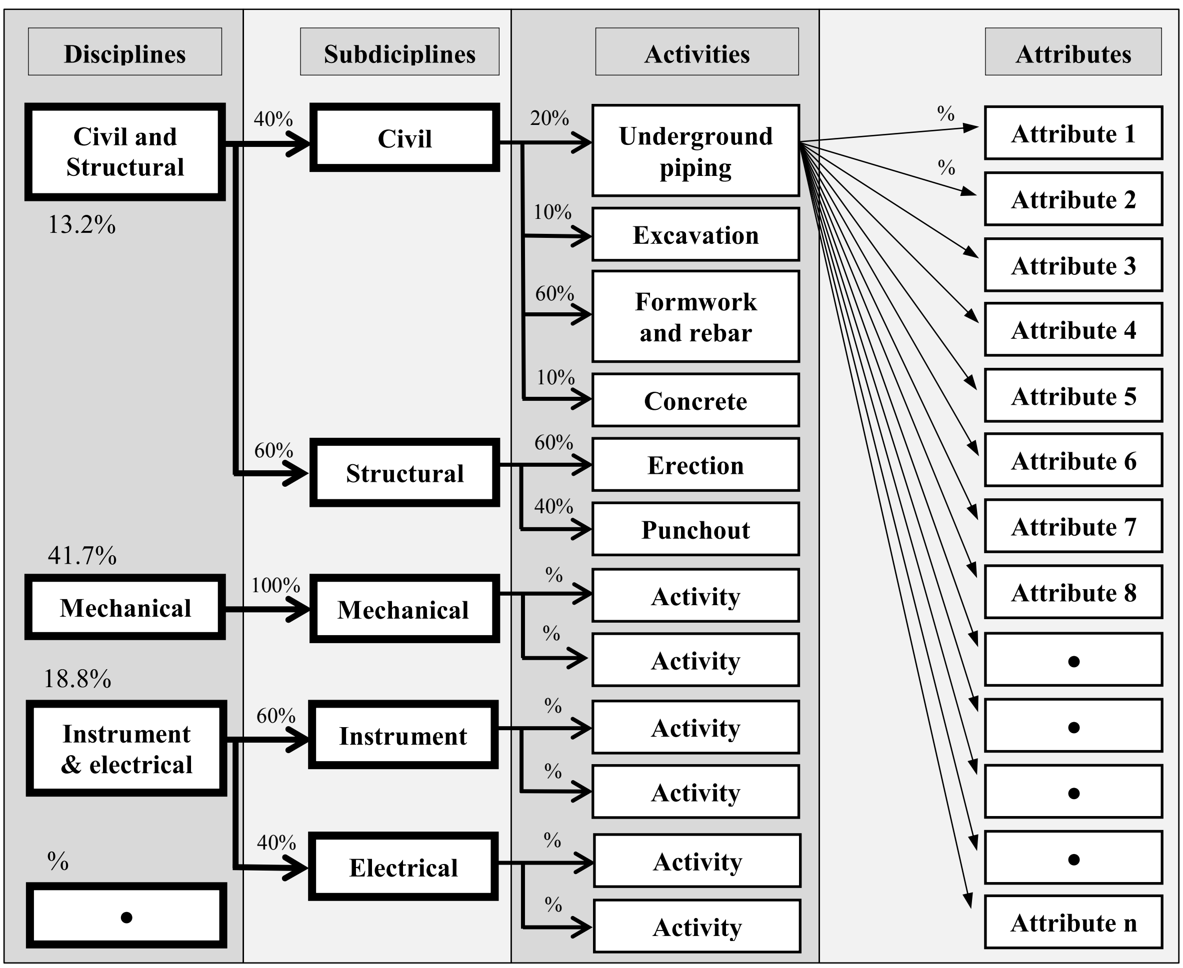

Figure 2. Exposure Database Creation Process

Once these exposure data were obtained for the attributes in each task, an exposure value was computed using (Equation 1). The global exposure value was then computed for the company's work as whole using (Equation 2). The global exposure values for all attributes are provided in Table 6.

$$Exposure = Discipline\% * Subdiscipline\% * Activity\% * Attribute\ Occurrence\%$$

