REQUISITE EMPIRICAL RISK DATA FOR INTEGRATION OF SAFETY WITH ADVANCED TECHNOLOGIES AND INTELLIGENT SYSTEMS

by

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Requisite empirical risk data for integration of safety with advanced technologies and intelligent systems

Thesis directed by Professor Matthew R. Hallowell

The Construction field is known to account for a disproportionate number of disabling injuries and fatalities. Unfortunately, the industry has reached saturation with respect to the 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, professionals have tried to adapt emerging technologies and intelligent systems to improve construction safety. Also, empirically driven attribute-based risk data have been introduced but have been limited in application to struck-by injuries (Esmaeili 2012). Despite these advancements, there are still major limitations with significant opportunities for improvement. In this study, the authors review the actual safety applications of ten technologies to highlight the quasi-systematic lack of robust safety data as sources. They then present an attribute-based risk analysis method as a mean to improve the quality and versatility with which safety data can be integrated with technologies in both design and construction. Our team vastly improves the quality and quantity of available data by considering all injury types and leveraging 7,033 detailed injury reports provided by a total of 243 independent contractors. In total, 79 safety attributes were identified following a strict manual content analysis procedure and an attribute-based risk analysis was conducted based on these robust and viable safety data. The findings indicate that 'No/Improper PPE' (69.49), 'Pontoon' (21.75), and 'Lifting/Pulling' (20.54) attributes presented the highest risks on construction sites. New safety applications and insights are detailed as primary uses of the attribute risk data with the technologies. The authors also discuss the combination of several technologies to

create an intelligent system that aims at reducing the number of injuries on worksites. The combination of attribute risk data and technologies is believed to have the potential to change safety managers' approach to construction risks, lay the foundations for innovative technological safety applications and make construction sites safer.

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INTRODUCTION

Despite significant efforts to improve safety and the increased implementation of injury prevention strategies in the past few decades, the construction industry still accounts for one of the highest fatal occupational injury rates among the U.S industry sectors. Indeed, according to the Bureau of Labor Statistics (2013) data, its preliminary fatal occupational injury rate equals 9.4 per 100,000 full-time equivalent workers for an annual all-worker fatal injury rate of 3.2. Moreover, the construction sector has consistently accounted for the most fatalities of any industry in the private sector since 2005, with a preliminary count of 796 fatal injuries in 2013. Even though these figures have significantly decreased following the inception of the Occupational Safety and Health Act (OSHA), construction injuries, illnesses, and fatalities still have a dramatic impact on the economy of the country and most importantly on workers' families. Because of economic and productivity impacts associated with these events, improving safety has become the priority of many construction professionals (Gambatese 2008).

Unfortunately, the industry has reached saturations with respect to the traditional safety strategies originally implemented to comply with OSHA regulations (Esmaeili and Hallowell 2012). Risk-based approaches have begun to emerge in an effort to formalize the safety management process and integrate it with other project management functions. Unfortunately, existing risk data upon which these methods are built are not robust enough to adapt the transient, dynamic, and variable nature of construction work. They usually are limited to a certain number of situations, work task scenarios, and are highly dependent of past injury cases or safety managers' experiences. As a consequence, the demand for both new injury prevention practices and more robust risk data has rapidly grown in the last decade.

Although the construction industry is well-known for its slow adoption of innovative products (Egan 1998; Navon and Sacks 2007), researchers and professionals have tried to adapt emerging technologies and intelligent systems to improve construction safety, which include Global Positioning Systems (GPS), Radio Frequency Identification (RFID), and Virtual Reality (VR). Although initial implementation of these technologies has shown promising results for safety, the safety information used in these technologies is severely limited as it is primarily based on regulations, intuition, or judgment (Hallowell et al. 2011). To address this issue, Esmaeili (2012) introduced empirically driven attribute-based risk data that model construction injuries as resultants of the spatial and temporal relationships among a finite number of characteristics of the work site. Such data have the potential to be integrated with advanced technologies and intelligent systems to address a wide array of potential construction scenarios early in the project delivery process.

In the initial demonstration of attribute-based safety risk analysis Esmaeili (2012) identified attributes for struck-by injuries from 1,771 brief injury reports contained in National databases. In this study, our team vastly improves the quality and quantity of available data by considering all injury types and leveraging 7,033 detailed injury reports provided by a total of 243 independent contractors. In this study, we also explore how these data can be integrated within emerging technologies and intelligent systems to address pervasive and systematic limitations of the application of these systems for safety management.

LITERATURE REVIEW

The focus of this literature review is on emerging technologies and intelligent systems that, according to the research community, have potential for improving construction safety. Specifically, this review discusses Barcode, Radio Frequency Identification (RFID), Ultra Wide Band (UWB), Global positioning System (GPS), Global Information System (GIS), Visual monitoring, Virtual Reality (VR), Augmented Reality (AR), Cyber-Physical System (CPS), and Building Information Model (BIM) and their respective applications to construction safety. Each section follows the same outline by providing a brief definition and the working principles of the technology, its general use in the industry and its current application for construction safety purposes. They are presented from the simplest to the more complex ones in term of functioning and also grouped by working principles.

Technologies	Tag-based	Radio frequencies	Satellite-based	Computer-based	Sensor-based
Barcode	✓				
RFID	✓	✓			
UWB	✓	✓			
GPS	✓		✓		
GIS				✓	
VM				✓	
VR				✓	✓
AR				✓	✓
CPS				✓	✓
BIM				✓	

Table 1. Working principles of the technologies of interest

Barcode

a. Definition and Principles

Barcodes are now well known and widely used in almost all industry sectors. Barcodes are considered to be the attributes to the Radio Frequency identification (RFID) technology; however, even though they share some similarities (e.g., storing information about the object tagged), they differ in their working principles. The barcode technology is based on symbology, which is composed of several standards such as encodation rules, dimensional tolerances, or print density (Bell and McCullouch 1988; Stukhart and Cook 1990). Barcode scanners are needed to access stored data associated with the scanner. These may be stationary or hand-held devices like laser scanners. Bar code symbols can be easily generated and commercially printed, which makes them inexpensive and accessible. The strengths of barcoding are its ease to use, low cost, and popularity.

b. General use in construction and safety

The barcode technology has a large number of applications in the construction industry, mostly related to identification and tracking functions. Tracking information flow such as available material, tasks achieved, or worker locations are vital on a construction site. Barcodes provide a means to uniquely tag resources so that, once they are scanned, the user may identify a resources location, availability, and installation status (Bell and McCullouch 1988; Rasdorf and Herbert 1990). Furthermore, researchers have shown that more than 50% of inspection time may be saved by using barcodes to track material delivery from the supply chain through construction (Bell and McCullouch 1988). Similarly, researchers have proposed to use barcodes in the design phase to identify documents, facilitate information flow and potential drawing revisions and notes (Rasdorf and Herbert 1990). Finally, barcodes are useful tools to identify workers on site, keep track of their specialty or work hours, and anticipate possible manpower needs. The technology can also be implemented to measure how often certain tools or equipment and strategically schedule preventive maintenance (Rasdorf and Herbert 1990). Interestingly, a thorough literature review has not yet revealed potential applications to safety although, as will be presented later, safety risk data may pose a new opportunity.

Radio Frequency Identification (RFID)

a. Definition and Principles

Tracking and localization technologies that capture the changing site information have been deployed in several sectors such as manufacturing, the distribution or the healthcare and have shown promising results. Among these technologies, radio frequency identification (RFID) systems have received the greatest attention in the construction industry.

The function of an RFID system is to detect and locate tagged objects or persons through the data they transmit. A typical RFID system consists of three elements: (1) tags or radio transponders; (2) a reader usually connected to a computer network to interpret and react to the data it receives; and (3) antennae (Figure 1). RFID systems use radio frequencies to establish a connection between tags and readers, also known as coupling. The communication between the two through antennas on a 120kHz to 980MHz frequency band allows the system to collect and transfer data at all time within a defined range. The lower the frequency, the slower the transfer rate (Bhuptani and Moradpour 2005).

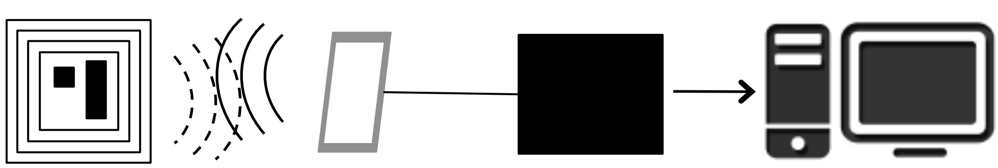

Figure 1. Connection between tag, antenna, reader and computer system

Maintaining sufficient signal availability in constantly changing construction sites is the main challenge for RFID tracking accuracy. Materials, equipment, structural elements, and even people cause signal attenuation and multipath, which alter signal power and quality, respectively (Pradhan et al. 2009; Lee et al. 2012). Solutions have been suggested and tested by researchers to reduce the impacts of these issues including the Time of Flight (ToF) method, Chirp Spread Spectrum (CSS) and assistant tags (Jiao et al. 2007; Lee et al. 2012).

b. General use in construction and safety

RFID technology was originally designed for automatic and effective data capture (Hightower and Borriello 2001). However, the use of RFID was later used as an accurate localization system considering the combination of its benefits such as tag data storage, reader data transfer capability, and relatively inexpensive installation cost.

RFID has been found to be a viable resource for tracking tools, equipment and workers. Specifically, Jaselskis and El-Misalami (2003) showed that tagging every large piece of equipment that enters or leaves a stock could save, on average, 30% of the time spent tracking and locating a specific material. It can also eliminate traditional paperwork needed for certifications and inspections. In addition, tagged machines could provide faster access to maintenance history, hours in use and other information for preventive maintenance. Finally, RFID could provide a better alternative for personnel management and job status than existing technologies.

In terms of safety, researchers have focused their efforts on one particularly promising application: a pro-active real-time personnel-warning system to alert workers and equipment operators of dangerous proximity (Chae and Yoshida 2008; Fullerton et al.2009; Hallowell et al. 2010; Lee et al. 2012). Pratt et al. (2001) showed that 51% of vehicle-related fatalities happened when the vehicle was in reverse mode, which they linked to the large amount of blind spots in the backside of a vehicle. Pratt et al. (2001) discovered that the best method to improve safety on a work zone is by altering the behavior of the individuals on the safety zone. By nature, workers on foot and equipment operators become unaware of their surroundings due to fatigue and task repetition, which directly impacts their hazard recognition skills (Pratt et al. 2001; Fullerton et al. 2009). To address this issue, researchers have developed a safety management support system based on active RFID technology to automatically alert machine operators when a worker on foot is nearby (Fullerton et al. 2009; Chae and Yoshida 2010).

RFID warnings are provided by a system with an Equipment Protection Unit (EPU) composed of an antenna, a reader, and an alarm installed in the cabin of the heavy equipment. Workers are equipped with a Personal Protection Unit (PPU), which contains a tag, a battery and an alarm. When an equipped worker enters the reception field of a programmed reader – a pre-determined 'unsafe' area around the vehicle – the alarm of the PPU is triggered and the information is instantaneously sent back to the reader, which in turn activates the in-cab alarm so that both the operator and the worker are aware of their proximity and the potential danger. Implementing this system is hypothesized to reduce the number of collisions due to poor visibility, inattention and/or blind spots during equipment maneuvers. A similar but simpler version has already been installed in some warehouses, mines and train depots to trigger visual and/or sound alarms when a forklift or vehicle is in approach in tight areas (Fullerton et al. 2009; Teizer et al. 2010).

Finally, the RFID system can also address the lack of information of near misses, which are unplanned events that didn't result in an injury or damage but had the potential to do so (Fullerton et al. 2009). Tags and readers can be programmed so they can store and record information such as the number of times a specific tag breach a safety perimeter, how close a tag and a reader were at all times, how operators behave in risky areas, etc. These data can then be analyzed to help decision makers and managers to take effective safety countermeasures (Pradhananga and Teizer 2012).

Ultra Wide Band (UWB)

a. Definition and Principles

The Ultra Wide Band (UWB) technology is similar to RFID in that it is a proximity and location detection system that uses radio frequencies and tags to track the location of an object or subject. UWB systems are composed of multiple slave sensors that decode the radio signal using Time of Flight (ToF) and Angle of Arrival (AoA) technics and are accountable to the master sensor that decrypt all the information received. However, compared to RFID, UWB can transmit large amounts of digital data over a wide spectrum of frequency bands at very low power (less than 0.5mW) (Ghavami et al. 2004). Moreover, although RFID tracking technology can be seriously impaired by signal reflections due to the construction environment, UWB systems are more stable as they can distinguish the direct path signal from the signal noises because they use short pulses that greatly enhance localization accuracy down to 10cm on a wide range (300 to 500m) (Giretti et al. 2009; Zhang et al. 2012).

b. General use in construction and safety

UWB systems tend to be applied for the same purposes as RFID systems. However, they are preferred when high accuracy and low error rate is essential such as collision avoidance as noted by several researchers who have applied UWB to safety. 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, which can sometimes fail the operators and signalmen. The risk of collision and other safety failures is greatly increased when multiple cranes are in use. To avoid such incidents, the researchers proposed a UWB system to monitor load trajectories and warn the operators with visual and audible alerts when a potential collision is about to occur.

