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# Information technology and safety

## Integrating empirical safety risk data with building information modeling, sensing, and visualization technologies

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Matthew Ryan Hallowell
*Civil, Environmental, and Architectural Engineering Department, University of Colorado at Boulder, Boulder, Colorado, USA*
Dylan Hardison
*Construction Engineering Management Department, University of Colorado at Boulder, Boulder, Colorado, USA, and*
Matthieu Desvignes
*Civil, Environmental, and Architectural Engineering Department, University of Colorado at Boulder, Boulder, Colorado, USA*

## Abstract

**Purpose** – The architecture, engineering and construction industry is known to account for a disproportionate rate of disabling injuries and fatalities. Information technologies show promise for improving safety performance. This paper aims to describe the current state of knowledge in this domain and introduces a framework to integrate attribute-level safety risk data within existing technologies for the first time.

**Design/methodology/approach** – The framework is demonstrated by integrating attribute safety risk data with information retrieval, location and tracking systems, augmented reality and building information models.

**Findings** – Fundamental attributes of a work environment can be assigned to construction elements during design and planning. Once assigned, existing risk and predictive models can be leveraged to provide a user with objective, empirically driven feedback including quantity of safety risk, predictions of safety outcomes and clashes among incompatible attributes.

**Practical implications** – This framework can provide designers, planners and managers with unbiased safety feedback that increases in detail and accuracy as the project develops. Such information can support prevention through design and safety management in advanced work packaging.

**Originality/value** – The framework is the first to integrate empirical risk-based safety data with construction information technologies. The results provide users with insight that is unexpected, counter-intuitive or otherwise thought-provoking.

**Keywords** IT strategies, IT/Design, IT building design per cent 26 construction, Health and safety, IT management, IT/CAD/VR

**Paper type** Research paper

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## Introduction and motivation

The architecture, engineering and construction (AEC) industry is known to account for a disproportionate rate of disabling injuries and fatalities. Unfortunately, the industry has reached saturation with respect to traditional safety strategies (Esmaeili and Hallowell, 2012), and the emerging risk-based methods have shown to not be robust enough to adapt the transient, dynamic and variable nature of construction work. To tackle these issues, researchers and professionals have tried to leverage emerging information technologies to improve construction safety. These technologies include virtual design, visualisation and simulation techniques and proximity sensing, and others. Although initial implementation of these technologies has shown promising results, the safety information modelled in these technologies is limited, as it is primarily based on expert judgment (Hallowell *et al.*, 2011) or is fabricated for purposes of illustrating the functionality of a new technological system. Until recently, there has been a dearth of safety information that is derived empirically and is robust enough to represent the wide variety of possible construction scenarios.

Researchers have, in fact, used a variety of data sources when attempting to model safety in emerging technologies. Although most researchers have presented application to safety conceptually, some have attempted to integrate rule-based data from government regulations such as Occupational Safety and Health Administration (OSHA). However, mature companies that currently use advanced technologies rarely struggle with basic compliance. Rather than regulation or rule-based safety information, mature organisations require objective knowledge of the location and timing of safety risks that are not necessarily intuitive. As hazard recognition skills are poor in construction (Albert *et al.*, 2014) and in design (Hansen and Hallowell, 2016), the AEC industry must rely robust and empirical risk-based information. Advanced technologies, in particular, require safety data that can be assigned to physical elements, construction materials and equipment, human tasks and modelled over time. Fortunately, attribute-based safety risk data have emerged that allow steps toward objective, four-dimensional (4D) safety risk modelling.

The attribute-based safety risk analysis theory holds that every injury is the resultant of the interplay between a worker or set of workers and a finite number of context-free attributes of the work environment. The theory derives its strength from the ability to model injury-causing characteristics of every possible construction situation in a finite, standardised format, regardless of the trade or project type (Esmaeili *et al.*, 2015a). Attributes include basic elements of the work environment such as uneven work surface, material at height, wind, light vehicle and many others. It is very important to note that no single attribute alone characterises the safety of the environment; rather, the environment is characterised by the aggregate and interrelationships among the multitude of attributes present in any environment. For example, the attribute "poor visibility" alone does not characterise the environment, but the composite of all of the observable attributes in an environment such as "poor visibility", heavy equipment", "uneven surfaces" and "mud" (Esmaeili *et al.*, 2015a, 2015b). According to Desvignes (2014), there are approximately 80 attributes that, collectively, can define the basic characteristics of any work environment.

In a multi-year process, Tixier *et al.* (2016) used natural language processing to transform unstructured injury reports to a structured database of attributes and safety outcomes. Using a combination of machine learning and graph theory, robust and accurate statistical models were created that can predict injury outcomes from combinations of attributes (Tixier, 2015). Such knowledge allows one to plan a construction environment, identify expected attributes of the work environment (e.g. welding, confined space and cold weather) and obtain probabilistic predictions of injury severity, body part affected, and injury type. Such data are well suited for technological integration because they can be assigned in three-dimensional (3D) space over time and only require a user to select from a finite list of possible attributes.

This paper describes the current state of knowledge related to the use of information technology for construction safety and codifies the literature related to the available attribute-based safety risk data. From this, a framework is proposed which integrates these data within existing technologies. The primary contribution is a new model for the objective integration of safety risk data with technological systems. If applied in practice, this model can provide designers, planners and managers with unbiased safety feedback that increases in detail and accuracy as the project develops. In theory, such information would support prevention through design and safety management in advanced work packaging. It should be noted that this paper does not present any technological development; rather, new data and the concept of risk-based integration are provided that may facilitate enrichment of current technologies or the development of new systems.

## Approaches to safety management using information technologies

Although there are many information technologies with the potential application to safety, the focus of this paper will be on the more prevalent technologies in literature, which include: barcode, radio frequency identification (RFID), ultra-wide band (UWB), global positioning system (GPS), geographic information system (GIS), visual monitoring (VM), virtual reality (VR), augmented reality (AR) and building information modelling (BIM). Each section follows the same structure, providing the reader with a brief overview of the technology, its application in construction and the specific ways it has been used to manage construction safety. This review is meant to provide context for the reader and is, by no means, a comprehensive review of all literature in the area of information technology.

### *Barcode*

Barcodes are now well known and widely used in almost all industry sectors. Barcode technology is based on printed symbol containing encoded rules, dimensional tolerances or print densities (Bell and McCullouch, 1988; Stukhart and Cook, 1990). Barcode scanners are needed to access stored data associated with the symbols. The strengths of barcoding are its ease of use, low cost and popularity.