(Equation 1)

$$Global\ Exposure = \sum Exposure\ (for\ each\ attribute\ within\ an\ activity)$$

(Equation 2)

For example, to know the value of Exposure of "*congested work space*" for "*Excavation*" activities, the exposure percentages estimated at different levels are used. Following the percentages indicated in Figure 2, Exposure would be calculated multiplying these percentages (Equation 1).

$$Exposure = 13.2\% * 40\% * 10\% * 50\% = 26.4\%$$

Then, the Global Exposure for "*congested work space*" attribute would be the sum of all the Exposure values for each activity (Equation 2):

$$Global\ Exposure\ (Congested\ work\ space) = \sum E_1 + E_2 + 26.4\% + \bullet + E_m = 41\%$$

CHAPTER 6 RESULTS AND ANALYSIS

6.1 Risk analysis

In order to quantify the attribute-level risks, the attribute database and exposure database were used, as shown in Figure 3.

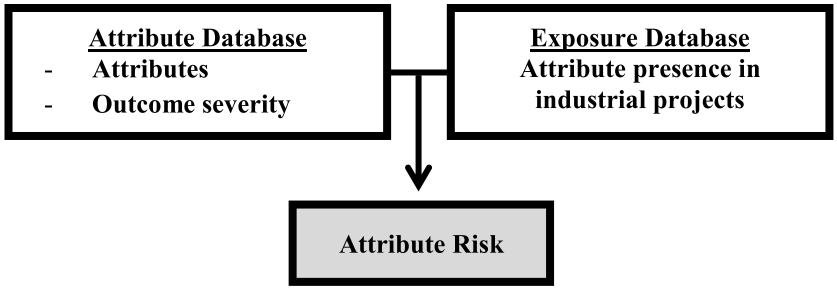

Figure 3. Risk Database Diagram

As described previously, the quantification methods employed by (Baradan and Usmen 2006) have been used. As illustrated in (Equation **3**, Unit Risk is the product of frequency and severity.

$$Unit\ Risk = Frequency * Severity \qquad \textbf{(Equation 3)}$$

In (Equation **3**, Frequency is the average number of events per unit of time and it is represented in terms of injury rates. This is the number of times an attribute contributes to an injury divided by the percent time it is present in work related incidents. Severity refers to the magnitude of potential outcome of an event, which was directly gathered from each injury report.

As shown in $Cumulative\ \ Risk = Unit\ Risk * Exposure$ **(Equation 4**, Cumulative Risk is the product of Unit risk times the Exposure. The total duration of contact with a particular attribute is the Exposure and it is typically represented by time units.

$$Cumulative\ Risk = Unit\ Risk * Exposure \qquad \textbf{(Equation 4)}$$

However, in our particular case, the exposure is represented by a relative percentage for each attribute. As a consequence, the Cumulative Risk calculated is a relative risk based on the attributes present in a particular activity. The Relative Risk for a particular attribute is:

$$Relative\ Risk = \frac{Attribute\ Count * Severity}{Attribute\ Exposure} \qquad \textbf{(Equation 5)}$$

Both, the attribute count and severity were obtained from the injury reports. Quantifying the frequency is a relatively easy process by counting the number of incidents where a particular attribute was present divided by the attribute exposure. However, each incident or injury had different severities.

In order to asses severity quantification to each outcome Hallowell and Gambatese (2008) created a set of objective risk scales that incorporate a complete spectrum of severity levels._Inspired on this severity scale an adjusted scale based on the six possible outcomes from the Attribute Database was created (Table 5).

Table 5. Severity Levels

Subjective Severity Level	**Severity Score**
Pain	12
1st Aid	48
Medical Case	138
Lost Work Time	256
Permanent Disablement	1,024
Fatality	26,214

At this point all the elements needed to calculate the relative risk has been presented. The following equation has been used to calculate the Relative risk of a particular attribute.

$$Relative\ Risk = \sum \frac{n_i * s_i}{e} \qquad \textbf{(Equation 6)}$$

The number of all the incidents related to this particular attribute registered in the Attribute Database (n_i) is multiplied by the correspondent severity score (s_i). Then this value is divided by the Global Exposure (e) of this particular attribute. Adding all these values the Relative Risk is obtained.