Researchers have also explored localization systems using the higher accuracy and noise-free UWB technology. Giretti et al. (2009) and Carbonari et al. (2011) implemented a human and equipment path monitoring system to prevent workers from accessing hazardous zones where the risk of being struck by falling objects is particularly high (e.g., under suspended loads). Their system was able to warn managers and workers before they were at risk.

Global Positioning System (GPS)

a. Definition and Principles

The Global Positioning System (GPS) was opened to the public in the 1990's. Since that time, GPS has spread widely when it was adapted to mobile phones use in 2004. Although the system is still controlled by the DoD, the signal is available to civilian users all around the world considering its continuing modernization and the recognition of its increasing potential for non-military purposes. Specifically, the system is composed of 24 GPS satellites that constantly orbit the Earth and transmit radio signals. It was developed in a way that anywhere 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. The Global Positioning System can be used everywhere in all weather conditions but offers greater accuracy with a clear line of sight.

b. General use in construction and safety

GPS use on construction sites has seen steady growth thanks to its increasing efficiency, range of application and decreasing cost. GPS has been used in earth moving operations to remotely monitor and control equipment in hazardous environment, where human presence is not encouraged (Oloufa et al. 2003). This technology is particularly beneficial in earth moving operations where the topology of the site keeps changing and the number of heavy vehicles involved is important. Also, GPS is the only known tracking technology that doesn't require pre-installed infrastructure and thus, doesn't suffer from dirty environments, large objects or changing environment where radar systems often fail (Behzadan et al. 2008). Moreover, GPS devices have now been installed on heavy equipment to track location and activity. GPS trackers have helped operators to calculate trajectories and optimal path during truck loading or compaction. Another area of application is quality control of compaction and paving operations. By combining GPS and RFID technologies or GPS and density sensors, the system was able to monitor asphalt-paving operations from the production to the actual spreading of the desired thickness at the right temperature (Peyret and Tasky 2002), or indicate to the operator the exact number of passes needed, the area he already covered and when the optimal compaction has been reached, in real-time (Jaselskis et al. 2001).

In terms of safety, GPS, like RFID and UWB, has been especially mostly for collision detection and avoidance. Thanks to the GPS technology, location, direction and speed of equipped heavy vehicles are known at all time and allow the collision algorithm to compute the potential point of impact of two converging equipment. The system is able to calculate the braking distance needed to avoid the collision. As soon as the safe braking area is breached, the program send alerts to the vehicles involved along with direction recommendations to prevent the accident (Oloufa et al. 2003). The system is, 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, tracking critical resources can be used to analyze safety conditions on construction sites and take proactive safety measures when unsafe activities are about to be undertaken. 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.

Graphical Information System (GIS)

a. Definition and Principles

A geographic information system (GIS) is a broad term to designate different technologies, processes, or methods designed to manage, analyze, and assess all types of spatial information and geographical data. GIS is a computer-based system that can associate unrelated information together by using location as the key variable. Geographical digital data mostly result from digitization of hard copy maps, survey plans, aerial photography, and satellite imagery through the use of Computer Aided Design (CAD) programs and geo-referencing capabilities. When using this technology, information of interest should be identified first and are usually organized in databases that are then mapped in layers and combined with geographical input. GIS addresses the lack of geospatial analysis of Building Information Modeling (BIM) or 4D Computer Aided Design (4D CAD) systems that can be vital in some projects. For instance, site topography, environmental conditions, access route planning or flooding areas are crucial safety information that can be modeled with GIS but not in BIM (Bansal 2011).

b. General use in construction and safety

Successful integrations of GIS systems can be found in many areas such as business analysis, urban planning, facilities management, transportation and civil engineering. For example, using GIS data, Li et al. (2003) were able to manage spatial information to optimize costs of transportation, select the most competitive price of material within a defined range, and propose efficient routes in order to deliver goods on construction sites. Moreover, Cheng and Yang (2001) developed a GIS-based tool called *MaterialPlan* to identify the suitable areas for materials storage to avoid organization conflict on sites and improve productivity. The authors also combined GIS with CAD to compute quantity takeoffs, assess materials and generate bills of material (BOM) based on the design drawings specifications. Bansal and Pal (2007) used AutoCAD combined with ArcView, a GIS software with a better user-friendly interface, to add a visual dimension to the quantity takeoffs. GIS has also been used to help project managers dealing with increased data and optimizing construction sequences in depicting spatial relationships between construction objects on concrete dam project (Zhong et al. 2004).

There have also been important applications where GIS has been used to improve construction safety. Bansal (2011) applied 4D GIS to safety planning on a construction project in India to integrate geospatial information that BIM models don't, such as topography, thermal comfort or flooding areas, which are important to consider in construction planning as they directly impact workers' safety. The author first developed a safety database in GIS that solicit safety data from experienced professionals and safety procedures found in the Bureau of Indian Standards (BIS) related to different activities. Then, to answer the questions of when and where safety measures are needed, he linked this database to the Construction Planning and Management (CPM) schedules so that safety managers can benefit from past accident cases. The 4D GIS system facilitated the analysis of execution sequence from a safety point of view by retrieving, managing and assessing non-spatial and spatial safety information. Safety recommendations appear when a specific geographical configuration or component is used in the 3D building model to ensure compliance to safety regulations during the design phase and provide help in deciding safe work methods during construction. The GIS system allows correcting a planned sequence before implementation in case of a recognized hazard situation so that the system keeps improving. Monitoring the time and location schedules of the construction tasks on the system allowed safety planners to recognize how workers affect one another and create dangerous situations, and thus they were able to know when, where and why intervening.

3D Range Imaging Camera & Visual Monitoring

a. Definition and Principles

Construction sites are constantly evolving environments that require managers and stakeholders to constantly revise their plans, drawings, and decisions. Up-to-date and accurate information about the site are key elements for efficient decision-making and management in general but site inspections are still mostly manual, error prone and resource intensive. Thus, visual monitoring on construction work sites through the installation of high-resolution digital cameras has received attention. Whether by taking static images or record videos, cameras offer a wide range of applications and can provide, in real time, information managers demand (Bohn and Teizer 2009).

3D range imaging camera systems or 3D Flash LADAR is another promising technology that supports capture of fast and safe range acquisition of untagged objects at a high lateral resolution. This technology measures absolute distances resorting to the time of flight

(TOF) principle with phase shift measurement. The camera illuminates the entire scene simultaneously with a modulated light and then, once the light wave is reflected back to the receptor/sensor chip by objects in the scene, the system is able to compute a 3D map of the actual scene (Lange and Seitz 2001; Teizer et al. 2007). 3D range imaging cameras offer high resolution, rapid acquisition and high update rate (1 second to 10Hz) to a distance of up to 50 meters and, thus, can adequately handle moving vehicles, equipment or workers while basic LADAR systems cannot (Teizer et al. 2005). Moreover, 3D range imaging cameras do not require long installation protocols and do not endanger workers when they are set it up in dangerous areas such as traffic zones. 3D flash LADAR can even be mounted on a vehicle and will adequately assess the work environment while integrating the displacements of the vehicle.

b. General use in construction and safety

Digital and 3D range imaging cameras are versatile in a sense that they offer multiple applications and can be applied to various activities within the construction industry. For example, the technology has been implemented to monitor construction task progress. By accessing time-lapse pictures or videos from a standardized site point of view, managers can assess potential problems with a specific task, detect re-work at its early stages, or predict upcoming roadblock and thus better anticipate heavy equipment trajectories (Bohn and Teizer 2009). Visual monitoring allows saving time and money on inspections as the task can be performed remotely (Brilakis 2007). As previously stated in other technology applications, enhancing communication and information flows are vital to improve decision-making and the accumulation of delays. Using visual monitoring and time-lapse photography can reduce information retrieval time, instantly provide the project status to the meeting participants and reduce confusion or misunderstanding that technical drawing can produce. In addition, these sequenced pictures can also be used for training, marketing strategies or even 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 recognized remotely and improper methods or missing protection equipment can be rapidly identified, especially at night, and then addressed during safety training (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 recognize crane activities and track jib rotation and trolley position based on a color density approach.

Virtual Reality (VR) and Simulation

a. Definition and Principles

Virtual Reality (VR) technology generates realistic environments in which the user is completely immerged in a computer model. This technology is based on highly dynamic and responsive computers and servers where the system can quickly respond to the user's interactions, decisions, and manipulations. VR models can process various input such as speech, gesture, sound or position (Blach et al. 1998). 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 revolutionizing data presentation and information access, going beyond simple 3D representations (Caneparo 2001). Multiple stakeholders can also experience a construction project, even remotely, when VR is created and shared online.

b. General use in construction and safety

Virtual reality systems are already heavily used to train vehicle drivers, pilots, and ship navigators. The success of these models has served as the impetus for the construction industry to develop VR for heavy equipment operator training (Wang and Dunston 2005). Professional personal training simulators have also 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.

The ability to virtually explore building and infrastructure has made VR a viable tool for collaboration and prevention through design; however, its efficiency is highly dependent of the level of the detail and realism of the construction model. As mentioned above, VR has been used to give updates of the design process, to share information with the project participants and can greatly enhance the understanding of the project (Caneparo 2001). By navigating the model, designers can better predict how their work would influence how people use and interact with construction objects and tasks. For example, VR can be used to model how crowds would behave with specific configurations and constraints (Caneparo 2001). Furthermore, Caneparo (2001) promotes shared virtual reality models where VR models are no longer individual experiences but, instead, are collective and collaborative experiences. Thus, while experiencing the model, individuals groups of project participants can quickly visualize and discuss design alternatives during virtual group tours.

Researchers have suggested various applications of VR to construction safety, ranging from application to enhance injury prevention through design to worker hazard recognition training. Hadikusumo and Rowlinson (2002) discussed how visualization of the construction project in its early stages could greatly improve the construction hazard prevention during design. One key element to promote injury prevention through design is to raise designer's awareness about their responsibility in this area. Viewing the facility in virtual reality may reveal hazards that typically remain latent until construction thereby enhancing safety concerns and compelling design changes that promote worker safety. Also, other authors suggested using VR for safety hazard recognition programs for workers (Hadikusumo and Rowlinson 2002; Albert et al. 2014). During safety training, workers would be able to survey the virtual site to detect dangerous zones or risks, and safety managers could monitor their performance and provide safety recommendations accordingly. For instance, Hadipriono and Barsoum (2002) developed an interactive training model for construction workers to prevent fall from heights while working on scaffoldings. In the virtual model, trainees were able to follow the safe form scaffolding erection steps and recognize hazardous situation in existing scaffolding structures.

Augmented Reality (AR)

a. *Definition and Principles*

Augmented reality (AR) is a technology that creates an environment where virtual objects and digital content generated by a computer are superimposed into the user's view of the physical world. While VR completely immerses the user into a simulated environment, AR gives the user the ability to leverage the familiarity and comfort of conventional workspaces with the flexibility and power of computers by inserting critical elements of the cyber world into the real world (Wang and Dunston 2005; Yeh et al. 2012; Lin et al. 2014). As many other technologies, augmented reality was first developed for military and medical purposes and was later adapted by the industrial, commercial, and entertainment fields (Azuma 1997). AR doesn't operate as a complete simulator where the user is completely immerged 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).

b. General use in construction and safety

Work on construction sites requires managers to constantly make decisions based on the information available as tasks evolve, the configuration of the workspace changes, and the project progresses. Such work demands constant updates and quick visualizations of the status key project conditions. Such information and visualizations are offered by augmented reality (Wang et al. 2013).

In addition to individual decision making AR systems can be used as a cooperation tool, designed to improve communication, reduce construction conflicts, and enhance information transfer (Lin et al. 2014). According to Wang and Dunston (2008), AR can foster communication and information sharing among architectural designer team members and improve design creativity as well as provides a powerful tool for design problem solving. Compared to 2D drawings, AR technology has been found to better facilitate collaboration tasks. Specific types of AR facilitate such collaboration, known as augmented reality-multiscreen system (AR-MS system), which is composed of a physical and a cyber-environment and information interaction. Lin et al. (2014) built a mobile device, *the BIM table*, which can display a wide range of data such as maps, drawings but especially BIM models so that managers can address conflicts directly on sites and quickly show new task instructions as well as safety recommendations to workers. Similarly, Wang and Dunston (2008) investigated how mixed-reality/augmented (MR/AR) reality systems could enhance construction clashes, problem solving and design review collaboration from the user point of view. In their MAR/AR model, the user is able to interact with the virtual objects he can see with a head mounted display by using computers. Their test results showed that the participants using the MR system were faster to identify design errors and that the system provides better quality of visual presentation, a larger level of immersion and more overall suitability for making decisions on design models compared to 3D paper drawings.

