The Role of Automation in Right-time Construction Safety

J. Teizer [a]

[a] RAPIDS Construction Safety and Technology Laboratory, Ettlingen, Germany
E-mail: jochen@teizer.com

Abstract –

Construction organizations continue to be challenged to adequately prevent accidents. Although the five C's (culture, competency, communication, controls, and contractors) have been focusing for many years on compliance, good practices, and best in class strategies, even industry leaders have only marginal improvements in recorded safety statistics. Right-time vs. real-time construction safety and health identifies three major focus areas to aid in the development of a strategic – as opposed to a tactical – response. (1) Occupational safety and health by design, (2) real-time safety and health monitoring and alerts, and (3) education, training, and feedback leveraging state-of-the-art technology provide meaningful predictive, quantitative, and qualitative measures to identify, correlate, and eliminate hazards before workers get injured or incidents cause collateral damage. Based on the current state-of-the-art of existing innovative initiatives in the occupational construction safety and health domain, a framework for right-time vs. real-time construction safety and health presents the specific focus on assisted safety and health data gathering, analysis and reporting to achieve a better safety performance. The practical as well as social implications in conducting a rigorous right-time safety culture in a construction business and its entire supply chain are tested in selected application scenarios and results are presented.

Keywords –

Right-time alert and warning technologies, automation and control, construction safety and health, historical safety statistics, lagging and leading indicators, performance measures, prevention through design, pro-active decision making, real-time monitoring and feedback, remote sensing, safety culture and climate, worker education and learning.

1 Introduction

Many safety studies that were led by industry or research experts focused greatly on traditional safety assessment and improvement techniques. In fact, these efforts have been successful and have changed the culture of safety. Today, many owners take safety very seriously and demand from contractors or subcontractors – and slowly from the entire supply chain in construction – to provide excellent track records and safety management on their jobsites. But even voluntarily reported safety performance statistics by industry leaders show that the real impact of safety best practices – which can be much stricter than existing federal or state safety rules regulations – hardly leads to further decreases in recordable incident rates. A valid question remains: How can the goal of zero accidents in construction and in any other hazardous workplace environments be achieved?

To review the magnitude of this problem, it is critical to consider construction with its significance to the economy of many countries. The U.S. construction industry, for example, accounts for $611 billion or 4% of the yearly gross domestic product (10% if equipment, furnishings, energy and other sectors are included), employs 7% of the total workforce, and invests $1.16 trillion every year in the economy [1]. A key message is that advances in emerging technologies offer significant opportunities to improve construction safety substantially and help meet other national challenges, such as becoming more efficient in work tasks. Thus, an investment in safety directly impacts the performance of other troubled industry sectors.

A key element that can help in objective data collection, processing, information, and knowledge generation of many of the mostly dynamic construction resources (personnel, equipment, and materials) [2] is automation [3]. Finding ways to achieve such automation and leveraging information that becomes available at the right-time vs. real-time is the topic of this paper. The author argues that such automation should be done at the right-time, enabling up-to-date safety data gathering, analysis and reporting when needed and with the ultimate goal of achieving better safety performance.

The paper outline has the following structure: the background reviews occupational safety and health literature; second, up-to-date safety performance statistics and performance measurement techniques are reviewed; third, the motivation for right-time vs. real-time pro-active construction safety and health is introduced by creating a framework and a strategic roadmap for implementation; fourth, examples of state-of-the-art research illustrate the feasibility of implementing the framework; fifth, the paper concludes with a summary of its contributions.

2 Background

2.1 Safety as a Key Problem in the World

More than a decade ago and varying by country, up to 50% of all the fatalities in work related accidents occurred in construction [4]. While today in Europe more than one in four fatal accidents take place within the construction sector, Australia and the US report about one fifth of worker fatalities [5]. It is reality that construction accidents occur significantly more often than in any other industry sector [6-8]. In addition to the loss of life, construction accidents result in serious and debilitating injuries. One of the key reasons for incidents are unsafe worksite conditions and human error [9]; in particular, carelessness or lack of awareness on the part of workers [10]. Workers often do not have good perception of the risks involved in executing work tasks and according to Rasmussen's model, their or their management's motivation to achieve high levels of productivity pushes them to work 'near the edge' (in terms of their exposure to risk beyond the zone of control or recovery) [11]. A major limitation of current practices though is that safety and health data is most often collected after the fact – when loss of life, injury, near miss, or at-risk behavior have already occurred – with no chance of return.

2.2 Safety Education and Training

Safety educating and training construction workers is required off and on jobsites, but it is largely undertaken through frontal teaching and instruction of hazards. Very little, if any, experiential training or practical education is carried out on job sites. It is a rare scene that a safe training mock-up structure on the jobsite is provided to workers [5]. Few receive individualized safety training or continued education on smaller or mid-sized operations. Other successful efforts that are underway [12] involve construction safety experts early in the design and planning process of construction projects. Their goal is to identify and eliminate hazards before they appear during operations. Owner buy-in and funding, however, is required.