As represented in Figure 3, aggregating this combination of data from both, the Attribute Database and the Exposure Database it is possible to create an attribute relative risk data (Table 6). This attribute relative risk data provides very interesting information about the most risky attributes in industrial construction projects. The highest relative risk goes to "*hazardous substances*" attribute scoring 1583.5. This high risk is due a very low global exposure but a high severity level. Some other attributes like "*heat source*" have a relatively low score (13.8) despite having the global exposure and frequency close to the average; this is explained due a low severity level from the injury reports related to this attribute. However, worksite tasks typically involve many attributes at a time.

In order to calculate the risk score of a particular task, the relative risk from each independent attribute that will be present is added to the total risk. The independence of the attributes reduces correlation to zero. This means that the total risk of a particular task is the simple summation of the relative risk for all the attributes involved (Equation 7).

$$Task\ Total\ \ Risk = \sum Relative\ Risk\ (for\ each\ attribute\ within\ a\ task)$$

(Equation 7)

For example, imagine that a worker is able to identify “grinding”, “working at height”, “powered hand tool”, and “sharp edge” attributes before starting a particular task. According to (Equation 7) and the values on data (Table 6), the Task Total Risk score would be:

$$Task\ Total\ \ Risk\ Score = 5.6 + 81.2 + 41.2 + 18.2 = 146.2$$

In this method, we consider the attributes to be independent and cumulative. Future risk analyses will challenge these assumptions with advanced statistics.

Table 6. Attributes identified with frequency, exposure and risk values

Upstream Attributes	Frequency n	Exposure s %	Relative Risk
Materials			
Concrete	16	1.53	176.0
Heavy material	62	31.11	51.7
Lumber	33	15.32	67.0
Piping	97	38.27	63.1
Rebar	30	3.89	192.0
Scaffold	82	32.90	46.6
Stairs	21	41.38	13.5
Steel Sections	53	35.08	38.5
Valve	4	27.28	2.3
Wire	29	42.10	13.8
Site-Design			
Congested work space	50	40.93	22.0
Door	9	21.97	7.0
Object at height	20	40.01	14.2
Object at height on same story	20	59.47	15.1
Working at height	20	40.93	81.2
Working below elevated workspace	17	17.10	18.0
Equipment			
Crane	12	12.54	75.9
Formwork	7	4.85	575.9
Grinding	5	15.99	5.6
Heat source	15	19.80	13.8
Heavy vehicle	15	12.29	44.8
Machinery	23	10.36	68.4
Manlift	7	7.55	33.9
Unpowered transporter	19	8.60	69.0
Welding	38	22.22	28.10

Transitional Attributes	Frequency n	Exposure s %	Relative Risk
Equipment & Tools			
Forklift	8	9.05	21.2
Ladder	7	13.54	11.3
Light vehicle	15	59.12	9.2
Powered hand tool	59	26.47	41.2
Small machinery	12	5.43	33.0
Unpowered hand tool	84	45.05	32.5
Materials & Substances			
Electrical source	3	33.09	1.2
Hand size pieces	44	46.18	15.7
Hazardous substance	47	0.65	1583.5
Small particles	107	31.02	53.1
Site Quality			
Sharp edge	22	37.29	18.2
Slippery surface	25	24.64	21.2
Unstable support / surface	12	31.36	43.6
Weather & Environment			
Ice / Snow	26	3.44	183.7
Mud	4	6.33	10.1
Poor visibility	5	23.56	10.3
Wind	28	37.57	13.8

Downstream Attributes	Frequency n	Exposure s %	Relative Risk
Site characteristics			
No / Improper PPE	24	67.62	5.9
Object on the floor	46	42.97	24.2
Poor Housekeeping	39	23.98	22.8
Uneven surface	55	31.74	43.6
Human behavior			
Improper body position	47	24.53	49.0
Improper security of material	32	12.81	71.3
Improper procedure	48	6.53	203.7
Safety equipment misuse	6	3.09	23.8
Other			
Insect	20	17.90	14.8

At this point, a total risk score for any task in the industrial construction sector can be quantified. However, this total risk score needs to be referenced in order to evaluate the risk level of the particular task. For the purpose of having a comparison basis for the Task Total Risk values with a Monte Carlo simulation has been performed.