Yeh et al. (2012) took advantage of the rapidly developing and increasingly powerful wearable devices to create projection-based augmented reality device called, *iHelmet*. The goal of implementing the device was to reduce the difficulties of on-site information retrieval by combining building information model (BIM) and AR technologies on a helmet so that the user can access construction drawings and models on demand. Coupled with a relatively small projector equipped on the helmet, the device is able to create an augmented reality environment by projecting the information retrieved in front of the worker, who can then review his tasks, consult safety recommendations or verify the adequacy of his work with the plans.

Augmented reality has also been used with Global Positioning System (GPS) technology and traditional Computer Aided Design (CAD) models to detect existing subsurface utility lines during excavation work. During such operation, hitting the utility system can greatly delay the project under construction, cause unwanted money spending and even be fatal. To avoid such accidents, increase safety of urban construction projects and reduce potential costs, Behzadan and Kamat (2009) proposed the integration of augmented reality and global positioning system technologies to accurately detect and display in real time the utility network's location to site managers and operators so that excavation operations can dodge utility lines.

Finally, another application domain for augmented reality is operator training. Wang and Dunston (2005) conceptually designed a training system by embedding an augmented workspace with virtual objects such as stockpiles, target positions into the existing real work environment. Because of its flexibility and endless possibilities of scenarios, the system can generate training sessions that focus on the operator's needs and progression. Furthermore, safety while operating a heavy vehicle or equipment can be greatly improved with the program by simulating risky conditions such as overload charges, tipping equipment, or fall of elevated virtual materials, and this without any ethical issues, over costs or even environmental concerns (noise, dust, etc.).

Cyber-Physical System (CPS)

a. Definition and Principles

A cyber-physical system (CPS) is the integration of physical devices such as sensors, tags, and cameras with informational components such as Building Information Modeling objects or sensed data to form a system that intelligently respond to dynamic changes of the real world (Tang et al. 2010). In other words, embedded computers and networks can monitor and control the physical processes with feedback loops, where the physical processes affect computations and vice-versa (Derler et al. 2012). The key feature of a Cyber-Physical System is its ability to bridge cyber information with the physical reality via sensors and data acquisition technologies (Wu et al. 2011) so that the modification of a physical component can be simultaneously reflected on the virtual model. Conversely, in a CPS, cyber information can affect the physical world, which generally means making control decisions to react to specific sensed information and physically control the building components (Akanmu 2012). Although, the term is relatively new, the concept is not and is already implemented in various sectors of activity such as the transportation system (intelligent traffic systems), the healthcare system or rescues with the support of the global positioning system (GPS), accelerometers and microphones or other various sensors. Applications in the construction field date back to 2009 when cyber-physical systems have been deployed for real-time structural health monitoring of civil structures (Lynch et al.

2009; Hackmann et al. 2014). More concretely, a cyber-physical system's architecture is divided into five layers in order to connect the physical world to the virtual model in both ways, from the sensing process to the actuation layer and vice-versa. The architecture of a CPS is showed in Figure 2.

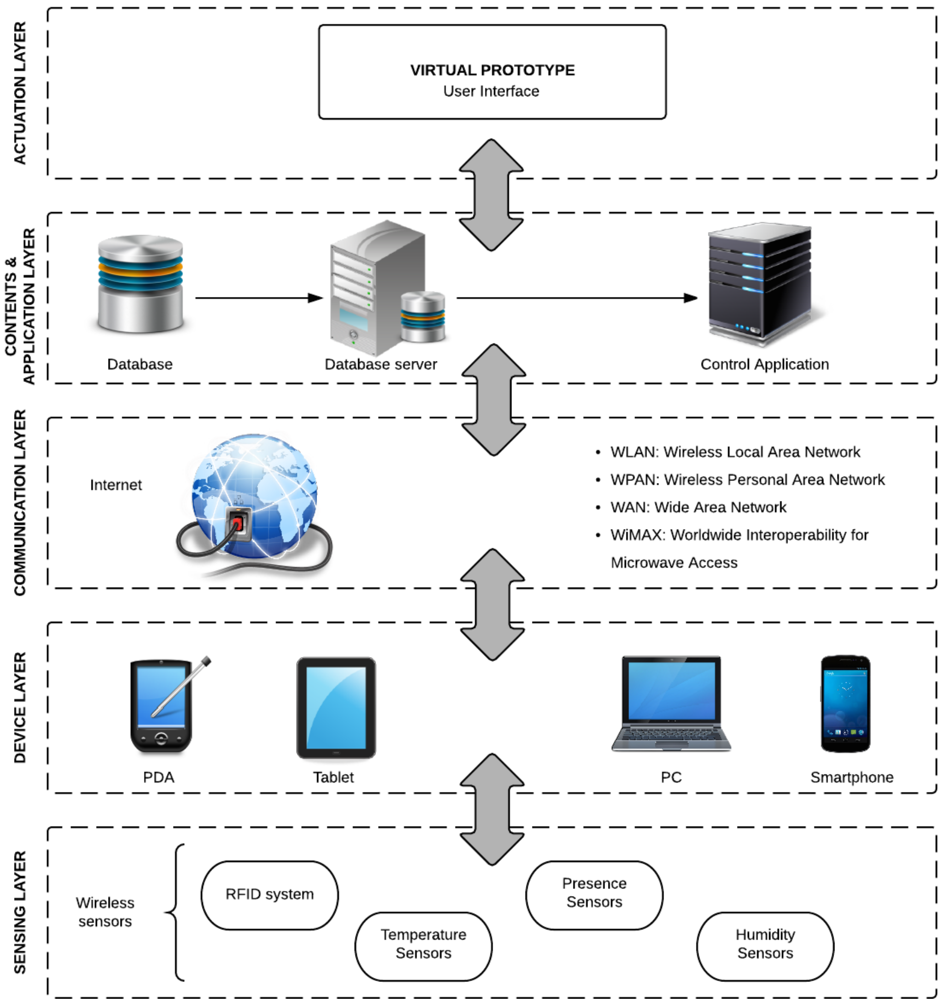

Figure 2. Cyber-Physical System architecture

b. General use in construction and safety

There have been several applications of CPS in construction. According to Anumba et al. (2010), cyber-physical systems have the potential to epitomize the paradigm shift construction needs to overcome its relatively poor productivity compared to other industries sectors, its lack of evolution in processes that are still mainly manual, and the general uncertainties that are characteristic of the construction field such as final costs or delivery dates. To that end, the authors proposed a project delivery process based on bi-directional flows of information to enable greater process control, improved predictability of outcomes, and more intelligent, sustainable facilities that are also safer to build.

Akanmu (2012) presented a cyber-physical system that could visualize, locate, monitor and control tagged light fixtures. The interaction between the virtual model and the physical light fixtures could enhance the energetic performance of the building and thus reduce energy losses, which are mostly caused by poor monitoring and control (Newsham et al. 2004; Boyce et al. 2003 as cited in *Towards cyber-physical systems integration in construction*, Akanmu, 2012).

Structural health monitoring (SHM) is another area of application for CPS explored by researchers. Hackmann et al. (2014) adopted a flexibility-based method to develop an energy-saving CPS system that identifies and locates in real-time damages on civil structures. Likewise, Lynch et al. (2009) used self-sensing materials for distributed sensing to create ultra-low power wireless sensors. The authors exploited the piezoelectric properties of their sensors to accurately identify deterioration areas on civil structures and map crack states in two or three dimensions.

Finally, cyber-physical systems have recognized the benefits of modeling for safety management of temporary structures (Chi et al. 2012; Yuan et al. 2014) and have used sensing technology to monitor formwork operations as a way of preventing structural failures (Moon et al. 2012). According to Fabiano et al. (2008), most of the time, temporary structures such as scaffolding, formwork systems or earth retaining structures are considered as static elements that do not need an increased control, and yet have proven that they can cause severe accidents as they are dynamic systems. Yuan et al. (2014)

explored two major applications of CPS to prevent temporary structures collapses. First, a CPS could serve as a checker to verify if the built assembly corresponds to the virtual model, as gaps between the engineered model and the actual installations constitute one of the primary causes of system failure (Thornton 2012 as cited in Yuan et al. 2014). Moreover, the installed sensing network could also monitor the performance parameters of the structures both during construction and while in use or during severe environment events. Second, the same approach could be used for scaffolding. By implementing a CPS on a scaffold, safety managers would be able to determine whether or not the structure is used within its design limits and predict its stability at all time by looking at the sensed data on the virtual model. In both examples, a CPS would provide real-time inspection, quick problem identification and potentially automatic stabilization depending on the performance of the system.

Building Information Modeling (BIM)

a. Definition and Principles

Building Information Modeling (BIM) is an efficient tool to accurately design and generate a virtual digital model of a physical structure or project. BIM software can represent all kinds of structural components such as concrete beams, steel columns, commercial floors and walls, and all their connections. The strength of the 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 or safety precautions. Numerous functions within the BIM software can provide the user all sorts of information he might need to compute quantity takeoffs, costs estimations or task schedules. Researchers have proven that resorting to BIM in construction and structural firms have greatly enhanced design, management and labor productivity, and have been beneficial for all stakeholders during the entire construction process (Kam et al. 2003; Kaner et al. 2008; Jordani 2008; Howard and Björk 2008; Goedert and Meadati 2008).

b. General use in construction and safety

The Building Information Modeling (BIM) technology has probably the widest range of applications of those reviewed in this paper. BIM for safety has been studied and successfully implemented at each stage of a project, from the marketing and design phase to the maintenance of the built structure through the actual construction phase. Researchers have consistently highlighted the powerful potential of BIM models to integrate various information into 3D or 4D models but to also to foster communication between designers, contractors and the stakeholders and to improve construction productivity as well as safety (Lopez del Puerto and Clevenger 2010; Yeh et al. 2012; Lin et al. 2014).

Safety concerns have been addressed at the design phase within BIM models to tackle risky situations, task congestion and fall hazards at the early stages of a project. Indeed, researchers such as Gambatese and Hinze (1999) and more recently Bansal (2011) have long emphasized the crucial role of designers in safety and have encouraged the involvement of experienced safety managers in the design review. To that end, Hammad et al. (2012) proposed a method for automatically identifying falling and collision risks and generating dynamic virtual fences (DVF) in BIM. Similarly, Zhang et al. (2013) with *Tekla Structures* and later Qi et al. (2014) with *Solibri Model Checker*, developed a rule-based system to automatically check, locate and correct identified safety hazards during the design phase. The system also proposed schedule for the implementation of proactive safety measures. According to Qi et al. (2014), the ideal prevention through design software should be able to help and guide designers during the main design phase by suggesting alternative construction configuration to minimize safety non compliance; run safety checking on the overall project at the end of the design phase; and be able to correct any safety detected issues. However, previous studies and the authors recognized that such software is often too intrusive and thus ignored by under-pressure designers, and that the number of safety recommendations should be limited.

Although BIM is essentially an information-rich design technology, it can also 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 experts opinions and safety risk factors in the model. BIM has also been employed 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). Yeh et al. (2012) combined BIM with augmented reality to provide on-site building information retrieval to managers so they could access buildings plans effortless and without carrying multiple drawings on-site. Likewise, more recently, Lin et al. (2014) proposed a device – the BIM table, which combine augmented reality and BIM technologies to facilitate information retrieval on site, improve communication between designers, managers and workers, and to better safety recommendation understanding. BIM models have also been paired with localization and tracking technologies such as RFID, UWB, GPS and GIS in order 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 also been helpful to enhance safety planning and training. Kim et al. (2014) proposed an automated information retrieval system that can automatically search for and provide, as a push system, similar accident cases. The retrieval system extracts building information modeling (BIM) objects and composes a query set by combining BIM objects with a project management information system (PMIS). In this case, a query set is composed based on work, work conditions, and laborers. This program is based on the result that similar accident cases provide direct information for determining the risks of scheduled activities and for planning safety countermeasures and on the fact that *"Laborers [...] do not tend to voluntarily retrieve past accident cases related to themselves due to their overconfidence in their experiences and skills"* (Kim et al. 2014, p.1). 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 make safety uneducated Indian workers visualize 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 optimize emergency evacuation within a virtual BIM environment. The flexibility of the BIM model allowed the researchers to evaluate the fire diffusion, its sources, the potential obstructions and how protective equipment would react or be accessible for rapid intervention. Analogously, Leite and Akinci (2012) studied the vulnerability of facilities during an emergency by triggering by a failure in the building system to identify which critical assets might be affected by the current emergency. By embedding electrical and plumbing network photographs into BIM, Lopez del Puerto and Clevenger (2010) showed that BIM could also be used to locate hidden components for maintenance and repairs.

Patterns and Limitations

Exploring patterns in safety applications between the various technologies may help to identify opportunities of improvement for future research. An overview of the technologies by safety applications along with their intervention phase presented in the literature review is given in Table 2. From this table, two main application trends can be identified.