2.3 Time Dimension in Safety Performance Measurement

Effective monitoring and control of construction safety in modern projects require sufficient planning and management to succeed. Various measures such as lagging indicators, leading indicators and safety climate have improved safety [13]. These traditional approaches of measuring safety performance rely on manual means and subjective measures (e.g. surveys or manual counts), which are often costly or slow to conduct, error prone in accurateness, and infrequently performed for effective project safety control [14]. In addition, the availability and usefulness of indicator data diminishes over a short period of time rather quickly due to the quick progress on construction sites. Edirisinghe et al. [15] introduced a good definition on leading indicator lifespans: "the time period the indicator remains useful relative to a potential incident". They added, time-delays between indicator data collection, result reporting, and responsive action can undermine any possible advantages of having such information available. According to the same study physical hazard indicators have the shortest lifespan and – due to the dynamic nature of the work environment – should be collected immediately, if necessary in real-time, to derive safety performance evaluations. Perception and management leading indicators – the terms are all introduced later in this article – are typically collected on a regular basis over time. While in-depth information about the root cause of accidents or incidents is important to prevent the same type from happening again, the time dimension in analyzing the causality of accidents and incidents is vital, but is very often overlooked in research studies and practical world applications [15]. Dyreborg [16] therefore argues that the 'time-window' to understand the 'cause-and-effects relationships' is rather important. Although, automation in the safety and health performance measurement processes is one solution [3], to date, there exists no formalized approach for right-time automated safety monitoring, data analysis, information reporting, knowledge generation, and/or visualization in the construction industry.

2.4 Technology for Safety Data, Information, and Knowledge Generation and Sharing

Although the uniqueness and short duration of construction projects might be reasons for the slow and limited adoption of technology in construction, multiple emerging technologies are suited to be applied to the safety problem [2]. To improve the time-lag between data recording and change in safety performance, several improvements are necessary:

1. It is important to identify classes of technology, since a proposed system must be robust in operation and readily incorporate technological breakthrough to make it worthwhile for companies to invest.

2. Data that has been gathered and processed to information might be applied and disseminated as new knowledge with all project stakeholders immediately rather than limiting it to few.
3. Feedback of any necessary kind must be shared pro-actively at the desired level-of-detail at the right-time to identify or predict safety issues, perhaps in real-time when life is at imminent risk.

An abundance of research literature exists on sensing systems for resource location tracking, rapid and robust visual progress and motion tracking, limited availability of worker warning, feedback and actuation technology, and virtual reality as data visualization environment. Several of these have been reviewed in [17] and are not further discussed in greater detail in this paper. Based on the previous sections of the literature review, construction safety and health research and applications for the past few decades can be grouped into clusters. Figure 1 illustrates a few of the topics that build the base for right-time construction safety and health research. A trend towards safety engineering – the use of advanced sensing and data mining technologies – becomes visible, while all other domains are necessary to build a strong foundation of safety within an organization.

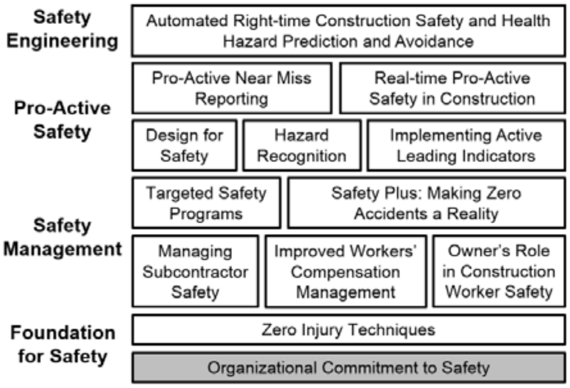

Figure 1. Existing domains in construction safety and health research

3 Method

3.1 Formalization of a Right-Time Pro-active Construction Safety System Architecture

Strategically-conducted safety research seeks to study the critical technological and algorithmic needs associated to the safety decision-making processes that require large-scale and data-intensive sensor networks for monitoring and visualization of infrastructure, human resources, equipment, and materials. Limited elements of this critical technology exist in hardware and software form to some degree. The design of a complete right-time pro-active safety system architecture has yet to be realized due to the:

1. impracticality of contemporary technology (data acquisition),
2. inefficiency or unreliability of existing data processing algorithms (data analysis),
3. lack of realistic methods for realizing a safety feedback system architecture (reporting and alerting), and
4. absence of proven safety management actions (safety culture).