6.2 Monte Carlo Simulation

A Monte Carlo simulation is a statistical sampling method that uses repeated and random sampling of a series of probabilistic inputs to obtain a distribution of outcomes for a particular event. Monte Carlo simulations are typically used as an '*alternative to analytical mathematics to understand a statistic's sampling distribution and evaluate its behavior in random samples'* (Mooney 1997). In essence, a Monte Carlo Simulation is an experimental approach to create a unique distribution of outcomes. This result to be very convenient to understand how the Task Total Risk values are placed into a statistical distribution created from the probability of combining random attributes.

The Monte Carlo simulation conducts hundreds of thousands of independent iterations in order to create a distribution of relative risk values for a given activity. The attribute Global Exposure and Relative risk data is used to run the Monte Carlo Simulation. A Binomial Monte Carlo simulation is conducted on the relative risk data to create the distribution. This means that a particular attribute will either be present or not present in each iteration of the simulation based on their occurrence. The occurrence is the Global Exposure data indicating the probability that a given attribute will be present during the activity.

A Binomial Monte Carlo simulation randomly select attributes based on their probability of occurrence associating the relative risk values when selected and zero when not. To exemplify, "*Lumber*" is located on just 15.32% of activities and have a relative risk score of 67.0 which means that has a probability of 15.32% to be selected in each iteration of the Monte Carlo simulation and adds a risk score of 67.0 when selected. All the attributes are evaluated in every iteration.

This analysis considers attributes as independent elements that do not have any relationship with each other. As a consequence, any correlation between attributes is not considered. When attributes were grouped under the same umbrella, it is precisely because they all are related to some extent. For example, a hammer and a screwdriver are both unpowered hand tools, and they co-occur onsite in tool boxes, tool belts, in warehouse shelves, etc.