First, computer-based technologies mostly intervene at the early stages of a construction project. As design is essentially virtual, it is not surprising that this type of technologies such as BIM, VR and GIS are the only technologies to integrate safety before construction even begins. These digital tools are used to check virtual models, suggest safer design alternatives, consider geospatial information, and provide step-by-step visualization of construction tasks for pre-planning and safety management support. Following Reason's (1990) human error causation model, virtual models and computer-based technologies are the first resort to reduce hazards and potential workers' unsafe behavior on sites. However, compared to the range of safety applications in the construction phase, only few tools are available in the design phase to assist designers in achieving construction safety, which confirms the findings of Zhou et al. (2012).

Researchers have long emphasized the necessity of implementing pro-active safety measures such as workers training or prevention-through-design tools to tackle future safety issues on site (Gambatese and Hinze 1999; Bansal 2011; Zhang et al. 2013; Qi et al. 2014), and yet construction safety applications in the design phase are less mature than those in the construction phase. Indeed, well-known construction companies, which can afford these types of technology on their projects, are usually aware of organizational health and safety regulations and do not struggle with their application, which most of DSFP tools are designed for.

	Description Approach	Phase	RFID	UWB	GPS	GIS	VM	VR	AR	CPS	BIM
Prevention through Design	Simulation and review of construction process for design related safety issues. Rules-based algorithms and software used to detect hazards in the design phase, incompatibility with OSHA rules, and suggest safer alternatives	Design						✓			✓
Geospatial considerations for safety	Integration of geospatial information in safety planning such as flooding area, topography, access route planning, light and temperature	Design, Pre- and Construction				✓					
Safety Training - Hazard recognition and Operator training	Training for workers and operators: hazard recognition, simulation exercise, crane operation, reverse mode maneuver, awareness of surroundings	Pre-Construction				✓		✓	✓		✓
Safety in Construction Planning Management	Decomposition of construction tasks into basic elements to remind the workers the correct steps, recognize hazards, provide safety recommendations	Pre-Construction				✓		✓	✓		✓
Safety information retrieval	Retrieve past accident cases based on workers' profiles to provide safety recommendations adapted to the tasks of the day	Pre-Construction							✓		✓
Structural risk assessment	Evaluation of operational risk levels and structural safety analysis	Pre-Construction, Construction								✓	✓
Decision Support System	Assist engineers and managers in safety monitoring and controlling construction tasks such as excavations, especially near utility lines	Pre-Construction, Construction				✓			✓		
Collision avoidance	Prevent worker-equipment, equipment-equipment, objects at height-worker collisions with tracking, braking distance, blind spot visualization and monitoring	Construction	✓	✓	✓		✓				
Warning system	Send visual, sound alerts to workers/operators when they are in the vicinity of equipment, craned loads, hazardous areas in real time	Construction	✓	✓	✓		✓			✓	✓
Crane monitoring	Monitor loads, trajectories, improve operator visualization	Construction	✓	✓	✓		✓				
Critical resource tracking for risk tracking	Tracking of large, heavy or hazardous material installation that are known to be accident prone to take preventive measures at the right place and time	Construction	✓	✓	✓		✓				
Remote safety control and inspection	Remote inspection and hazard recognition of on-going or future construction task. Detect, model and track the position of static or moving obstacles, resources, and workers.	Construction					✓			✓	✓
Information collection and near misses	Collect information that will potentially serve for future analysis, hazard recognition and prevention such as frequency of proximity with equipment, hazardous area. Record info before/during accident.	Construction, Post-Construction	✓	✓			✓				

Table 2. Safety applications by technologies

Second, tag-based technologies constitute the core body of pro-active safety applications on sites. These technologies are based on information transfer between the tags and the reader to track, locate and monitor in real-time assets such as workers, equipment or materials. These technologies have shown great potential and encouraging results in safety monitoring and pro-active safety measures. Nonetheless, based on our previous literature review, applications have been limited in scope to collision avoidance and warning systems to alert in real-time workers when they are in the vicinity of heavy equipment or have entered a predefined hazardous area.

From Reason's causal model perspective, if computer-based technologies constitute the first resort to reduce future safety issues on sites, tag-based technologies are the final safety barrier to potential accidents workers have, should all the other safety practices and training fail. Regarding these systems, some limitations in application have already been identified. In fact, Hallowell et al. (2010) questioned the implementation feasibility of such pro-active safety systems especially in terms of the volume of warnings. Some tasks on the field require both heavy equipment and workers-on-foot to work in concert, excavation operations or embankment works for instance. Implementing collision avoidance systems with such activities would generate continuous false alarms and could lead workers to deactivate their personal protection unit while the collision risk is still present. The same remark applies for equipped workers who are performing a task in an automatically predefined hazardous workspace due to their activity, as described in Hammad et al.'s (2012) dynamic virtual fences system.

Some researchers have emphasized that tracking technologies could also be used to collect data about near misses to help managers correcting and improving their safety strategies. However, such articles often lack details on the nature of the data that should be collected, how they could be used and how safety managers could benefit from them.

The most critical limitation of previous research is the tenuous link between theoretical safety applications the aforementioned technologies can achieve and real applications on sites. Table 3 summarizes the data sources and data use of every safety application articles cited in the literature review. The color-coding in the data source column aims to highlight the general trends in the safety data researchers have integrated in their intelligent systems. Red was used to show the absence of robust data sources or that the application parameters were left to the user's discretion. Yellow emphasize that researchers resorted to experts' opinions to identify risks and improve the application scope of their systems. Finally, green means integrating safety data such as regulations and governmental safety recommendations as data sources to address safety issues. All technologies except BIM have no safety data sources or only rely on experts' knowledge and judgments whereas BIM resort to both experienced managers' opinions and health and safety regulations. Because OSHA regulations and safety codes in general are limited to fall hazard prevention, the BIM safety application scope has been restricted to detect openings and risky configurations and specify where guardrails are missing and/or needed.

There is a clear lack of viable and robust safety data to justify what, when, where and why injuries happen and safety applications are needed, which are the major issues safety managers have to tackle. Previous studies usually address only one or two of these perspectives. The integration of health and safety regulations at the design phase and all studies that aim to reduce accidents by identifying risks associated with specific activities fail to address when and where accidents occur. Other pro-active safety applications have combined pre-planning, task schedule and regulations to propose safety management support tools but they did not address the necessary questions of where and why these particular measures are important. Construction plans, procedures and safety codes typically address what types of safety measures are needed and why, while safety planners can answer when and where they are required. These two types of applications need to be linked to fully tackle safety issues on sites. However, as hazard recognition and safety planning highly depend on the level of knowledge and experience of managers in most presented technological systems, safety strategies can suffer from dissimilarities, human errors and capacities or incorrect safety priorities that empirically driven risk data could address as developed later on. Because construction projects differ from one another in terms of configuration, location or crews, safety strategies should be adequately prioritized to tackle the actual risk situation of the worksite that risk analysis can reflect. By giving an objective numerical value to a specific risk, safety managers would be able to identify more risks and know how to prioritize safety resources to address them regarding their relative importance and not because of subjective judgments or in reaction of the accident.

Technology	Authors	Data sources	Data use
RFID	Fullerton et al. 2009	None	Proximity and warning device Collision avoidance
	Chae and Yoshida 2010	None	Proximity and warning device 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
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 system
	Zhang et al. 2012	None	Crane operator support Collision avoidance Warning system
GPS	Oloufa et al. 2003	None	Vehicle Tracking Collision avoidance Warning system
	Pradhananga and Teizer 2012	None Arbitrary proximity areas (10m)	Continuous collection of location/proximity data between workers, equipment and hazardous areas
GIS	Cheng et al. 2002	Experts' knowledge and experience Individual's judgments and past experiences	Geographic data collection for computer-aided decision support in excavation operations
	Bansal 2011	Experts' knowledge and experience Bureau of Indian Standards (BIS) codes Risk factors related to an activity	4D GIS for construction safety planning
Visual Monitoring	Everett et al. 1993	None	Real-time crane operator support system
	Bohn and Teizer 2009	Experts' knowledge and experience At user's discretion	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) Occupational Safety and Health Act (OSHA) Construction Site Safety Regulation of Hong Kong Hong Kong Housing Authority's accident report	Design for safety tool Hazard recognition at the design phase
	Albert et al. 2014	Experts' 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 Reaction to a known delay prone and sometimes life threatening problem	Utility lines damage prevention Warning system
	Yeh et al. 2012	None	(Safety) information retrieval system
CPS	Moon et al. 2012	Contractors' discretion with preset guidelines and engineers' stability calculus	Data collection of temporary structure parameters Monitor stability via sensor/computer based system
	Yuan et al. 2014	Engineers and experts' knowledge Construction site experience Reaction to a known life threatening problem	Warning system Sensor and computer-based system to check correct erection and monitor stability of temporary structures to prevent collapse or potential hazards

Table 3. Data sources and uses by technology

Technology	Authors	Data sources	Data use
BIM	Lopez and Clevenger 2010	Engineering controls Administrative controls Experts' knowledge and experiences	BIM-enabled safety controls Elimination and substitution of hazards at the design phase + 3D visualization of construction sequences to prevent pinch-point accident
	Hammad et al. 2012	Safety Code of Quebec Provence	Generation of Dynamic Virtual Fences Collision avoidance + Fall protection Warning system based on RTLS
	Chi et al. 2012	Workplace Health and Safety Queensland (WHSQ) Occupational Health and Safety legislation (OHS) Experts' knowledge and experience	3D BIM scaffolding and formwork objects for incorporation with safety features and constructability elements BIM checklist for safety inspection
	Zhang et al. 2013	Occupational Safety and Health Act (OSHA) Construction Best Practices	Automated safety rule checking PTD computer software-based system Compliance checking and safety suggestion
	Qi et al. 2014	Experts' knowledge and experience UK Health and Safety Executive (HSE) Safety design manuals and checklists CII researchers recommendations Occupational Safety and Health Act (OSHA)	Automated safety rule checking PTD computer software-based system 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	Korean Occupational Safety and Health Act (KOSHA) UK Health and Safety Executive (HSE) Occupational Safety and Health Act (OSHA)	Safety information retrieval based on workers' profile for hazard recognition program
	Collins et al. 2014	Industry safety professional survey to get likelihood, severity, risk factor and risk level for each step of a scaffolding setting, monitoring and dismantling	4D BIM system for safety management of scaffolding activities at each stage of the project

Table 3. Data sources and uses by technology (continued)

Risk Analysis

Risk defines a potential event that results in an unplanned outcome. The risk value is the product of a probability, or chance of occurrence, and a severity, the magnitude of the undesired outcome (Yi and Langford 2006). In construction safety, risks are interpreted as potential accidents and the outcomes as injuries.

For safety risk, while probability can be measured in terms of worker-hours per incident, severity can be assessed in monetary terms or in terms of the degree of injury (Pain, first aid, medical case, lost work time, permanent disablement and fatality) but is much more difficult to evaluate. Risk has also been quantified as the product of a probability, a severity and an exposure, which is defined as the frequency of occurrence of a particular hazard (Jannadi and Almishari 2003; Hallowell and Gambatese 2007).

Risk quantification methods usually result from opinions of experts and government statistics but rarely from robust empirical data. Based on their field experience, managers are asked to evaluate on Likert-type scales the risk frequency associated with a particular activity. Combined with statistics from governmental studies, these methods have been used to help safety planners to identify high-risk activities on site, prioritize appropriate safety precautions more efficiently and thus prevent potential accidents (Jannadi and Almishari 2003; Baradan and Usmen 2006; Hallowell and Gambatese 2009). Nonetheless, such methods are task-based and only applicable to a restricted number of construction scenarios. The dynamic and transient characteristics of jobsites and the variety of construction tasks have limited their widespread use.

To expand the application area of risk quantifications, researchers have tried to break down general activities into simpler task or trade they could more easily assess (Baradan and Usmen 2006; Shapira and Lyachin 2009). However, by considering tasks or trades independently, they omitted the on-going interactions that actually occur on a construction site and that are a critical factor in risk management. To overcome such limitations, some researchers have proposed to interpret construction activities and environment in terms of safety attributes. The attribute-based risk analysis relies on the theory that every construction accident results from the conjunction of a finite number of hazardous precursors. Preliminary studies with this new approach have produced robust and viable safety risk data but have yet been limited to the study of struck-by accidents (Behzad Esmaeili 2012).

POINT OF DEPARTURE

Despite the advancements in integrating technologies in the construction industry and the various safety applications presented in previous literature, there are still major limitations with significant opportunities for improvement. For example, no safety application for barcodes has been encountered in the literature, even if the technology has shown a great potential in other areas. Moreover, the analysis of the given safety applications have shown that most of them lack viable and robust safety data sources, and that they essentially rely on experts' judgment and intuition. This study takes a step back from previous literature to provide the reader a global picture of the trends in use and limitations of current safety applications. Additionally, this study offer attribute-level safety risk data as a means to improve the quality and versatility with which safety data can be integrated with technologies in both design and construction.

To this end, the following sections aim to highlight safety application patterns among technologies, address the quasi-systematic lack of robust safety data as sources by introducing and conducting an attribute-based risk analysis, suggest ways to integrate such data with the emerging technologies, propose a general framework to combine multiple technologies in one intelligent safety-oriented system, and finally give the reader some insights about future research and potential improvements.