Barcode technology has a large number of applications in the construction industry, mostly related to identification and tracking functions. Barcode technology is capable of reducing the amount of time for tracking materials, production or personnel on construction sites (Bell and McCullouch, 1988). The technology can also be implemented to measure how often certain tools or equipment is used and strategically schedule preventive maintenance (Rasdorf and Herbert, 1990). Furthermore, barcodes can be used in the design phase to identify documents, facilitate information flow and potential drawing revisions and notes (Rasdorf and Herbert, 1990). Interestingly, a thorough literature review has not yet revealed potential applications of barcodes to safety although, as will be discussed later, safety risk data may pose a new opportunity.

### *Radio frequency identification*

The function of an RFID system is to detect and locate tagged objects or persons through the transmission of data. A typical RFID system consists of three elements:

1. tags or radio transponders;
2. a computerised reader connected to a network; and
3. antennae.

RFID systems use radio frequencies to establish a connection between tags and readers, allowing the system to collect and transfer data in real time (Bhuptani and Moradpour, 2005).

RFID technology has been implemented widely in construction and has resulted in significant improvements. For example, Jaselskis and El-Misalami (2003) showed that the use of RFID can save 30 per cent of the time spent tracking materials and equipment. Additionally, these systems can record information such as the number of times a specific tag breaches a safety perimeter, how close a tag and a reader are at all times, and how operators react in risky areas (Fullerton *et al.*, 2009; Pradhananga and Teizer, 2012).

Researchers have applied this technology to safety by building real-time systems to alert workers and equipment operators when they become dangerously close to one another (Chae and Yoshida, 2008; Fullerton *et al.*, 2009; Hallowell *et al.*, 2010; Lee *et al.*, 2012). RFID technology, which has the ability to constantly monitor the physical distance between a tag and reader, is used to automatically alert machine operators of nearby ground workers (Fullerton *et al.*, 2009; Chae and Yoshida, 2010). Systems are typically composed of an antenna, a reader and an alarm in the equipment cabin. Ground workers are equipped with a Personal Protection Unit, which contains a tag, a battery and an alarm. When an equipped ground worker enters the reception field of a programmed reader both alarms are activated. Similar systems have been installed in warehouses, mines and train depots to notify employees when equipment approaches safety critical areas (Fullerton *et al.*, 2009; Teizer *et al.*, 2010).

### *Ultra-wide band*

UWB technology is similar to RFID in that it is a proximity and location detection system that uses radio frequencies to track the location of an object. Although more expensive to implement than RFID, UWB can transmit larger amounts of digital data (Ghavami *et al.*, 2004) and are less prone to signal disruptions because they can distinguish the direct signal path signal and provide better locational accuracy (Giretti *et al.*, 2009; Zhang *et al.*, 2012).

Even though UWB and RFID systems are similar in their applications, UWB is preferred when high accuracy and low error rate is essential. For example, Hwang (2012) and Zhang *et al.* (2012) investigated an application of UWB collision-prevention for tower crane safety. They highlighted that the efficiency and safety of tower crane operations highly depend on human cognitive ability, constant attention and intuitive perception. To reduce the risk of incidents, the researchers proposed a UWB system to monitor load trajectories and warn the operators when a potential collision is about to occur (Hwang, 2012; Zhang *et al.*, 2012). Additionally, Giretti *et al.* (2009) and Carbonari *et al.* (2011) implemented a human and equipment path monitoring system to alert workers when accessing hazardous zones.

### *Global positioning systems*

GPS are composed of satellites that constantly orbit the Earth and transmit radio signals. It was developed in a way that any location on the planet is in the line of sight of at least four satellites. By measuring the travel time of radio signals between a satellite and a receiver, GPS receivers are able to accurately determine the location in terms of latitude, longitude and altitude.

GPS use on construction sites has seen steady growth due to its increasing efficiency, range of application and decreasing cost. For example, GPS has been used in earth-moving operations to remotely monitor and control equipment in harsh environments (Oloufa *et al.*, 2003). Also, GPS is the only known tracking technology that does not require pre-installed infrastructure and does not suffer from dirty environments, large objects or changing environments where radar systems often fail (Behzadan *et al.*, 2008). GPS trackers have helped operators calculate trajectories and optimal path during truck loading or compaction activities during paving activities. By combining GPS and RFID technologies, the system was able to monitor asphalt-paving operations from production to the spreading of the desired thickness and temperature (Peyret and Tasky, 2002). Furthermore, it is used to indicate the number of required passes, areas previously covered and when the optimal compaction has been reached (Jaselskis *et al.*, 2001).

GPS, like RFID and UWB, has been used for collision avoidance and location tracking. Owing to GPS technology, the location, direction and speed of equipped vehicles can be monitored at all times and allow for the detection of a potential point of impact between equipment, people and physical objects. For example, GPS systems are able to calculate the braking distance needed to avoid collisions and can provide the necessary data for the automatic braking of equipment (Oloufa *et al.*, 2003). Current systems are, however, limited by the accuracy of the technology, the conditions of the site environment and the potential delays in delivering warnings or executing the command. Furthermore, GPS units can be used to track personnel. As an example application, Pradhananga and Teizer (2012) tracked workers on roofs or in the vicinity of equipment and used continuous data collection to identify zones where most unsafe activities take place and develop future safety plans.

### *Geographic information systems*

GIS is a broad term to designate different technologies, processes or methods designed to manage, analyse and assess all types of spatial information and geographical data. In construction, Li *et al.* (2003) used GIS systems to manage spatial information to optimise costs of transportation, select best value materials and propose efficient routes to deliver goods on construction sites. Moreover, Cheng and Yang (2001) developed a GIS-based tool called *MaterialPlan* to identify the best areas for materials storage. The authors also combined GIS with computer-aided design (CAD) to compute quantity takeoffs and generate bills of material. Bansal and Pal (2007) used AutoCAD combined with ArcView GIS software to add a visual dimension to the quantity takeoffs. GIS has also been used to help project managers depict spatial relationships and conflicts between construction objects on concrete dam projects (Zhong *et al.*, 2004).

GIS has been applied to construction safety. Bansal (2011) used it to integrate geospatial information such as topography, thermal comfort and flooding areas into construction planning. The author also developed a GIS safety database that was linked to construction schedules that would show when and where safety measures were needed. This system derived information from regulations and company policies and focused on managerial issues associated with common work types. During the design process, safety recommendations appear in the 3D model when a specific geographical configuration or component is used.

### *3D range imaging and visual monitoring*

3D range imaging camera systems measure the size, shape and location of objects within a camera's scene. By using laser systems, computers are able to take a physical environment and produce a computer image by measuring its physical characteristics (Lange and Seitz, 2001; Teizer *et al.*, 2007). These systems offer high resolution, rapid acquisition and high refresh rate and, thus, can adequately handle moving vehicles, equipment or workers (Teizer *et al.*, 2005).