Thus efforts are warranted into the identification and resolution of critical needs in right-time data acquisition, data processing, and reporting in the complex and data noisy construction environments. Implementation of right-time pro-active safety and health research requires addressing several open research questions: Which traditional safety information from accident causation models and safety indicators is useful for a right-time or real-time construction safety and health process? What type of data gathering sensors, processing techniques, and data visualization environments can provide efficient, effective, reliable, fast, and accurate safety information in a highly dynamic, unstructured, and/or cluttered environment? Even if such fast and accurate sensor, information, and visualization technologies are available, how can the proposed framework that is ultimately targeting safety applications, handle large amounts of data, reduce measurement errors, in what data file format and which existing open software interfaces, and perform all of that at the right time, eventually in real-time or near real-time? How are the potential construction hazards recognized early, preferably at the planning stage, and how can previously unrecorded safety data be gathered to assist safer construction design? What safety information provides the most relevant feedback to the project stakeholders and how can it be communicated to workers so they utilize it in their transition from skill-based to knowledge-based decision makers and how can organizations transform safety management actions? To address these challenges, the author proposes to use right-time data collection and processing techniques and immersive visualization environments as a catalyst for the conversation of safety and health information.

3.2 Linking Accident Causation Models and Safety Indicators

The main concept behind the accident triangle of [18] is that severe accidents can be prevented if one takes care of the more frequent unsafe acts first. Bellamy [19] noted that the investigation of accidents can help preventing similar ones of the same type. As Edirisinghe et al. [15] argue, however, both studies did not consider the time dimension in analyzing causations. They note "it is essential to consider the time dimension in causality analysis in order to undertake an evaluation of the time-sensitivity of the different types of indicators".

The author issues the following definitions to explain the context of data types in the developed framework:

- *Right-time (real-time) construction safety*: "The (latest) point in time when knowledge is required to prevent an injury or collateral loss." Right-time in real-world applications might frequently be real-time, for example, when a worker-on-foot requires real-time situational awareness and instant reaction time to avoid being struck by equipment traversing in too close proximity to a work area.
- *Physical accident/incident precursor indicators:* "Evaluation of the characteristics of the physical work environment." These include (pre-) work site conditions (e.g., weather, illumination, road conditions, and availability and condition of tools and materials), the presence and state of resources (e.g., static, moving, or interacting workers, equipment, and materials), work crew and equipment interfaces, and risk exposures and management approach.
- *Management leading indicators:* "Counting safety management activities" (e.g., frequency and number of inspections, safety walks or checks by contractor's and client's safety representative, training sessions, hazard reports, and the time it takes to address issues).
- *Perceptions or situational awareness leading indicators:* "Periodic measurement of worker's and management's perception of safety climate" (e.g., surveys measuring effectiveness of safety and health program, level of quality to commitment to safety culture).
- *Safety levels related to events:* "Measurement of accidents (e.g., injury or fatality), minor incidents (e.g., first aid treatment or small collateral damage), near-misses (e.g., unsafe act or event almost leading to accident/incident), and situational or personal issues (e.g., state of communication, supervision, and worker health and fatigue, behavioral factors of humans)".

It is important to understand the time-sensitivity associated with leading safety indicators. Some might even be dismissed if the time lag between data capture and analysis is too great. According to Lingard et al (2013), a great emphasis is on selecting the appropriate frequency of useful data capture and reporting.

3.3 Organization for Right-time Safety

Figure 2 depicts the complex time-dependent nature of safety performance indicator data that become available to different levels within an organization through the use of manual and/or automated recording methods. As construction stakeholders require different pieces of safety information at different time intervals, technology may assist in this task; in particular early in a project through automated safety in design checking. Construction safety planning is important, but less time-critical, since it typically occurs months or weeks (in other words 'at the right-time') in advance of construction. Perception and management indicator measurement frequencies vary accordingly from weeks to months depending on the organization's resources it has committed. Although these indicators identify gaps in an existing safety program, they have a limited ability to detect any potential hazards near real-time. Data from these indicators require though execution of appropriate actions once holes are detected. Once the severity of the hazard intensifies, injury, illness, or death may become more likely.

Figure 2. Right-time construction safety framework: 'movable layers for protection' address the critical time window for accident prevention and response

On-site real-time hazard monitoring is vital to detect physical hazard indicators. Real-time warning and alert feedback is required. As Edirisinghe et al. [15] noted, a good strategy is to use real-time captured leading indicators as a hazard precursor and execute appropriate actions immediately once holes are detected or intensify. A "movable layer for protection" – shown in an example as a layered barrier in Figure 2 – prevents a fatality using – at the latest – real-time data recorded on a construction site once the perception or situational awareness of site personnel fails. The time window to prevent accidents and incidents accordingly narrows the worse the outcome of one gets.