RESEARCH METHODS

As mentioned earlier, there is a lack of independent, robust and viable safety data managers can use to assess safety risks on construction sites. Indeed, actual technological safety applications mostly rely on experienced field managers' opinions to identify hazardous situations and take preventive actions to reduce injuries on worksites. Although qualified safety planners know that many factors can cause an accident, they rarely perceive the degree of risk associated with a particular construction site. Thus, identifying attributes and their interactions to find the real causes of accidents and quantifying their risk would help safety managers to adopt the most effective pro-active measures depending on the configuration and the different actors present on their jobsites. Such data have the potential to be integrated with advanced technologies and intelligent systems to address a wide array of potential construction scenarios early in the project delivery process.

To achieve these objectives, a team of 9 researchers was formed to conduct a structured manual and automated content analysis on 7,033 injury reports provided by a total of 243 independent contractors. The raw data consisted of various detailed information about the injuries or fatalities such as a description of the accident circumstances, the worker's domain of activity or the injured body part. This document is the result of the partner firms' safety department initiative to reduce its internal injury rate. It reports the incidents that happened between the beginning of 2013 and February 2014.

Manually analyzing such a volume of data would have been time-consuming, cumbersome and error prone thus, the research team implemented a combined manual content analysis to extract viable and robust safety precursors, building on the work of Prades (2014). A content analysis is defined as "a research method for the subjective interpretation of the content of text data through the systematic classification process of coding and identifying themes or patterns" (Hsieh and Shannon 2005), which was appropriate to identify the latent hazardous attributes in the accident descriptions.

Because existing literature on safety precursors is limited and would benefit from further research, the team followed the protocol of a directed content analysis as described by Hsieh and Shannon (2005). This involves beginning the analysis with prior methods of coding and theory. Data that cannot be coded are identified and analyzed later to determine if they represent a new category or a subcategory of an existing code. This approach is generally used to contradict or on the contrary further refine, extend and enrich prior research. As our team vastly improves the quality and quantity of available data by considering all injury types, the automated part of this analysis is still in progress. Consequently, this paper only details the manual analysis part of the overall project, which consisted in analyzing a set of 1,280 randomized injury reports. The results of this first phase were then used to generate a list of keywords that serves as input for the automated process in order to analyze the rest of the dataset.

Objectivity, reliability and viability

Directed content analysis present however some limitations that need to be addressed to improve data quality. One particular issue was to achieve objective and unbiased results, which are prerequisites to reliability. The team had to deal with a large amount of data and might have found evidence of attributes that resulted from personal interpretations of the accident descriptions. Objectivity describes the fact that the analysis should be meticulously designed so that neither the research team members, nor external factors can affect the results (Campbell et al. 1981). Imperfect methodologies are detrimental to the objectivity of an experiment. In this study, objectivity was enhanced by following a strict protocol and by using inter-subjective agreement: if two or more observers can agree on a phenomenon, their collective judgment can be said to be objective (Lincoln and Guba 1985). Reliability is in turn a precondition to validity; an unreliable measure cannot be valid (Lincoln and Guba 1985). To achieve an acceptable level of reliability, it must be reasonable "to assume that each repetition of the application of the same, or supposedly equivalent, instruments to the same units will yield similar measurements" (Ford 1975, p.324). In order for the coding schemes and the results yield to be used as robust data sources for future applications, intercoder reliability had to be assessed. Researchers worked independently from each other using the same instructions and an agreement coefficient was computed to ensure reliability and thus reproducibility. "In content analysis, reproducibility is arguably the most important interpretation of reliability [...] Reproducibility is about data making, not about coders" (Krippendorff, 2004, p. 215). This was realized by asking two independent experts to code a randomized fraction (15%) of the analyzed injury reports of each process iteration and computing an agreement rate (Neuendorf 2002; Krippendorff 2004). A goal of 95% agreement was set at the beginning of the analysis and was calculated using the following formula:

$$\text{Agreement rate (\%)} = \left(1 - \frac{\text{Number of wrong reports}}{\text{Total number of reviewed reports}}\right) \times 100 \qquad \textbf{(Equation 1)}$$

In cases of inconsistency or disagreement, the overall set of reports was reviewed by the members of the team before resubmitting another portion of the results to the experts. Moreover, another challenge of this type of analysis is to develop a complete understanding of the context, which, in case of misinterpretations, can result in findings that do not accurately represent the data. This criteria is what Lincoln and Guba (1985) defined as *internal validity* and what Cook and Campbell (1979, p.37) describe as "the approximate validity with which we infer that a relationship between two variables is causal or the absence of a relationship implies the absence of a cause". The internal validity of the study was enhanced through activities such as peer debriefing and member checks as suggested by Lincoln and Guba (1985) and Manning (1997).

External validity may be defined as "the approximate validity with which we infer that the presumed causal relationship can be generalized to and across alternate measures of the cause and effect and across different types of persons, settings, and time" (Cook and Campbell 1979, p.37). To ensure optimal external validity injury reports were randomly selected so that resulted precursors were representative of the overall dataset and expected to be general enough to adapt the transient, dynamic, and variable nature of construction work.

Extraction Protocol

For the extraction protocol, the team followed the recommendations of Lincoln and Guba (1985), Neuendorf (2002), Krippendorff (2004), and Hsieh and Shannon (2005) in terms of methodology, objectivity and reliability. As mentioned earlier, our team resorted to the results and industrial attributes of Prades (2014) to begin the manual data extraction process. Precursors that could not be categorized were analyzed later to determine if they constitute new safety attributes. Based on past experience of the initial project (Prades 2014), an attribute was considered as a new safety precursor when found at least eight times in the analyzed injury reports and was discussed among the researchers. Accident reports with too few details, collisions between two equipment and near misses were omitted in this analysis to avoid data interpretations, to focus on human safety risk and to assess actual resulted injury severity. The manual content analysis protocol and the keyword dataset generation process are presented in Figure 3 and detailed in the following paragraphs.

Attributes are independent elements identifiable in the design phase or on the jobsite before a task is initiated. Attributes can be physical elements such as equipment, tools, materials, design features, but also conditions of the work environment or weather conditions. Following Prades' methods (2014), attributes were classified in three major categories: upstream, transitional and downstream safety attributes.

Upstream Attributes that can be reasonably identified during the design phase of a project, before construction begins and that are 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 sub-categories: *Materials*, *Equipment* and *Design*.

Transitional Attributes that can be reasonably identified before construction begins but that require some research and/or projections of environmental conditions and construction means/methods. Transitional attributes are generally the responsibility of the contractor, as he or she is required to provide a safe workspace according to OSHA regulations. Transitional attributes can be divided into five sub-categories: *Equipment & Tools*, *Materials & Substances*, *Site Quality*, *Weather & Environment* and *Other*.

Downstream Attributes that could not be observed and identified until construction actually begins. Downstream attributes can be divided into two sub-categories: *Human behavior* and *Site Characteristics*.

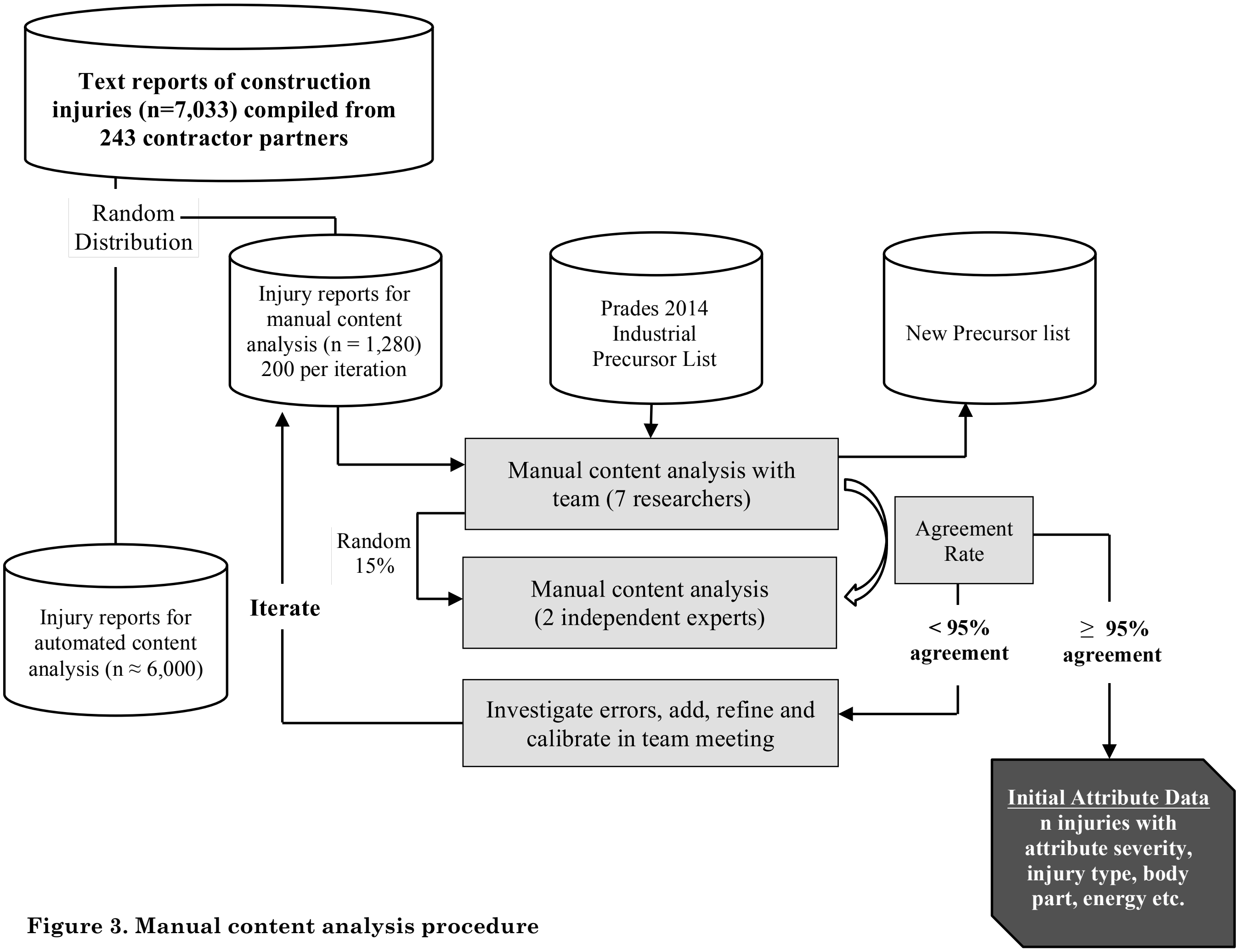

Figure 3. Manual content analysis procedure

One iteration of the process consisted in analyzing 200 injury reports from the 1,280 randomized dataset. First, researchers were asked to individually identify upstream, transitional and downstream attributes but also the severity and maximum potential severity of the injury, its energy source and its injury code as described by OSHA regulations, Prades (2014) and Albert et al. (2014), in 30-50 injury descriptions. Second, a peer review system was implemented to keep the results updated and provide a primary verification. In pairs, the team members reviewed each other's work, discuss potential change, disagreement or lack of attributes and update their results regarding the adoption of new precursors. Shifting pairs every new iteration enhanced these benefits and limited the spread of misinterpretations. When precursors were extracted from the 200 reports, the two independent experts reviewed 15% of the results and computed the agreement rate on a strictly basis: a missing or incorrect attribute was counted as a False/Wrong. Their conclusions were then submitted during weekly meetings so that researchers could be on the same page. These meetings also aimed at discussing the introduction of new precursors, defining their boundaries and their application.

Attribute-based Risk Analysis

a. Exposure data

In order to perform a safety risk analysis, the exposure data for every identified attribute were needed. Exposure data represent the relative time value or the probability a given safety attribute is likely to be found on a construction site. To obtain such data, the research team conducted a two-rounds survey among project managers of the 243 independent contractors of the study. Based on their field experience, managers were asked to evaluate the percentage of time a given crew would be likely to find each of the 79 characteristics or attributes on a site. To ensure consistent interpretations of the various attributes, precursor descriptions were provided along with the questions.

After the first round of surveys, the data were aggregated and the median exposure and the variances for each attribute were computed to evaluate the level of consensus as an important step toward quality data. A second round was needed to refine the degree of consensus in which experts were asked to accept or reject the median responses from the first round and provide their final ratings if they rejected it. Giving the high volume of responses, a consensus among the managers was reached after the second round. Moreover, to collect robust and reliable data, threats to internal and external validity were addressed, as detailed in Table 4 and Table 5, as advised by Campbell et al. (1966) and LeCompte and Goetz (1982).