Digital and 3D range imaging cameras are versatile in a sense that they offer a variety of uses within the construction industry. By accessing time-lapse pictures or video, managers can assess potential problems with a specific task, detect re-work at its early stages or predict upcoming roadblocks and anticipate heavy equipment trajectories (Bohn and Teizer, 2009). The use of VM and time-lapse photography can reduce information retrieval time and much more. In addition, these sequenced pictures can also be used for training, marketing strategies and legal purposes such as dispute avoidance and litigation (Bohn and Teizer, 2009).

Work safety can also benefit from the 3D range imaging technology. Hazards can be recognised remotely, improper work methods can be detected and missing protective equipment can be rapidly identified (Bohn and Teizer, 2009). Furthermore, Everett and Slocum (1993) introduced a video system – CRANIUM – to transmit a real-time picture of the loads to the crane operator for improved communication and safety. Finally, coupled with computer vision algorithms, Yang *et al.* (2011) demonstrated that the technology could recognise crane activities and track jib rotation and trolley position based on a color density measurement.

### *Virtual reality and simulation*

VR technology generates realistic environments in which the user is completely immerged in a computer model. To make a simulation an authentic experience, the system operates in near real time with response rates fast enough to make the movements and the numerous possibilities unconstrained and intuitive. Virtual reality technology could be a major element in revolutionising data presentation and information access, going beyond simple 3D representations (Caneparo, 2001). For example, Lin *et al.* (2011) created a simulation environment that integrates previously created training information into a navigable 3D environment. Additionally, the System for Augmented and Virtual Environmental Safety (SAVES) was developed that integrates a BIM with real photographs of hazardous energy sources and allows the operator to detect hazards and obtain immediate feedback (Albert *et al.*, 2014).

Professional VR training simulators have been developed for operators of tower cranes, excavators, mining trucks and bulldozers. In each of these simulations, the operator is asked to perform different maneuvers, lifts and loadings to practice for the real work environment (Wang and Dunston, 2005). During safety training, workers can survey the virtual site to detect dangerous zones or risks, and safety managers could monitor their performance and provide safety recommendations accordingly (Hadipriono and Barsoum, 2002; Hadikusumo and Rowlinson, 2002; Albert *et al.*, 2014). Furthermore, the ability to virtually explore buildings and infrastructure has made VR a viable tool for collaboration and prevention of safety hazards through design.

### *Augmented reality*

AR is a technology that creates an environment where real world objects and virtual objects are integrated and presented to the user. Unlike virtual reality, which is 100 per cent computer model, AR blends the real and virtual world. AR does not operate as a complete simulator where the user is totally immersed in the virtual world; rather, it operates as a tool to supplement reality by providing the individual with the elements needed to better interact with the environment (Lin *et al.*, 2014).

Wang and Dunston (2005) designed a training system by embedding an augmented workspace with virtual objects into the existing real work environment. Because of its flexibility, the system can generate training sessions that focus on the operator's needs and progression. Later, Wang and Dunston (2008) investigated how AR systems could enhance construction clashes, problem solving and design review. In their model, the user is able to interact with the virtual objects seen with a head-mounted display. Their test results showed that the participants using the system were faster to identify design errors. AR has also been used with GPS technology and traditional CAD models to detect existing subsurface utility lines during excavation work (Behzadan and Kamat, 2009).

## Building information modelling

BIM is an efficient tool to accurately design and generate a virtual digital model of a physical structure or project. The strength of BIM technology is its ability to enrich a virtual model with geometric properties of building elements with other information such as site schedule sequencing, product information and safety precautions (Kam *et al.*, 2003; Kaner *et al.*, 2008; Jordani, 2008; Howard and Björk, 2008; Goedert and Meadati, 2008).

Because BIM is an information-rich design technology, it can be used as a tool for safety management to monitor and diminish safety hazards during the construction phase. Collins *et al.* (2014) studied the use of 4D BIM throughout scaffolding activities to assist safety managers in implementing preventative measures by integrating expert's opinions and safety risk factors into the model. BIM has also been used for real-time work progress monitoring. By comparing as-planned BIM designs with the as-built structure captured by laser scanning technology, managers were able to effectively detect missing safety components such as guardrails or safety nets (Ciribini *et al.*, 2011, as cited by Chi *et al.*, 2012). BIM has also been paired with localisation and tracking technologies such as RFID, UWB, GPS and GIS to create sensing-warning systems that send alerts to workers when they enter a BIM predefined hazardous zone (Chae and Yoshida, 2008; Fullerton *et al.*, 2009; Costin *et al.*, 2014).

BIM technology has been helpful to enhance safety planning and training. Kim *et al.* (2014) proposed an automated information retrieval system that can search for and provide accident cases. The retrieval system extracts BIM objects and composes a query set by combining BIM objects with a project management information system. Lopez del Puerto and Clevenger (2010) illustrated BIM applications in safety planning by investigating potential pinch-point accidents ahead of actual material installation. Bansal (2011) has mixed BIM and GIS systems to help workers visualise the construction sequences along with its surrounding, so they better understand task interactions and safety recommendations.

Finally, some studies have investigated BIM's benefits for safer facility management, emergency plans and maintenance. Ruppel and Abolghasemzadeh (2009) assessed different fire safety scenarios to optimise emergency evacuation within a virtual BIM environment. Similarly, Leite and Akinci (2012) studied the vulnerability of facilities during an emergency by triggering a failure in the building system to identify critical assets.

The major limitation in this domain is that past research has focused extensively on technological development through automatic rule checking, integration of regulations and interoperability with other technologies. The systems could be improved through the use of reliable safety information that provides users with objective, empirically driven feedback that is not intuitive or easily accessed in regulations. This is especially important for mature organisations whose safety efforts have exceeded compliance and basic rule-based systems. This paper aims to address this information gap (Table I).

## Attribute-based risk assessment theory and available data

Safety risk analysis has emerged as a promising technique for objectively modelling the safety of various aspects of construction work. In contrast to advances achieved in risk analyses for other project management functions like cost control, the development of safety risk analysis has lagged because data sources are generally derived from human ratings of risk that are vulnerable to biases in subjective probability judgment, and the units of analysis are either so overly broad that they have limited application to specific work scenarios or addition to existing data sets requires a laborious research process. Attribute-level safety risk analysis addresses these limitations and has proven both robust and extensive in its applications.

Attribute-based safety risk data and theory has been developed over the past few years, including initial content analysis and basic analyses (Esmaeili *et al.*, 2015a), data for specific construction sectors such as industrial (Prades, 2014) and infrastructure (Desvignes, 2014), relationship between attributes and outcomes (Esmaeili *et al.*, 2015b), safety clash data Tixier *et al.* (2016) and natural language processing to improve the quality and quantity of available data. This manuscript provides a detailed review of the state of the art within this field and describes the composite data available from the plethora of data from past research.