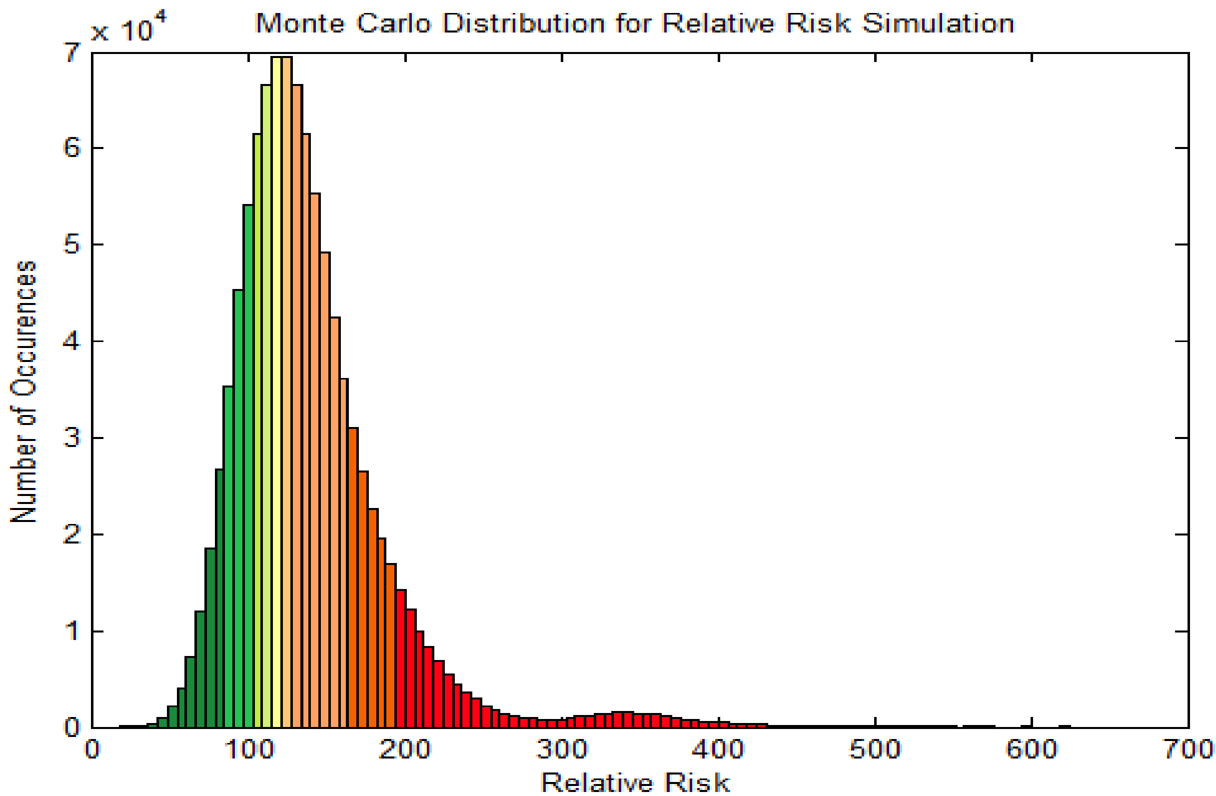

Figure 4. Total Relative Risk Score Distribution

This iteration was repeated 100,000 times, in which the risk values randomly calculated were recorded on a histogram (Figure 4). This histogram is the distribution of the total relative risk needed to create a basis for comparison.

As previously indicated, the total risk value is referenced to the Monte Carlo distribution basis to evaluate the risk level of the particular task. In order to create a user-friendly form to compare the Total Task Risk with the Monte Carlo distribution a simplistic color indicator is created. This color indicator associates the risk level to a color breaking down the distribution into five basic sections. The percentiles of the distribution are the chosen divisions for the five different risk levels. From bright red for the highest risk to dark green for the lowest risks the five risk levels are: "*Very low*", "*Low*", "*Moderate*", "*High*", and "*Very high*" risk (Table 7).

Table 7. Risk Level Color Legend

Risk Level	Percentile	Relative Risk
Very Low	10%	90.2
	20%	102.8
Low	30%	112.5
	40%	121.3
Moderate	50%	130.1
	60%	139.7
High	70%	151.2
Very High	80%	166.9
	90%	193.5

Recovering the previous example, the worker that identifies "*grinding*", "*working at height*", "*powered hand tool*", and "*sharp edge*" attributes before starting a particular task would have a Task Total Risk score of 146.2. According to Table 7, this task would be considered a High risk activity.

CHAPTER 7 APPLICATION

The Attribute Risk database presented in this paper could be directly used by safety managers and designers in different industrial construction phases. Safety managers would be able to perform a better site safety by (1) quantifying the associated risk for specific activities in any industrial construction project based on the present attributes; (2) quantifying and compare the risk for alternative construction methods where different attributes are present, and also (3) creating a project risk profile (Hallowell et al. 2011) by integrating the different activities and their associated risk into the project schedule.

Furthermore, identifying the attributes with highest relative risk, comparing alternatives, and creating project risk schedules from this risk database would be possible to perform the most effective strategies to (1) conscientiously accept high risks for core activities, (2) mitigate risk by using alternative construction methods, and (3) transfer risk by rescheduling specific activities so reducing high risk periods.

On the other hand, safety prevention through design could be also widely improved. Such data can serve for construction designers as attribute-based safety data that can be attached to Building Information Models (BIM) and other forms of technology. Including risk levels during the design phase to compare alternatives on materials and methods, designers would have the opportunity to actively participate in safety prevention strategies.

Alternatively, developers would be able to integrate this Risk data and the Monte Carlo simulation basis into a software application providing warning signs on risk levels for workers before initiating an activity based on the selected attributes. It could also include other information attached to the risk database as the most likely energy source, injury code, or the part of the body most susceptible to be injured.

Finally, this attribute database can be used for injury investigation purposes. Relations between the injury codes and energy sources can be explored and, at the same time, combined to the presence of attributes providing interesting statistics that can be also studied including the severity of the incident and the part of the body affected. Cluster analysis on these relations between the different variables included in the database can show interesting relations. For example, we could discover which part of the body is more likely to be injured when certain attributes are present.