Relevant threats to Internal Validity (Campbell et al. 1966)		Solutions
History	The specific external events occurring between the first and second measurement other than the experimental variables.	Wide geographical and occupational dispersion of the participants
Maturation	Processes operating within the respondents as a function of the passage of time per se.	All participants provided data in a single session.
Testing	The effect of taking a test upon the scores of a second testing. Participants usually do better on their second test than the first one.	Not applicable
Instrumentation	Changes in the observers or scores used.	Observers and units kept consistent
Regression	Tendencies for movement toward the mean when comparison groups have been selected on the basis of initial extreme scores or positions.	This threat could not be controlled
Differential Selection	Effects of comparing essentially non-comparable groups.	Attributes were modeled as independent
Experimental Mortality	The effect of differential loss of respondents from comparison groups, rendering them non-comparable.	The high number of initial participants from which initial median scores were obtained
Maturation Interaction	An effect that in certain designs may be mistaken for the effect of the experimental variable.	Not applicable

Table 4. Threats to internal validity and solutions

Threats to External Validity (LeCompte and Goetz 1982)		Solutions
Selection effect	The fact that constructs being tested are specific to a single group, or that the inquirer mistakenly selects groups to study for which the constructs do not obtain.	All project manager leads were included and responded representing the entire population of knowledgeable experts
Setting effect	The fact that results may be a function of the context under investigation.	Not applicable
History effect	The fact that unique historical experiences may militate against comparisons.	Data obtained from multiple raters and medians reported
Construct effect	The fact that constructs studied may be peculiar to the studied group.	Not applicable

Table 5. Threats to external validity and solutions

b. Relative risk values

The risk analysis was conducted using the attribute database results from the manual content analysis and the exposure values obtained from the survey. As described earlier, risks were assessed using the methods developed by Baradan and Usmen (2006):

$$\boldsymbol{Cumulative\ Risk} = \boldsymbol{Frequency}\ \ (\boldsymbol{n}) \times \boldsymbol{Severity}\ (\boldsymbol{s}) \times \boldsymbol{Exposure}\ (\boldsymbol{e}) \qquad \textbf{(Equation 2)}$$

By definition, the frequency is the number of accidents that happened per unit of time. It corresponds to the number of times an attribute is identified as part of an injury divided by the percentage of time this particular attribute is found on a construction site, which we defined earlier as the attribute exposure. Therefore, the previous equation can be reformulated as follow and provide the relative risk value of an attribute, based on its actual occurrence on a jobsite:

$$\boldsymbol{Relative\ Risk} = \frac{\boldsymbol{Attribute\ occurrence}}{\boldsymbol{Attribute\ exposure}} \times \boldsymbol{Attribute\ severity} \qquad \textbf{(Equation 3)}$$

In order to translate the qualitative data of the attribute severity into quantitative data and scale the risks accordingly, the research team resorted to the severity scores (s_i) table (Table 6) proposed by Hallowell and Gambatese (2009).

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

Table 6. Severity scores

The occurrence or frequency per level of severity (n_i) of a particular attribute was assessed by determining the number of time it was found in the analyzed incident reports. Finally, the relative risk of a specific attribute was computed as follow:

$$\boldsymbol{Relative\ Risk} = \sum \frac{\boldsymbol{n_i * s_i}}{\boldsymbol{e}} \qquad \textbf{(Equation 4)}$$

RESULTS

This attribute-based analysis is the first attempt and the first step to vastly improve the quality and quantity of available data by considering all injury types and leveraging such amount of detailed injury reports. The manual content analysis of the randomly distributed set of 1280 injury reports required 6 iterations of the procedure described in the research methods. Departing from Prades' (2014) dataset of 51 independent industrial attributes, finding new precursors was an on-going objective during the data extraction process, which required constant refinements of the model and previous analysis. The research team expected to find additional precursors more suitable to the four domains of activities of the construction partners. By the end of the process, 28 precursors for a total of 79 independent attributes were added based on their coherence with the reports and their number of occurrence. Upstream, transitional and downstream attributes are described in the following tables (Tables 8 to 17). All the reports associated with each attribute were then used to generate a keyword list for the automated part of the content analysis. The description and the details of the automated part of this project are not in the ambition of this paper.

Description	Sheet metal worker was cutting panels using a circular saw when foreign body entered his left eye. Worker went and flushed his eye then he notified his supervisor. The employee's eye was flushed about half an hour until the eye was clear. He reported that there is no irritation in his eye.
Upstream	Steel/Steel section
Transitional	Powered hand tool, Small particle
Downstream	No/Improper PPE
Severity	First Aid
Maximum Severity	Medical case
Energy source	Motion
Injury code	Struck-by

Table 7. Manual content analysis result example

Upstream Attributes

a. Materials

Attribute	Description
Concrete	This attribute refers to concrete, cement and mortar in its solid state. It includes concrete structural elements like beams and columns as well as tasks involving rigid concrete like chipping or grinding.
Concrete pouring	Concrete pouring refers to concrete, cement and mortar in their liquid form. It applies to the action of pouring and all related injury and also the action of curing or transporting liquid concrete.
Heavy Material	Heavy material defines material with a considerable weight. It is also used when the description states a two digits weight for this particular material (≥10 lbs.).
Lumber	Any kind of timber elements including timber, plywood, 2x4, 2x8, etc.
Grout	This attribute refers to liquid and dry grout whether the worker is mixing, applying or removing it.
Pontoon	A flat-bottomed boat or hollow metal cylinder used with others to support a temporary bridge or floating landing stage. 'Pontoon cell' already includes the idea of confined workspace.
Soffit	The underside of an architectural structure such as an arch, a balcony, or overhanging eaves.
Valve	Valves are used to control the passage of a fluid through a pipe or a duct.
Piping	This attribute refers to any kind of pipes that are used in the construction field. Working on or being struck by a pipe requires using this attribute.
Conduit	A conduit is defined as a long and usually flexible channel with a small diameter to convey cables and wires. A conduit can be buried underground or suspended from the ceiling using trays.
Scaffold	Raised platform used to access and work at height. Scaffold can also refers to smaller parts of the components like planks or scaffolding. Lumber or steel members that are used to erect the scaffold are already included in this attribute.
Stairs	Any kind of stairs including single steps except ladders. Stairs in itself are not sufficient to describe a 'slip and fall' or 'miss a step' incident as the cause of the slip is unknown and can't be observed before the actual incident.
Steel/Steel section	Any steel components that are used on the site. Steel/Steel section also includes angles, rods, flanges and can be designated by their section or their dimensions e.g. I-beam or 2"x6"x6".
Metal studs	Metal pieces used to build outdoor and indoor partition walls. Metal studs are also used to frame windows or as parts of a roof structure.
Wire	Wire refers to steel wires used to assemble rebar. Cables are not included in this attribute.
Rebar	This attribute refers to any steel reinforcement bars whether they are bundled or installed on the site. However, it does not include rebar made dunnages or rebar mat when they designate walking surfaces, which are uneven surfaces, a separated attribute.
Door	Doors and door frames in general.
Cable	Any kind of cable: electrical, communication, etc. Different from hose that are basically hollow.
Cable Tray	System used to support any kind of cables in general.
Dunnage	Material used to load and secure cargo during transportation, or support jacks, pipes, air conditioning and other equipment above the roof of a building.
Spool	Any kind of spool/reel: electrical cables, film, magnetic tape, etc.
Tank	A large receptacle or storage chamber, especially for liquid or gas. This attribute already includes the idea of a confined workspace.

Table 8. Material upstream attributes

b. Equipment

Attribute	Description
Crane	This attribute is used when a crane is involved in the incident or in the activity that led to an injury like spotting the hook or giving directions to the crane operator.
Heat source	Each time a worker is exposed to an unprotected source of heat like a steam pipe or a machine. Concrete or chemical burns are not defined as from a heat source.
Heavy vehicle	Large and heavy vehicles that are used to transport materials or equipment like trucks or to perform heavy tasks like bulldozers, rollers, graders, etc.
Machinery	This attribute refers to any kind of machines used on site like generators, pumps or light-plants.
Welding	Welding refers to the activity in itself but also to all powered and unpowered hand tools a worker uses to performs his weld. It also includes torching and cutting with torch. In that perspective, heat created by the action of welding a metal piece is already included in this attribute and thus, it does not require selecting 'Heat source to' describe the incident.
Grinding	Grinding refers to the activity in itself but also to all powered and unpowered hand tools a worker uses to performs the task. For instance, selecting grinding includes using a grinder and thus, the attribute 'Powered hand tool' should not be selected.
Drilling	Any action that consists of drilling holes with a powered or unpowered tool, on any kind of material.
Chipping	Chipping concrete or a weld, removing material excess or breaking into small pieces a layer of concrete.
Stripping **Disassembling** **Dismantling**	Stripping is the action of removing lumber elements from a formwork after the concrete or a similar material has strengthened. Although the definition already mentions lumber parts, 'Lumber' and 'Formwork' should also be selected to correctly assess this incident. If mentioned in the description, some precisions about the tools used should be added in the transitional attributes e.g. Pry bar as an unpowered hand tool.
Formwork	This attribute refers to the erection and all activities related to erecting or disassembling a formwork. If mentioned in the description, some precisions about the tools used should be added in the transitional attributes.
Job Trailer	Some incidents occur in the job trailer or while accessing/exiting it. In these cases, this attribute should be selected to describe the environment and the potential cause of the injury.
Unpowered transporter	Unpowered transporter refers to any kind of trolleys, wheeled barrow or carts used to manually transport material or equipment.
Guardrail **Handrail**	Barrier used to keep workers or equipment from accessing a specific area or prevent falls. Handrails are steel components that
Manlift	Manlift is a motorized passenger elevator that allows the worker to access an elevated workspace and perform his task from it.

Table 9. Equipment upstream attributes

c. Design

Attribute	Description
Working Overhead	Activities or tasks that the worker has to perform directly above his head.

Confined workspace	A confined workspace is a design issue. It refers to a closed and restricted area where the air evacuation is limited, light and sounds are amplified and heat exacerbated. A confined workspace can be a box or a cell. This attribute does not include tanks, which are separated attributes, but they give a good illustration of a confined workspace.
Congested workspace	A congested workspace is a site management issue. It refers to any area where there is a limited egress essentially due to the accumulation of material or equipment or because of the structure under construction itself. E.g. Having a lot of workers and equipment in activity in the same area.
Object at height	Attribute used to describe any object or material at height. The object should be higher than the story directly above the injured worker for this attribute to apply.
Object at height on same story	'Object at height on same story' refers to objects or materials from a reaching distance of the worker or directly above the worker. This attribute does not apply to describe the fact that the worker is working on a material above his head. In that case, 'Working overhead' is more appropriate.
Working at height	This attribute describes the fact of working from an elevated platform.
Working below elevated workspace	An elevated workspace is defined as a potential platform or work area overhead where workers can walk on and work from it. E.g. the above story on a scaffold. This attribute is used to highlight the consequences of having workers above your head when you are performing a task.

Table 10. Design upstream attributes

Transitional Attributes

a. Equipment & Tools

Attribute	Description
Forklift	A forklift is a vehicle with a pronged device in front for lifting and carrying heavy loads.
Powered hand tool	Any kind of hand tools using electricity, gas or pressure to operate. E.g. electrical drill, chain saw.
Unpowered hand tool	Any kind of hand tools, tool bags, tool belt and ropes that only requires human power to operate. E.g. saw, screwdriver, wrench, etc.
Ladder	Any kind of ladders.
Hose	Any kind of hoses or lines used to convey water, pressurized steam or air or any fluid in general.
Wrench	Any kind of wrench.
Hammer	Any kind of hammers. E.g. hammer, sledge hammer, etc.
Light vehicle	'Everyday' vehicles/cars people used to commute which also include pick-up truck.

Table 11. Equipment and tools transitional attributes

b. Materials & Substances

Attribute	Description
Nail	Any kind of nails.
Screw	Any kind of screws that helps to fasten pieces together.
Bolt	Any kind of bolts that helps to fasten pieces together.

Hand size pieces	Any kind of materials or objects that is small enough to fit in human hands except hand tools, nails, screws, bolts.
Electricity	This attribute is used to describe injuries due to electrical chocks in general whether they are from an equipment dysfunction or lightning. It can also apply from tasks involving an electrical panel.
Hazardous substance	Substances that are toxic, acid, irritating or are known to cause cancer and long term diseases when they contact human skin or are inhaled. For instance, liquid concrete, asbestos, fiberglass, oil, gas, etc.
Sharp edge	This attribute refers to exposed sharp edges and materials. E.g. the extremities of a cut tube
Slag/Spark	Small steel particle that results from the operation of grinding or welding and thus can be incandescent or not. In case of a burn injury related to a spark, the attribute 'Heat source' is already included in 'Slag/Spark'.
Splinter, Sliver	A small, thin, sharp piece of wood, glass, or similar material broken off from a larger piece.
Small particle	It refers to "foreign object" or "foreign body", "small particle", "small debris" that was found in the eye. E.g. saw dust, air born particle, dust, etc.

Table 12. Materials and substances transitional attributes

c. *Site Quality*

Attribute	Description
Cleaning	Action of cleaning the workspace or the site in general. However, it does not include the action of cleaning a weld or cleaning a piece of material by using a grinder for instance.
Slippery surface	This attribute refers to surfaces that do not ensure a normal grip. Most of the time, it designates wet surfaces due to heavy rains for instance. Stairs, concrete floors or wooden platforms are not slippery surfaces because they are not supposed to be slippery even if the description clearly mentions that the worker slipped or tripped.
Unstable support/surface	Any unstable surfaces, usually temporary supports or loose planks to access a specific workspace.