The attribute-based safety risk analysis framework was originally described by Esmaeili *et al.* (2015a) who focused on identifying the basic, context-free elemental characteristics of construction work. By focusing on the elemental conditions (e.g. wind, stairs, insects and lumber), risk was shown to be characterised independently of a task or environment. Yet, the elemental risks can be aggregated to characterise nearly any common environment. That is, the attribute-based approach is built upon the theory that safety risk of a specific situation is characterised not by the trade or activity type but, rather, the aggregate of specific characteristics of the environment.

**Table I.** Studies that have used information technology to improve construction safety

| Technology | Authors | Data sources | Data use |
|---|---|---|---|
| RFID | Fullerton *et al.* (2009) | None | Proximity and warning devices; Collision avoidance |
| | Chae and Yoshida (2010) | None | Proximity and warning devices; Collision avoidance |
| | Teizer *et al.* (2010) | None–At user's discretion | Proximity and warning device; Collision avoidance |
| | Lee *et al.* (2012) | None | Real-time locating system; Possible warning system |
| | Marks and Teizer (2013) | None | Proximity and warning device; Collision avoidance |
| UWB | Giretti *et al.* (2009) | None–At the user's discretion | Real-time locating system; Virtual fences for dangerous zones; Warning system |
| | Carbonari *et al.* (2011) | None–At the user's discretion | Real-time locating system; Virtual fences for *overhead* hazard zones; Warning system |
| | Hwang (2012) | None | Crane operator support; Collision avoidance; Warning |
| | Zhang *et al.* (2012) | None | Crane operator support; Collision avoidance; Warning |
| GPS | Oloufa *et al.* (2003) | None | Vehicle Tracking; Collision avoidance; Warning system |
| | Pradhananga and Teizer (2012) | Arbitrary proximity areas (10 m) | Continuous collection of location/proximity data between workers, equipment and hazardous areas |
| GIS | Cheng *et al.* (2002) | Experts' knowledge and experience<br>Individual's judgments and past experiences | Geographic data collection for computer-aided decision support in excavation operations |
| | Bansal (2011) | Experts' knowledge and experience<br>Bureau of Indian Standards (BIS) codes | 4D GIS for construction safety planning |
| VM | Everett and Slocum (1993) | None | Real-time crane operator support system |
| | Bohn and Teizer (2009) | Experts' knowledge and experience | Site camera monitoring for remote hazard recognition |
| VR | Hadipriono and Barsoum (2002) | Experts' knowledge and experience | Virtual training for scaffold erection and hazard recognition in existing platforms |
| | Hadikusumo and Rowlinson (2002) | UK Health and Safety Executive (HSE)<br>Occupational Safety and Health Act (OSHA) and other government regulations | Design for safety tool<br>Hazard recognition at the design phase |
| | Lin *et al.* (2011) | Safety training materials | Virtual hazard recognition training |
| | Albert *et al.* (2014) | Expert knowledge and experience | Virtual hazard recognition training |
| AR | Wang and Dunston (2005) | None–At user's discretion | Equipment operator training |
| | Behzadan and Kamat (2009) | Construction site experience<br>Reaction to a known life-threatening problem | Utility lines damage prevention Warning system |
| | Yeh *et al.* (2012) | None | Safety information retrieval system |

(*continued*)

Table I.

| Technology | Authors | Data sources | Data use |
|---|---|---|---|
| BIM | Teizer *et al.* (2005) | Bureau of Labor Statistics work zone fatality and injury statistics | Real-time laser geometric 3D modeling of transportation infrastructure |
| | Teizer *et al.* (2007) | 277 total experiments of video capture | Automatic tracking of static and mobile construction objects and personnel for obstacle detection and warning |
| | Lopez del Puerto and Clevenger (2010) | Engineering controls<br>Administrative controls experts' knowledge and experiences | BIM-enabled safety controls<br>Elimination and substitution of hazards at the design phase + 3D visualization of construction sequences |
| | Hammad *et al.* (2012) | Safety Code of Quebec Provence | Generation of dynamic virtual fences<br>Collision avoidance + Fall protection<br>Warning system based on RTLS |
| | Chi *et al.* (2012) | Workplace Health and Safety Queensland<br>Occupational Health and Safety legislation<br>Experts' knowledge and experience | 3D BIM scaffolding and formwork objects for incorporation with safety features and constructability<br>BIM checklist for safety inspection |
| | Zhang *et al.* (2013) | Occupational Safety and Health Act (OSHA)<br>Construction best practices | Automated safety rule checking<br>Prevention through design computer software compliance checking and safety suggestion |
| | Cheng and Teizer (2012) | None | 3D BIM evaluation of tower crane positions for construction safety planning |
| | Qi *et al.*, 2014 | Experts' knowledge and experience<br>Safety manuals and checklists<br>Government regulations | Automated safety rule checking<br>Prevention through design software-based system<br>Compliance checking and safety suggestion |
| | Lin *et al.* (2014) | None | Enhance discussion by using a BIM table to provide visual content and quick information retrieval, task schedule and construction processes |
| | Kim *et al.* (2014) | UK Health and Safety Executive (HSE)<br>Occupational Safety and Health (OSHA) and other government regulations | Safety information retrieval based on workers' profile for hazard recognition program |
| | Kim and Teizer (2014) | Occupational Safety and Health Act (OSHA)<br>Scaffolding Regulations | Automatic design and planning of scaffolding systems using BIM |
| | Collins *et al.* (2014) | Industry safety professional survey of risk factor and risk level for scaffolding | 4D BIM system for safety management of scaffolding activities at each stage of the project |

Solar panel installation provides a strong example of the application of the attribute-based risk analysis method. Traditionally, a researcher would attempt to quantify the safety risk of the generic task *solar panel installation*. However, solar panels may be installed in a variety of different circumstances. For example, they may be installed at height or on the ground, on flat or uneven surfaces, in windy or calm conditions, using manual or power tools and so forth. The attribute-based risk analysis method suggests that the true safety risk of *solar panel installation* is actually characterised by the elemental attributes and is independent of the task label. Although Esmaeili *et al.* (2015a) identified some of these elemental attributes, Desvignes (2014) expanded upon this work to uncover 80 the attributes shown in Table II. These attributes represent all basic characteristics observed in over one million worker-hours of data.