The attribute database opens a multitude of opportunities to improve safety in different levels and perspectives. Summarizing, this database can be applied for (1) site safety planning, (2) prevention through design, and (3) injury investigation for a better understanding of the injuries in construction is possible

CHAPTER 8 LIMITATIONS

The application of this Attribute risk database has certain limitations. (1) It can only be applied to industrial construction projects in developed countries. Attributes from other constructions sectors may be different and therefore not included in this database disabling it to be exported to the whole construction industry. Additionally, (2) interactions between attributes are not included in the Monte Carlo Simulation. That means that probabilistic correlations between attributes are considered null. When some attributes were separated (e.g., "*valve*" from "*piping*" because valve is so frequent), it was not due the independence of these attributes but to make more accurate predictions and inferences from the data. Indeed, these attributes remain highly dependent to each other. Despite the 1611 injury reports analyzed, (3) low frequency-high severity attributes may be omitted and consequently not included in the risk analysis. Moreover, even considering the extended descriptions included in these injury reports, (4) some elements present when the injury occurred may not be recorded. Finally, (5) exposure data obtained from project controls experts would not be as precise as the empirical project controls. These biases from expert opinion data could eventually provoke high variations on risk levels for very low exposure values.

CHAPTER 9 CONCLUSIONS

A practical safety quantification method (1) founded on robust and extended database, (2) covering a large sector of construction industry, and (3) based on elements that are not intrinsic or characteristic from certain environments, activities, or physical conditions is missing in the literature. To address this limitation, an attribute based risk analysis on 1611 injury reports on industrial projects from 233 contractors has been analyzed through an exhaustive manual content analysis.

It was found that the likelihood of occurrence for accidents in industrial construction can be predicted by 51 independent attributes. Comparing to the study realized by Esmaeili and Hallowell (2012a), most of the 38 identified attributes are different from the ones in this current study. However, attributes like "*wind*", "*snow*", or "*poor visibility*" coincide. It was also found that "*hazardous substances*" and "*formwork*" are the attributes with higher relative risk scoring 1583.5 and 575.9 respectively. Additionally, the 50% percentile risk score for a task in industrial construction resulted to be 130.1 in the zero to infinity scoring scale (Table 7). This implies that tasks that involve "*hazardous substances*" and "*formwork*" attributes are already considered Very High Risk tasks. Past literature resulted to have a limited application. Scopes used in previous studies only covers small portions of the whole industry. Otherwise, the attribute base risk analysis presented in this paper covers all the possible environments and situations in industrial construction projects. This difference in scope and methods makes comparisons between results almost invalid.

As far as the content analysis also includes the part of the body affected, would be interesting to evaluate and include which part of the body has more probabilities to be injured when the attributes for a particular task are selected. Similarly, the injury code and energy source data could be used for the same purpose. Finding out correlations between the different statistical populations may result to uncover hazardous combinations of attributes for particular energy sources or parts of the body allowing safety managers and designers to perform even more effective strategies oriented to, for example, mitigate arm injuries. In a different way, applying the attribute base risk analysis results on worksites through the different possible preventive methods previously commented and then tracking any improvement would be an interesting exercise to know the effectiveness of the method. Finally, by amplifying the content analysis to contractors related to other sectors of the industry, the risk analysis and application would be extended to the whole construction industry.

As previously indicated, the attribute-base risk analysis performed in this study would allow designers to actively participate on safety performance during the design phase by providing alternative upstream attributes with lower risk. Additionally, safety managers would be able to perform risk profiles based on the attributes in a project. And finally, at a construction worker level, workers would be able to use the attribute-base information eventually implemented in a tablet that will assess risk for the particular activity a worker is about to perform.

The attribute identification process resulted to be the most challenging and crucial part of this study. Without any valid precedent on identifiable attributes on industrial construction projects, effort and rigor was required to our research team. Having the attribute list from this study would facilitate future studies having a benchmark to start with.

Concluding, we believe that this study can potentially become the foundation for future studies setting an attribute list and their associate risk values. This can be used for multiple purposes and can potentially improve safety in construction at different levels.

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