Table 13. Site quality transitional attributes

d. *Weather & Environment*

Attribute	Description
Poor visibility	This attribute refers to any situations where the visibility is limited or reduced due to smoke, steam, fog, dust or darkness for instance. It also includes dazzling lights and non visible objects.
Snow/Ice	Snow or ice on the ground or at height
Mud	Mud that can result from heavy rains or melting snow but also mud/sludge from sewer, working near water (pontoon), mud from hazardous waste materials.
Wind	Natural wind, gust of wind or explosion blast.

Table 14. Weather and environment transitional attributes

e. Other

Attribute	Description
Exiting, transitioning	Exiting machinery, equipment, vehicle, job trailer, elevated platform… More generally transitioning from one area or workstation to another.
Lifting/Pulling Material	Lifting, pulling and manual handling.
Insect	Any kind of insect (e.g. wasp, bugs, etc.). 'Insect' includes the idea of venom and thus does not require selecting the attribute 'Hazardous substance'.

Table 15. Other transitional attributes

Downstream Attributes

a. Human Behavior

Attribute	Description
Improper body position	Body position that isn't defined as common practice and that is contrary to the activity procedure. An improper body position can result from inattention, taking shortcuts for the task or a congested workspace among others. It is usually refer to as 'awkward position'.
Improper security of tools	Tool that wasn't tangled to the worker or properly secured on the site. Improper security of tools refers to dropping and/or falling tools from height. A tool is not supposed to fall, and thus, if such an injury occurs, we systematically add this attribute.
Improper security of materials	It refers to unsecured bundled material or an improper installation of a structural element that fails to achieve its primary purpose. It also applies for protruding material that should have been secured. For instance, a protruding nail that should have been hammered down or bended.
Repetitive Motion	Repetitive movement that led to an injury and that is clearly stated in the description of the incident. Repetitive motion means undertaking a similar action over a long period of time e.g. Tightening bolts all afternoon.
Fatigue	This attribute includes both physical and psychological fatigue such as stress, time constraints, pressure management, etc. It ranges from small breaks to exhaustion.

Table 16. Human behavior downstream attributes

b. Site Characteristics

Attribute	Description
Uneven surface	Uneven surface can designate slopes and non-flat surfaces in general but also long-lasting installations on the floor like rails, unistrut or bolt anchored in the ground for instance.
Poor Housekeeping	A poor housekeeping refers to objects or piece of equipment on the floor that are not supposed to be there and should be disposed or stored in a more adequate place. Housekeeping is the idea of the global organization and reasonable cleanliness of the site that should provide a safe workspace.
Object on the floor	Object on the floor means the presence of an object that is supposed to be on the floor at the time of the incident. It can also be a part of the task like a piece of material or a tool. Here, object means that it is not a part of the surface and it is supposed to be removed later in the project. E.g. cable trays
No/Improper PPE	Absence or incorrect personal protection equipment. No or improper PPE should be clearly mentioned in the description of the incident and not be the result of interpreting how less severe the injury could have been vs. what it actually is. Exceptions to this rule are eye injuries and concrete burns, which always call for No/Improper PPE.

Table 17. Site characteristics downstream attributes

Attribute-based Risk Analysis Results

a. Exposure data (e)

The survey targeted the construction managers of the partner firms of this study with no specific restriction regarding their years of experience or domain of expertise. The research team expected to obtain a large number of responses so that a consensus could be rapidly reached. The recommended volume of answers for traditional surveys is a panel size of at least 8 experts. We received 68 responses but 2 of them were dropped because of missing data and incomplete survey. The average number of years worked in the construction industry of these 66 managers was 18.7 years. Considering their domain of activity, 11% of the respondents worked in Building, 23% in Energy, 64% in Infrastructure and 3% in Mining. However, due to the important number of responses and the activity domain repartition, the variances of the exposure for several attributes were too high. As described earlier, the degree of consensus was not reached in the first round and in order to refine these results, a second round was needed. Most exposure median values were accepted in the second survey. The exposures (e) for each attribute are shown in the risk analysis tables (Table 18 Table 20).

b. Attribute severity occurrence (n_i)

The research team obtained the frequency of occurrence of each attribute for each level of severity (n_i) by simply counting the number of reports in which a particular attribute contributed to an accident resulting in pain, first aid, medical case, lost work time, permanent disablement or fatality.

c. Relative risk values

The results of the attribute-based risk analysis are shown in the following tables. Each attribute has a relative risk value that typically indicates how risky this particular precursor can contribute to an accident if observed on a jobsite. In other words, the higher the relative risk value is, the more 'chance' the attribute is likely to be part of an incident or cause a severe injury. Indeed, a high relative risk value can be explained by the combination of a very low exposure but a high level of severity for the accidents resulting from the attribute. Similarly, an attribute with a low exposure and a high frequency of occurrence will be qualified as risky and would require particular attention if observed.

The highest relative risk value in the upstream attributes is 'pontoon' (21.75) because it combines a very low exposure (4%) and a low frequency (8) but a high severity: 25% of the accidents involving pontoon can cause a lost work time. However, metal studs have the highest potential impact considering the maximum potential severity (288.52). On the contrary, the attribute 'congested workspace' presents a very high exposure and a relatively low frequency and thus has the lowest relative risk value in the upstream precursors (0.77). In other words, congested workspaces are common on jobsites but rarely contribute to an accident, and when it does, the severity is generally low (83% of the accidents resulted in first aid). In transitional attributes, the highest value is 10.03 for 'hazardous substances' and the lowest 'Forklift' (1.05) besides 'Poor visibility' (0). The highest relative risk value can be found in the downstream attributes and corresponds to 'No/Improper PPE' (69.49), which seems logical: the absence of adequate PPE is rare on sites but when it occurs, the risk of suffering an injury is very high. Finally, the lowest one in downstream is repetitive motion (1.69), which is present 50% of the time on sites but rarely causes an accident and has a low severity.

			SEVERITY						Relative Risk	MAXIMUM POTENTIAL SEVERITY						Relativ e Risk
			12	48	138	246	1,024	26,214		12	48	138	246	1,024	26,214	
UPSTREAM ATTRIBUTE	n	e	Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality		Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality	
Pontoon	8	4.0%	0	5	1	2	0	0	21.75	0	1	3	3	1	0	55.60
Steel/Steel section	126	40.0%	18	98	5	5	0	0	17.10	0	10	59	47	8	2	202.01
Piping	71	30.0%	7	60	2	2	0	0	12.44	0	3	33	34	1	0	46.95
Confined workspace	31	19.0%	2	27	1	1	0	0	8.97	0	0	20	9	2	0	36.96
Scaffold	52	35.0%	15	33	2	2	0	0	7.23	0	6	25	16	4	1	108.53
Metal studs	12	10.0%	1	9	2	0	0	0	7.20	0	1	6	3	1	1	288.52
Timber	75	60.0%	1	67	6	1	0	0	7.17	0	4	36	28	5	2	115.99
Heavy material	82	73.0%	17	54	3	8	0	0	7.09	0	1	30	46	4	1	62.76
Concrete	40	56.5%	2	28	6	4	0	0	5.63	0	1	24	11	3	1	62.57
Working at height	30	50.0%	4	18	2	6	0	0	5.33	0	4	4	11	7	4	230.95
Rebar	50	55.0%	5	43	0	2	0	0	4.76	0	2	24	24	0	0	16.93
Working below elevated wkspace	24	27.0%	4	19	0	1	0	0	4.47	0	3	9	8	2	2	214.19
Wire	32	40.0%	1	30	0	1	0	0	4.25	0	5	25	1	0	1	75.38
Concrete pouring	28	48.0%	2	20	5	1	0	0	4.00	0	1	16	8	3	0	15.20
Stairs	31	50.0%	6	22	1	2	0	0	3.52	0	3	8	20	0	0	12.34
Door	13	25.0%	1	10	2	0	0	0	3.07	0	1	6	4	1	1	116.39
Grout	10	22.5%	0	9	0	1	0	0	3.01	0	0	8	0	2	0	14.01
Conduit	13	22.5%	2	10	1	0	0	0	2.85	0	0	6	6	1	0	14.79
Soffit	7	22.5%	0	6	0	1	0	0	2.37	0	0	5	2	0	0	5.25
Valve	10	22.5%	1	8	1	0	0	0	2.37	0	1	7	1	1	0	10.15
Tank	10	24.0%	0	10	0	0	0	0	2.00	0	0	8	2	0	0	6.65
Object at height	12	59.0%	1	9	1	1	0	0	1.40	0	0	1	6	3	2	96.80
Object at height on same level	7	24.5%	0	7	0	0	0	0	1.37	0	0	5	1	0	1	110.82
Sharp edge	14	50.0%	0	14	0	0	0	0	1.34	0	0	13	1	0	0	4.08
Congested workspace	6	63.0%	0	5	0	1	0	0	0.77	0	1	3	1	1	0	2.75

Table 18. Relative risk of upstream attributes

			SEVERITY							MAXIMUM POTENTIAL SEVERITY						
			12	48	138	246	1,024	26,214	Relative Risk	12	48	138	246	1,024	26,214	Relative Risk
TRANSITIONAL ATTRIBUTE	n	e	Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality		Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality	
Hazardous substance	47	32.0%	4	32	10	1	0	0	10.03	0	0	35	10	2	0	29.18
Small particle	111	71.0%	7	94	10	0	0	0	8.42	0	5	96	10	0	0	22.46
Slippery surface	46	30.5%	9	33	1	3	0	0	8.42	1	1	17	24	2	1	119.91
Hose	34	30.0%	7	21	4	2	0	0	7.12	0	2	14	14	4	0	31.89
Powered hand tool	81	81.0%	10	64	4	3	0	0	5.53	0	5	44	21	10	1	59.18
Unpowered hand tool	88	81.0%	14	68	5	1	0	0	5.39	1	9	47	27	4	0	21.81
Snow/Ice	22	25.0%	5	12	5	0	0	0	5.30	0	1	5	15	0	1	122.57
Ladder	46	70.0%	6	31	3	6	0	0	4.93	0	2	13	23	7	1	58.47
Hand size pieces	56	64.5%	7	47	0	2	0	0	4.39	1	7	28	19	0	1	54.42
Hammer	44	72.0%	2	37	3	2	0	0	3.76	0	3	20	20	0	1	47.28
Slag/Spark	24	30.0%	3	21	0	0	0	0	3.48	0	3	18	3	0	0	11.22
Nail	28	60.5%	0	25	1	2	0	0	3.02	0	1	16	7	2	2	96.62
Uneven surface	34	65.0%	4	28	0	2	0	0	2.90	0	1	16	15	1	1	51.05
Wind	20	43.5%	0	18	1	1	0	0	2.87	0	2	14	2	1	1	68.41
Unstable support	15	25.0%	2	13	0	0	0	0	2.59	0	1	3	10	1	0	15.78
Insect	11	25.0%	1	10	0	0	0	0	1.97	0	0	9	2	0	0	6.94
Mud	10	33.0%	0	9	1	0	0	0	1.73	0	0	9	1	0	0	4.51
Forklift	9	60.0%	0	8	0	1	0	0	1.05	0	0	6	0	3	0	6.50
Electricity	2	60.5%	0	1	0	1	0	0	0.49	0	0	0	0	0	2	86.66
Poor visibility	0	20.0%	0	0	0	0	0	0	0.00	0	0	0	0	0	0	0.00

Table 19. Relative risk of transitional attributes

			SEVERITY						Relative Risk	MAXIMUM POTENTIAL SEVERITY						Relative Risk
			12	48	138	246	1,024	26,214		12	48	138	246	1,024	26,214	
DOWNSTREAM ATTRIBUTE	n	e	Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality		Pain	First Aid	Medical Case	Lost Work Time	Permanent Disablement	Fatality	
No/Improper PPE	136	11.0%	10	112	12	2	0	0	69.49	0	5	107	20	3	1	447.38
Lifting Pulling	233	60.5%	49	165	7	12	0	0	20.54	1	12	100	110	9	1	127.07
Improper security of materials	42	20.0%	2	36	3	1	0	0	12.06	0	0	19	16	5	2	320.53
Cleaning	29	40.0%	1	26	1	1	0	0	4.11	0	1	19	7	1	1	79.08
Object on the floor	29	34.5%	2	26	1	0	0	0	4.09	0	0	11	18	0	0	17.23
Working overhead	32	50.0%	6	24	1	1	0	0	3.22	0	2	23	7	0	0	9.98
Improper security of tools	9	19.0%	0	9	0	0	0	0	2.27	0	1	2	6	0	0	9.47
Poor housekeeping	8	30.0%	0	7	0	1	0	0	1.94	0	1	2	5	0	0	5.18
Improper body position	13	30.5%	2	11	0	0	0	0	1.81	0	1	2	8	2	0	14.23
Repetitive motion	21	50.0%	7	13	1	0	0	0	1.69	0	6	6	9	0	0	6.66

Table 20. Relative risk of downstream attributes

IMPLICATIONS

In the literature review we identified the major trends in application and limitation of the technologies of interest. The major flaw in actual technological safety applications is that they mostly rely on experts' judgments and experience on sites to determine what safety measures, why, when and where they are needed. Besides experts' opinions, BIM technological applications have used safety regulations to help designers achieve safer construction projects. However, using such regulations and codes has limited its application scope to fall prevention hazards.