The power of the attribute-based method of safety risk analysis lies in the predictive validity of the attributes and the discovery that attribute pairs, when incompatible, represent distinct safety clashes that should be avoided. To build a suitable data set for large-scale data science, Tixier *et al.* (2016) developed a natural language processing system capable of automatically extracting structured attribute data from unstructured written injury reports. The system has achieved 97 per cent reliability using a rule-based lexicon. With this system, Tixier *et al.* (2016) extracted data from over 7,000 reports, which were subsequently analysed using diagnostic and predictive statistics as shown in Figure 1. The various analytics performed on the data and the resulting practical outcomes are described below. As an example, the simple statement "worker was bolting a steel connection with a wrench and loose bolts with no gloves […]" returns the attributes "bolt", "steel section", "No/improper personal protective equipment (PPE)" and"Hand tool".

| Cable tray | Rebar | Screw | Grout | Bolt | Working overhead |
|---|---|---|---|---|---|
| Cable | Scaffold | Slag | Guardrail | Cleaning | Improper body position |
| Chipping | Soffit | Spark | Heat source | Forklift | Improper procedure |
| Pontoon | Spool | Poor visibility | Heavy material | Hammer | Insecure materials |
| Concrete | Stairs | Small particle | Heavy vehicle | Small pieces | Improper security of tools |
| Conduit | Steel | Cold | Job trailer | Hose | No/improper PPE |
| Confined | Stripping | Hand tool | Machinery | Insect | Object on the floor |
| Congestion | Tank | Unstable surface | Man lift | Ladder | Poor housekeeping |
| Crane | Lumber | Wind | Slippery surface | Mud | Uneven walking surface |
| Door | Valve | Wrench | Object at height | Nail | Repetitive motion |
| Dunnage | Welding | Lifting/pulling | Piping | Powered tool | Working below elevated |
| Electricity | Wire | Light vehicle | Transporter | Splinter/sliver | Hazardous substance |
| Formwork | At height | Transitioning | Concrete liquid | | |
| Grinding | Drill | Stud | Sharp edge | | |

**Table II.**
Complete list of attributes

## Prediction of safety outcomes

If the attribute-level theory holds true, attribute combinations should predict potential safety outcomes. In other words, the observable attributes of workplace that exist prior to an incident should predict the outcomes of the incident such as the injury type, severity, body part injured and energy involved (Figure 2). Tixier (2015) tested this theory by using two prominent machine learning algorithms: stochastic gradient boosting and random forests. The models were verified by measuring the extent to which the outcomes of set-aside injury reports could be predicted by the attributes observable prior to the outcome. The results indicated strong skill for injury type, body part affected and energy source but low skill for the prediction of injury severity. The implication is that, by simply identifying a set of attributes for a new observation, existing algorithms can be used to create a probabilistic forecast of several safety-related outcomes. Such feedback is well-suited for integration with information technology because a user may simply assign attributes in the BIM model and safety-related outcomes can be reliably forecasted. An upstream user (e.g. designer or planner) can attempt to reorganise work to improve safety or to communicate safety concerns to downstream users (e.g. construction managers and work crews).

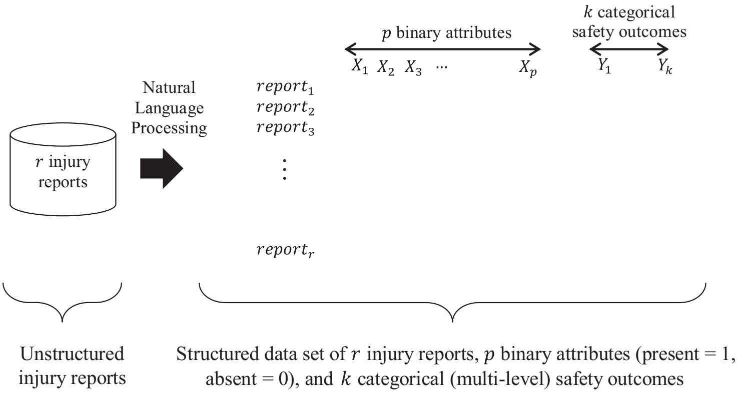


**Figure 1.** Representation of the process of converting raw, unstructured injury reports into a structured binary data set

**Source:** Tixier *et al.* (2016)

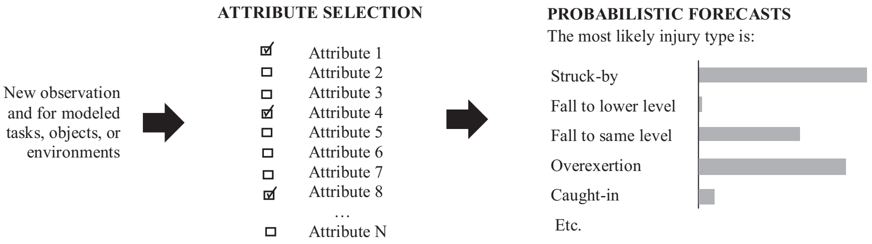


**Figure 2.** Creating probabilistic forecasts for a new observation by identifying attributes and using machine learning

**Source:** Tixier *et al.* (2016)

## Risk analysis

To complement probabilistic forecasts of safety outcomes, risk analysis of the attributes has been performed by multiple researchers (Prades, 2014; Desvignes, 2014). By simply computing the risk of each attribute, the overall risk has been computed by summing the risk of the individual attributes for a new observation. The risk of the attributes has been computed for the large-scale data set using a frequentist approach. With Monte Carlo analysis, a new observation can be interpreted as low, medium, high, very high and extreme based on the comparison of a new observed risk magnitude and the full distribution of all past risk magnitudes. Researchers and practitioners have long desired to map safety risk early in the design process. However, actual risk data were elusive. The risk values computed by Prades (2014) and Desvignes (2014) show great potential for n-dimensional modelling of safety risk in information technologies. This work is different from Esmaeili *et al.* (2015a) in that the data analysed are for industrial construction projects (Prades, 2014) and infrastructure project (Desvignes, 2014) rather than general industry data. Additionally, the data of Prades (2014) and Desvignes (2014) were collected from detailed contractor-provided accounts of injuries, whereas Esmaeili *et al.* (2015a) used very brief OSHA reports available from a national database.

## Diagnostics for clashes

The large-scale data set created by Tixier *et al.* (2016) was analysed to discover rare but valid incompatibilities among fundamental attributes that would not be identifiable based on the experience of any one person alone. That is, the goal was to identify clashes among fundamental attributes that should be avoided. To achieve this goal, two unsupervised machine-learning techniques were leveraged: graph mining and hierarchical clustering on principal components. The inquiry revealed that there are a definitive set of clashes that should be avoided that include working at height and unpowered tools; wind and hazardous substances; welding and working below elevated work surfaces and others. As will be shown, these clashes are very well suited for safety modelling in BIM and other information technologies because they can be programmed to flag a clash based upon very simple rules (i.e. flag when attribute A is present in vicinity of attribute B).

As discussed, the purpose of this paper is to showcase how emergent information technologies and promising attribute-based safety data can be paired to facilitate safety feedback that is reliable, timely and information-rich. Rather than modelling safety rules based on regulations, company rules or expert opinion, feedback can be derived from empirical aggregated from millions of worker-hours of observation. The subsequent section describes a vision for this data integration using several examples of previously reviewed information technologies.

## Research methods

This paper does not follow a “traditional” methodological approach *per se*. Rather, it “blends” a mixed methods approach to purposefully conceptualise, identify and classify objective safety data (re: integration) - cognisant of emerging information technologies. Acknowledging this, a series of exemplars are provided to support the narrative. By leveraging nascent attribute-level safety risk data, diagnostics and predictive models, a framework is described that allows users to assign safety information in IT and obtain a litany of objective, research-validated feedback in the various phases of the project lifecycle. The framework has been developed by reviewing and codifying literature related to predictive safety modelling and IT and logically connecting these previously disparate bodies of knowledge. It is important to note that only empirical, validated safety risk data are leveraged in this framework to preserve the veracity of the data and the overall framework.

## Integrating safety risk with information technologies

The principal theory for integration involves the assignment of one or more of the attributes listed in Table I to the physical objects, tasks, construction objects and other items that characterise a construction environment. Once assigned, algorithms developed by Tixier (2015)), Desvignes (2014) and Prades (2014) can be used to:

- measure and interpret risk;
- predict safety outcomes such as body part affected and injury type;
- flag clashes; and
- identify vulnerabilities to downstream attributes such as misuse of PPE.

In other words, the simple assignment of attributes in a binary format (i.e. attribute exist or not) provides a user with a plethora of feedback.

There are some general rules that help to describe when a particular attribute can be modelled using a particular technology. For example, tag-based technologies such as barcodes and RFID can only be used on physical objects (e.g. a tool) or environmental conditions associated with a physical object (e.g. poor visibility in a piece of equipment). Tasks and most environmental conditions cannot be easily tagged, as they are not always associated with physical objects. Likewise, BIM and GIS technologies involve the creation of virtual models of actual projects and, as such, can only be used to model attributes that are reasonably identifiable prior to construction. Similarly, VM can be used to track observable objects and tasks when time lapse videos are used; however, it cannot be used to model more abstract elements such as heat or small objects like insects. Fortunately, simulation technologies can be used to model a wide range of attributes because a programmer has freedom to design the elements of the environment. Although some attributes would be very complex to model (e.g. improper procedure), it is technically feasible. Table III is provided to map a sample of attributes to the technologies reviewed. We used only a sample for brevity.

In addition to the specific examples of data selection shown above, the output of the machine learning, risk and clash algorithms have a variety of applications across technologies. For example, safety clash data can be used in any dynamic location or tracking technology or visualisation system when various objects, workers or tasks may interact in space and time. By pre-assigning attributes associated with each object or task and programming potential clashes as a set of rules, information technologies can proactively alert users of incompatibilities. Similarly, safety risk can be integrated with technologies that involve visualisation and information retrieval. Table IV is a crosswalk matrix showing the application of safety data in the salient technologies.

Some detailed examples of the vision for integration of these data with technologies is described with graphics below. For brevity, integration with four types of technologies was used to illustrate potential integration methods: information retrieval, proximity sensing, BIM and augmented virtuality (AV).

| Attribute | Classification | Information technology<br>Barcode | RFID | UWB | GPS | GIS | VM | VR | AR | BIM |
|---|---|---|---|---|---|---|---|---|---|---|
| Chipping | Task associated | | | | | | × | × | × | |
| Concrete | Physical facility element | × | × | × | × | × | × | × | × | × |
| Conduit | Physical facility element | × | × | × | × | × | × | × | × | × |
| Congestion | Task associated | | | | | | × | × | × | |
| Crane | Tool or equipment | × | × | × | × | × | × | × | × | × |
| Door | PHYSICAL Z | × | × | × | × | | × | × | × | |
| Formwork | Physical construction element | × | × | × | × | × | × | × | × | × |
| Grinding | Task associated | | | | | | × | × | × | |
| Rebar | Physical facility element | × | × | × | × | × | × | × | × | × |
| Scaffold | Physical construction element | × | × | × | × | × | × | × | × | × |
| Visibility | Environmental condition | | × | | | | | × | × | |
| Cold | Environmental condition | | | | | | | × | × | |
| Hand tool | Tool or equipment | × | × | × | × | | × | × | × | |
| Unstable surface | Task associated | | | | | | × | × | × | |
| Wind | Environmental condition | | | | | | | × | × | |

**Table III.** Crosswalk table showing sample attributes that can be assigned and modelled within IT

| Attribute data type | Information technology<br>Barcode | RFID | UWB | GPS | GIS | VM | VR | AR | BIM |
|---|---|---|---|---|---|---|---|---|---|
| Safety risk | × | | | × | × | × | × | × | × |
| Predictions of outcomes | × | | | | | | | × | × |
| Safety clashes | | × | × | | × | × | × | × | × |

**Table IV.** Crosswalk table showing the data output and potential integration with IT

## Information retrieval

Machine readable barcode systems are an excellent tool for information dissemination. Barcodes can be placed on construction materials, tools and equipment and be accessed by employees smartphones or other designated scanners to view necessary product and safety information. Figure 3 shows a form of barcode known as quick response (QR) code. This type of barcode can be linked to custom websites that include any form of safety data. In the example shown in Figure 3, one could scan a QR code and obtain a report indicating the riskiness of the tagged item, types of safety outcomes typically associated with the item, main causes of past injuries and safety recommendations. When a part of a more complex construction environment, the website could also contain potential clashes and vulnerabilities. Once created, the associated websites could remain in use for multiple projects and construction trades. Most importantly, the information retrieved could be integrated with job safety analyses and other pre-task safety planning techniques. Additionally, such information could be used for dynamic safety planning. As workers encounter new situations barcodes that hag construction attributes could be used to retrieve pertinent safety information.

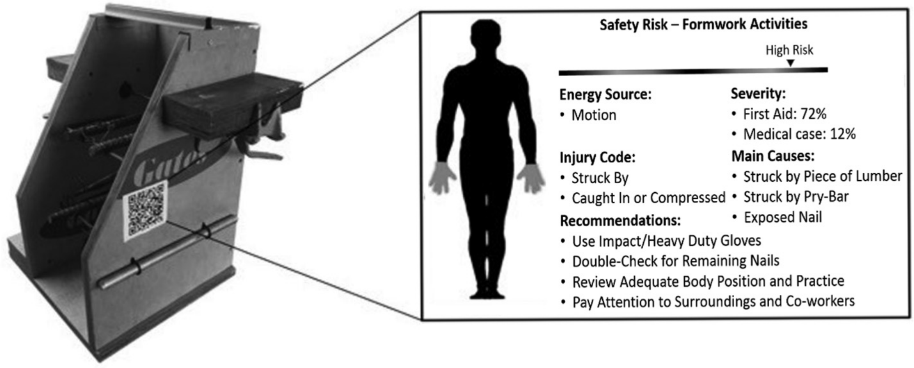
Despite potential benefits of the proposed integration, there are many limitations with using barcodes as described. A construction site is not conducive to stickers or paint, which are common methods for affixing barcodes. Barcodes on construction equipment such as concrete formwork, trench boxes, ladder jacks and scaffolding may be damaged in a rough construction environment. Also, if the project site does not have internet connectivity or precludes the use of mobile phones, workers would need a designated reader and a local intranet.