The results of our attribute-based risk analysis specifically aim to address this lack of safety data. The attribute-based risk analysis relies on the theory that every construction accident results from the conjunction of a finite number of hazardous precursors. These are the real cause factors that lead to an accident. Thus, identifying the attributes that are present on a construction site will help safety managers find the causes of potential accidents independently from any environmental conditions. Moreover, integrating such viable and robust data within emerging technologies and intelligent systems could provide new opportunities of applications, refine or widen their application scope and help safety planners prioritize the adequate technologies depending on the attributes they observe on their jobsites.

In our review of the literature of the different technologies we also found no evidence of a practical safety application for barcodes. Combined with attribute data and the newly developed risk analysis, barcodes have the potential to contribute in turning construction sites into safety information rich environments. In fact, barcodes can become an integral part of jobsites and could be disseminated in various areas where risky attributes have been identified. Prior his task or as a mandatory step to achieve it or start an engine, a worker would be invited to scan a barcode that would display the attached safety recommendations and retrieve relevant information as more complex intelligent systems have tried to implement. Barcodes could also improve worker safety trainings by giving safety managers the tools to illustrate particularly risky events attribute-based risk analysis have highlighted. For instance, instead of using immersive virtual reality models, the intelligent system developed by Albert et al. (2014) to recognize safety hazards on sites could be transpose to reality by using barcodes. In groups or individually under the supervision of a safety manager, workers could walk through a barcoded worksite to identify hazardous situations and scan a barcode to access the gaming platform the authors sought in the first place.

By considering the highest relative risk values instead of experts' opinions, the application scope of intelligent systems could be redefined to specifically address the major risks a worker is likely to encounter. On the contrary, resources allocated to what is found to be a low relative risk value attribute could be reinvested to high priority attributes. Indeed, tag-based technologies such as RFID, UWB and GPS could benefit from attribute-based risk analysis to know what, why, when and where to tag specific areas, workers, equipment or materials. This new method could also help safety managers who use 3D range imaging to determine the best spots to install their cameras in order to focus on the particularly risky operations highlighted by the risk analysis. Algorithms that have been developed to track crane activities could be expanded to monitor specific material and equipment attributes to detect abnormalities or their relative proximity. The BIM technology could also greatly benefit from the integration of attribute-based data in order to extend its application scope beyond fall prevention by automatically detecting missing guardrails around openings. Attributes could provide the reliable and wide application range data sources that BIM models lack to assess risk at the design phase. Rules checking programs could be improved by suggesting design alternatives to designers in order to reduce the impact of the upstream design attributes early in the project. Furthermore, the BIM technology is so versatile that it has been coupled with several other technologies to propose new safety applications. With these technologies, BIM essentially serves as an information source, in which data are attached to every virtual object. Technologies use virtual models generated with BIM to interact with the user, to allow him or her to visualize tagged objects and construction progress, define dangerous zones based on on-going or future tasks, and issue alerts when safety hazards are detected. Integrating attribute-based data within BIM could thus improve their efficiency and potential as combined intelligent systems. Attribute-based risk analysis could be the keystone previous authors were expected to encourage designers to get involved in achieving safer projects. For instance, the combination of BIM and VR for immersive attribute-based safety design reviews would replace the necessary meetings between designers and experienced safety managers to detect hazards at the design phase that previous researchers have recommended.

CPS is a sensor-based system that enables communication between the physical and cyber worlds. Besides monitoring temporary structures as suggested in previous literature, the personal protection equipment available to construction workers could also benefit from this technology. Indeed, a wide range of sensor-based applications has been developed in the last few years and especially to provide health monitoring. Thus, some attributes related to human behaviors could be assessed such as 'repetitive motion' or 'fatigue'. By creating a safety jacket that includes gyro-sensors, a health oriented CPS system could warn the worker and help safety managers anticipate injuries caused by movement repetitions such as back pains which are frequent on jobsites. Moreover, some contractors have required their crews to avoid any work overhead due to the high number of resulting muscle pains, eye injuries and general discomforts or soreness. Integrating an inclinometer sensor or a gyro-sensor on hard hats could also assist workers to prefer a more adequate body position and thus minimize ‘working overhead’ incidents. Other small devices like flex sensors could ideally prevent ‘improper body positions’ and dangerous ‘lifting, pulling materials’, which account for one of the highest relative risk values according to our attribute-based risk analysis (20.54). To address the particularly risky attributes ‘No/Improper PPE’ and ‘small particles’ that essentially results in eye injuries, selective infrared short-range proximity sensors could be attached to both eye protection equipment and specific tools that are known to generate dust and ‘small particles’, so that the powered hand tool could not be used without the appropriate matching safety glasses. Optical dust sensors have also been developed and could shut down any equipped tool when a too dense dust cloud is generated, which is the most frequent cause of eye injuries in ‘confined workspaces’. To power all these low-consumption sensors, safety jackets could be equipped with kenetic energy chargers. Some sensors could also be randomly triggered by incoming radio signals like RFID passive tags in order to communicate their actual state to the combined RFID/CPS system. Sensors alone cannot evaluate the data they measure, this is why such RFID/CPS intelligent system would be necessary to collect and analyze all these information to detect any body position, environmental or equipment abnormalities. Other applications could be used to assess adverse environmental conditions with a combination of CPS and GIS systems. On construction sites where the attribute ‘Insect’ is particularly prominent, ultrasonic generators could be periodically activated by the general system to repel pests. Gas sensors to assess the concentration of volatile substance could warn workers in case of hazardous concentrations and situations. Linking geotechnical information with humidity, temperature sensors data and meteorological records could create a real-time condition map of the different areas of a worksite, and might be used to forecast the formation of mud or slippery surfaces that have shown to be one of the attributes in some accidents.

The GPS technology is the outdoor tracking and locating system by excellence. Another way to address the risk of ‘No/Improper PPE’ would be to merge this technology with a similar CPS sensor-based system as previously described to send visual and/or sound alarms to a worker when he enters a predefined area with inadequate personal protections. For instance, some construction zones where attributes such as ‘welding’, ‘grinding’, ‘slag/sparks’ or ‘small particles’ and ‘wind’ have been identified would not be accessible to personnel without appropriate safety glasses. The GPS/CPS system could also be able to retrieve the altitude at which a particular worker is performing his task, and automatically determine if he or she is properly equipped and thus help to reduce ‘working at height’ related injuries. Likewise, it could also detect simultaneous tasks and track crews so that ‘working below elevated workspace’ situations can be avoided if possible, or at least it could raise workers’ awareness of their surroundings and that there is an on-going task above or below.

Technologies	Primary uses of the attribute risk data
Barcode	This technology could transform worksites into safety information rich environments. Barcodes could provide information retrieval based on attributes identified on site during safety trainings, meetings and pre-task. It could also be used to display prerequisite safety recommendations before starting an engine or using a powered hand tool.
RFID	Attribute-based risk analysis yield which attributes are critical to track and monitor in order to prevent accidents. The results could be used to determine what physical asset should be tagged, why, when and where. RFID would allow longer distance communication between sensors and computer-based system in CPS.
UWB	The UWB technology is very similar to RFID but can achieve a better accuracy and is less subject to multipath signal issues. Thus, RFID applications can also be applied with UWB.
GPS	Determine what asset should be tagged, why, when and where. Combined with CPS, this technology could determine if workers are properly equipped when entering a predefined area where hazardous attributes have been identified. It could also raise workers' awareness of their surroundings such as on-going simultaneous tasks above or below.
GIS	Attributes can be displayed on a map of the construction site in GIS software. Combined with a CPS sensor-based system, the technology could provide real-time evolution of certain environmental and site characteristics attributes.
Visual Monitoring	Depending on the attributes present on sites, managers would be able determine the best spots to install the 3D range imaging cameras and monitor specific tasks or equipment. Additional algorithms could be developed to monitor various assets at the same time and track the evolution of particularly risky attributes during the project life.
VR	Combined with both attribute risk data and BIM, virtual reality could help designers address a wider spectrum of risk in the design phase and thus considerably strengthen the first barrier to potential accidents in Reason's causal perspective.
AR	Basically, AR is used to reveal hidden information and project objects informatically designed. No particular safety application has been found other than the ones suggested in previous literature such as revealing hidden utility lines by combining GPS with this technology. Some VR applications might be transposed to AR.
CPS	Combined with RFID, this technology could be used to implement a sensor-based system to periodically or continually monitor workers' health status to prevent injuries related to repetitive motion, working overhead or fatigue. The system could also be used to reduce eye injuries with dust sensors and/or selective PPE detection.
BIM	Similarly to VR, BIM could benefit from attribute risk data that would help designers address a wider range of potential risks at the design phase and inspire more safety design alternatives based on existing attributes. Upstream attributes are typically the precursors that could be addressed at the design phase.

Table 21. Primary technological use of the attribute risk data

LIMITATIONS

While several promising and exploratory insights about the integration of attribute-based risk data with emerging technologies and intelligent systems have been given, this study has some limitations that should be considered. First, the attribute 'No/Improper PPE' particularly reflects the lack of adoption of adequate safety glasses that led to eye injuries as mentioned in the description of this precursor, which explains the high relative risk value of this attribute. Eye injuries have systematically been identified as the absence of proper personal protection, which might not be the case regarding the safety policies of the firm. Nonetheless, the analysis clearly proves there is an issue with the application of proper PPE that needs to be addressed.

Second, the research team did its best to identify and define attributes so that no ambiguity remains. However, even if the attribute descriptions have been provided with the surveys, different interpretations could exist between the research team and the managers and that the number of responses could not minimize.

Third, "Many methodological problems in testing reliability stem from violating the requirement for coders to be truly independent, working with coding instructions they cannot follow or applying them to data that they fail to understand" (Krippendorff 2004, p.415). All efforts have been focused on implementing a strict procedure and on collecting high quality safety data, which is the issue this paper stands for. Nonetheless, some limitations might also exist in the manual extraction process.

Fourth, the attribute list is believed not to be exhaustive. Even if the distribution of the injury reports was randomized, the research team put aside several potential attributes due to their low frequency of occurrence (<8 occurrences) and thus, the automated part of the content analysis could yield additional precursors. These attributes were extracted from injury reports of U.S contractors, which might restrict the application scope of the presented risk analysis method. Moreover, evolution in technics and practices on sites could challenge the attribute-based analysis regarding the exposure values.

Finally, even if looking at attributes instead of task or trades like previous risk analysis has overcome most limitations regarding task interactions, they still need to be addressed from the attribute perspective. For example, 'small particles' and 'No/Improper PPE' are highly correlated in our risk analysis due to the important number of eye injuries including both attributes. On-going interactions between attributes have been barely developed in this paper and require further research to refine the model and compute more precise risk value. Ideally, interactions between 3 to 5 attributes would be significant enough to obtain risk values developed to the 3^{rd}, 4^{th} or 5^{th} order that reflect actual risky situations on sites.

CONCLUSION

This study discussed Barcode, Radio Frequency Identification (RFID), Ultra Wide Band (UWB), Global positioning System (GPS), Global Information System (GIS), Visual monitoring, Virtual Reality (VR), Augmented Reality (AR), Cyber-Physical System (CPS), and Building Information Model (BIM) and their respective applications to construction safety. The authors found that most of them lack viable and robust safety data sources, and that they essentially rely on experts' judgment and intuition. The findings also revealed that most intelligent systems applications of interest are still theoretical and that previous research fails to provide practical considerations to make safety on site real. To address this issue, this research drew on and is a continuation of the work of Esmaeili (2012) but has vastly improved the quantity and the quality of the process by considering all types of injuries of a 1,280 large injury reports database provided by 243 independent contractors. The introduced attribute-based risk analysis was designed to reinforce this tenuous link between theory and practice. In addition, it was found that the relative risk values for each potential hazard attributes that can be found on a worksite could provide the robust and viable tool safety managers need to effectively identify risky situations, prioritize safety strategies more efficiently and implement adequate intelligent systems. Such data are independent from any environmental conditions and thus can be adapted to the transient and dynamic nature of construction sites at almost every stages of a project. Integrated to intelligent systems, they are the answer to what, why, when and where safety is needed on sites but also how technologies could make construction sites safer. Examples of integrations of attribute risk data with the technologies have been developed as well as technology fusion applications to tackle safety issues.

As mentioned in the limitations section of this paper, future research should focus on improving the model by exploring how attributes interact with each other and if consistent links between some of them could be measured to refine the attribute-based risk analysis methods. The authors also advocate practical implementations of the suggested technological systems that are believed to have the potential to change safety managers' approach to construction risks and make construction sites safer.

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