### Location and tracking

RFID technology has been used widely to provide workers with warnings as they enter unsafe work zones. However, most applications are limited to equipment-worker or equipment-equipment interactions. By tagging construction materials, equipment, tools and other physical attributes with RFID tags and linking the tag to the RFID network, workers could be alerted to potential clashes among a wide variety of elements. As previously described, Tixier (2015) identified a plethora of safety clashes that exacerbate construction safety risk. As clashes are predetermined spatial conflicts that would occur when a hazardous attribute enters a pre-determined hazard zone surrounding another hazardous attribute, these are well-suited for RFID tagging.

Figure 4 illustrates the example of a chemical and a confined space. This a very important clash, identified in the diagnostic analysis of attribute-level data, because methylene chloride displaces oxygen causing dangerous deficiencies known to cause multiple fatalities each year. The example shows that an RFID tag could be placed both on the chemical container and at the entry of the confined space to provide a warning when the two attributes are in proximity. Another example of a clash that could be avoided with the use of RFID includes tagging the mast of a forklift and overhead objects such as electrical boxes, lighting and sprinkler systems to avoid contact. In theory, RFID could be used to tag and track a plethora of dangerous attributes through and could be the primary mechanism by which safety clashes could be detected and avoided during construction.

There are some limitations with the application of RFID tags. First, RFID tag signal transmission can be disrupted by objects in the path of signal travel. In this case, UWB is stronger than RFID but can still suffer signal disruptions from nearby objects (Ghavami *et al.*, 2004). Furthermore, from the example above, employees may perceive it to be safe to bring hazardous chemicals into an area if they begin to rely upon but do not



**Safety Risk – Formwork Activities**

**Energy Source:**
- Motion

**Severity:**
- First Aid: 72%
- Medical case: 12%

**Injury Code:**
- Struck By
- Caught In or Compressed

**Main Causes:**
- Struck by Piece of Lumber
- Struck by Pry-Bar
- Exposed Nail

**Recommendations:**
- Use Impact/Heavy Duty Gloves
- Double-Check for Remaining Nails
- Review Adequate Body Position and Practice
- Pay Attention to Surroundings and Co-workers

**Figure 3.**
An example of how a QR Code/Barcode can be applied to concrete formwork for product safety information retrieval

**Note:** This information would appear on cell phone or designated reader

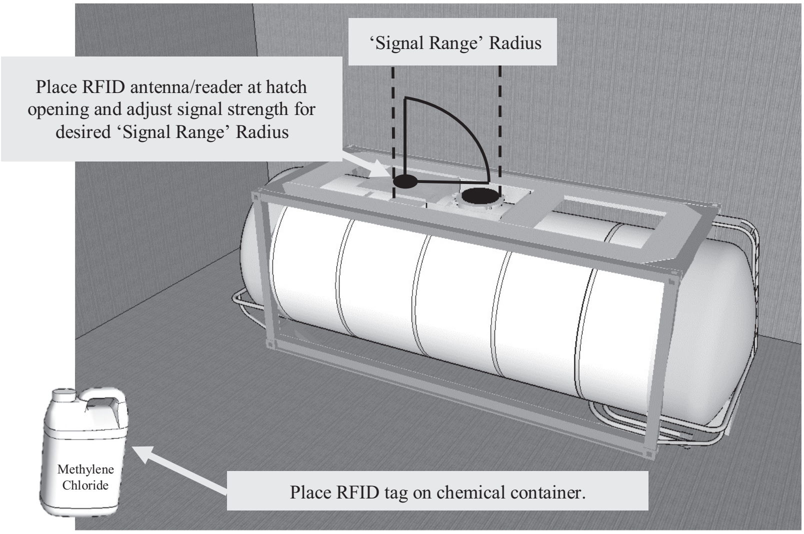


**Figure 4.**
Example integration of attribute clash data and RFID tagging

receive RFID warnings. Finally, it may be challenging to implement RFID applications in construction as construction sites are dynamic in nature and the costs of tagging and un-tagging attributes could be laborious and expensive.

## Building information modelling

Attribute-based safety risk data are very well suited for integration with BIM. The concept of tagging virtual elements with specific data is a principal function of BIM. Currently, BIM systems track time, cost, resources and many other items as assigned by a user. Systems even are able to detect and avoid time-space conflicts among building components. Unfortunately, safety in BIM has seen comparatively little emphasis, despite the potential to identify and correct safety concerns early in the project lifecycle.

The integration of the attribute safety data with BIM requires three components:

1. functionality to allow a user to assign safety attributes to BIM elements;
2. embedment of risk and prediction algorithms; and
3. empirical rules associated with temporal and spatial conflicts among attributes.

If included, feedback in terms of risk, prediction and safety clashes can be automated following the creation of the model and assignment of the attributes. Figure 5 shows the concept of assigning attributes to BIM and receiving feedback. The figure shows two BIM elements (welded connection and doorway framing), their attributes and the associated feedback. Although crude, the figure is intended to show that simply selecting the characteristics of the element can provide feedback based on empirical evidence derived from past observation.

In addition to what is shown in Figure 5, numerical risk can be linked to BIM to reflect high risk locations and periods. A basic interpretation (i.e. low, medium, high) could be used to create a 4D heat map of safety risk. Such a heat map, when also integrated with the schedule, could provide valuable insight on what is dangerous, when danger is

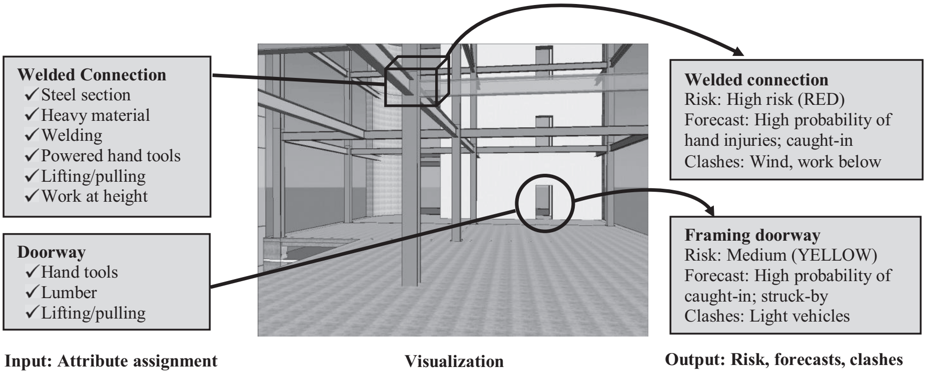


**Figure 5.**
BIM with attribute selection and safety feedback

posed and where the danger resides. With this information, risk can be prioritised and controlled before it is encountered by workers.

With hazard inventories tagged to building model components, BIM users can have access to the information needed to make informed safety decisions. This information can be used to alter the design or construction processes to reduce risk and avoid clashes. Residual safety concerns can be communicated to downstream stakeholders and can inform job hazard analyses used in pre-task safety meetings. Finally, remaining attributes can be used to forecast risk for maintenance operations.

There are limitations of this suggested integration. First, the attribute safety data do not include all hazards posed, instead a user may model an environment based on commonly encountered characteristics. Therefore, there are many hazardous situations that may not be included in the dataset. Thus, the feedback must be considered supplemental other safety techniques. Second, tagging safety attributes to each building component is tedious, as there is a great deal of elements and attributes. Fortunately, some elements are stable and consistent with their associated attributes and, as such, can be modelled consistently across models. Additionally, other rule checks can be added to assist with automation. The result would be a combination of manually assigned and automatically assigned attributes. Even though there are some barriers, safety in BIM using empirical data could be a transformative improvement for the industry as it moves safety upstream.

## Augmented reality

Various AR and AV systems exist that have been used for safety training and education. As the systems are immersive, with an avatar and high-fidelity representations of construction work environments, they are well suited for integration of rich safety data. Current systems, like SAVES (Albert *et al.*, 2014), have a small number of identified hazards used for training and feedback. These systems would benefit from risk-based feedback that can be automatically integrated via attribute assignment. As the training environments are pre-programmed, safety-related data can be integrated one time and remain stable within the systems. Similar to BIM, heat maps would provide very valuable feedback and training scenarios to assist with hazard identification and risk perception calibration.

Figure 6 shows how attribute safety data can be integrated with an AV environment. The figure depicts attribute assignment and very basic feedback. Additional feedback in terms of prediction and clashes could also be provided. Here, steam piping is selected to show how safety risk changes based upon location. In the top scenario, the height of a fall is maximised. In the middle scenario, there is a risk of falls and also risks associated with working directly below an elevated workspace. Finally, the bottom scenario shows work on the ground below elevated spaces. This figure illustrates that the risk of injury can be defined by subtle changes in the defining attributes. Using the risk data, heat maps of risk could also be provided in the systems if spatial effects of the attributes are assigned. Such information would greatly enhance the training environment and would add strategy to the game play.

## Conclusion

This paper provides a thorough assessment of the current state of the art associated with using information technology to improve construction safety, and has introduced a series of studies that provide empirical safety data that can be used to enhance existing models. The underlying proposition offered is that fundamental attributes can be assigned to design and construction elements and existing risk and predictive models can be leveraged to provide a user with objective, empirically driven feedback.

To support the proposed methods, technologies must be altered to accept attribute assignment and embed existing algorithms that can produce risk, prediction and clash feedback. The conceptual mechanics are relatively simple. A user simply needs to select the attributes associated with an element and existing algorithms could use this binary input to yield feedback. Such integration in practice would require programming and partnering with the data scientists who have created the predictive models to ensure that the systems produce correct forecasts and feedback. Once developed, the systems must be carefully field tested to understand the implications that new feedback has on perception of safety risk, decision-making, collaboration, communication and other safety-critical constructs to avoid undesired consequences.

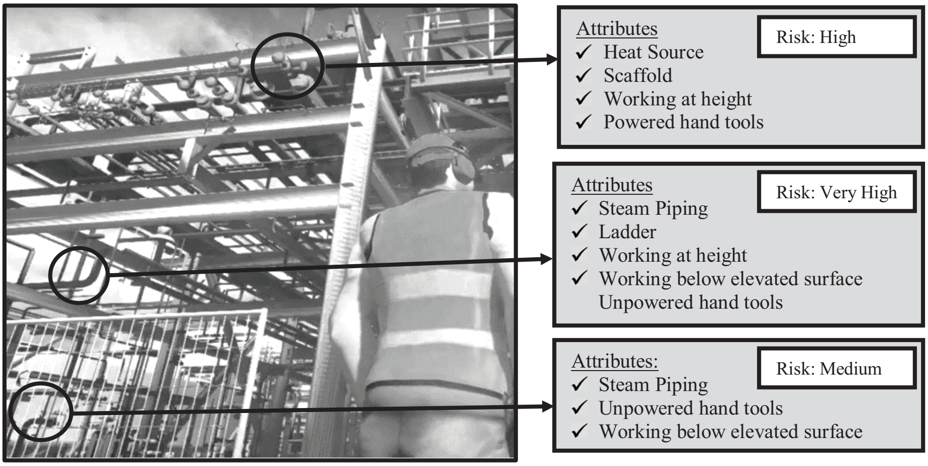


**Figure 6.**
Example integration of attribute risk data with SAVES

There are several limitations associated with the data presented and the integration proposed. First, the predictive models have been created from reports of past injuries. As such, the models only allow one to predict the outcomes of an injury *if one should one occur*. In other words, the models are not able to distinguish between failure and success. Second, the clashes and predictive models show an association between the attributes and outcomes but causal inferences cannot be inferred. Third, although the algorithms exist, the developmental activities to integrate them with technologies have yet to be performed, and there have yet to be any field tests to measure the extent to which the information supports the awareness of the users. Such field validation would be an important extension of this research that could translate theory into practice. Fourth, as previously discussed, not all attributes can be used in all technologies. For example, visibility issues, human errors and regulatory and violations cannot be identified reliably in design or pre-construction thereby limiting their application in BIM. Finally, for barcode and RFID tagging, the tagged aspects of the work must be physical elements.

Researchers may wish to explore how attribute-based safety data could be used to support interoperability among multiple systems. For example, data modelled in BIM maybe useful for GIS, sensing and barcode systems during construction. As the major resource requirement needed to use the models is the time required to assign attributes, the concept becomes more feasible if some attributes are assigned in design and planning and the information is carried forward to and supplemented in the construction phase. This longitudinal process of data enrichment could serve as a new model of safety planning that is derived based on a very large volume of past observation rather than being driven by the limited experience of a small number of safety professionals.

The intent of this paper was to provide a new concept for safety data integration that complements but does not replace existing methods of safety in IT. As indicated in the background, there has been a great deal of high-quality research in this domain. The proposed method offers an opportunity to leverage a high volume of empirical data to create reliable feedback that may provide insight that is unexpected, counter-intuitive or otherwise thought-provoking. It is through such discourse that safety decisions can be improved and safety management can mature past compliance.

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## Corresponding author

Matthew Ryan Hallowell can be contacted at: matthew.hallowell@colorado.edu