3.4 Techniques for Right-time Safety

To achieve the ambitious goal of building such a system, the roadmap builds on technologies for right-time safety data collection, processing, and reporting. Figure 3 depicts the proposed technological approach of a pro-active control system for construction safety.

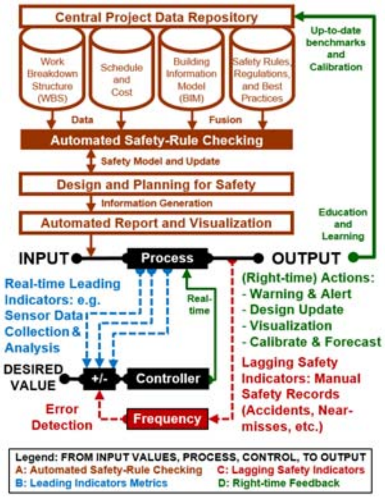

Figure 3. Technical right-time safety system architecture: Influence of safe design and indicators on control and output of a safe construction process

It consists of input (e.g., data collection), processing (e.g., data analysis), feedback (e.g., reporting and alerting), and output (e.g., management actions). The system includes several modules that are explained in more depth:

- *Pre-project and pre-task execution data collection, early rule checking, and reporting to prevent hazards:* This module captures project-related data from various sources in a central data repository, including important operations data such as work breakdown structure (WBS), schedule and cost, building information modeling (BIM), safety rules and regulations, and best practices data. Project data, if held in a central data repository and fused, can be checked using automated rule checkers [20]. These design and plan for construction safety and health during the pre-construction phase.
- *Lagging indicators vs. real-time leading indicators collection:* This module collects and processes lagging safety and health indicator data by applying conventional data collection approaches (e.g., manual use of smart phones). While many researchers noted that manually collected lagging indicators provide value detecting errors in the system, they cannot contribute from preventing hazards that appear in real-time. Therefore, Edirisinghe et al. (2014b) and Lingard et al. (2013) envision real-time benchmarks to be set across work groups, projects, organizations, and industry sectors and propose forecasting as a second type of analysis, which includes time series and trend analysis to identify deviations from normal conditions. The module on real-time leading indicators collection collects and processes leading indicator safety and health data in real-time. It takes place in the entire construction supply chain, before and throughout the construction operation duration, and eventually beyond.
- *Control through desired safety benchmark values:* They are responsible for accurate safety performance according to a-priori established safety and health benchmarks. Benchmarks are set up-to-date using various leading indicator values. Reporting and alerting mechanisms are based on real-time pro-active feedback technology or conventional management actions. Any control task creates new data that itself can calibrate existing data in the central data repository.
- *Right-time (real-time) feedback and management actions:* This module includes three steps: (a) real-time control, (b) near real-time or slower control, and (c) forecasting. As Teizer et al. [21] stated, “sensing and actuation technology provides an additional level of protection”. They further noted, the specific application determines whether pro-active real-time hazard detection, identification, analysis and feedback techniques are required to prevent loss of life or severe collateral damage. Aside real-time control, near real-time or less frequent feedback enables reporting to various management or executive levels of an organization with the focus on changing mid- or long-term goals of established occupational safety and health policies. The last step is forecasting. All gathered information can be used to predict and rectify any potential future risk early in projects.

4 Results to Conceptual Proof of Concept

Several existing real-world application scenarios tested the right-time pro-active safety framework and its system architecture: (1) Safety rule checking to prevent hazards [20], (2) location data tracking and analysis to determine leading indicators [14, 22], (3) near real-time monitoring for rapid response [14], and (4) advanced education and training [23]. The first and third are explained while results to the second and fourth are discussed extensively in the mentioned literature.

4.1 Automated Safety Rule Checking to Detect and Eliminate Hazards Upfront

Zhang et al. [24-26] developed a safety rule-checker and safety ontology that integrate available project data (Building Information Model, work breakdown structure, schedule, etc.) and checks domain knowledge, e.g. official safety code, automatically using machine readable language. Necessary protective equipment will then appear for safety violations where and when needed, e.g. guardrails for building edges or covers for holes (see Figure 4). Similar to a structural clash detection tool, testing for safety violations in existing BIM designs (hazard model) uses parametric conditions of BIM objects. Visualization, simulation of alternative ways of construction over the project duration, optimization of work phases, and accurate quantity take-off of protective safety equipment becomes feasible. Visualization through BIM, however, will be limited to static protective safety equipment or hazard clash/location identification data. Currently, commercially-available BIM software is not able to engage users less on any of the data from dynamic resources that exist in the construction environment, such as workers and equipment movements. Real-time 3D immersive environments utilizing real field data, explained later, offer such capability, however, require further development towards safety applications.

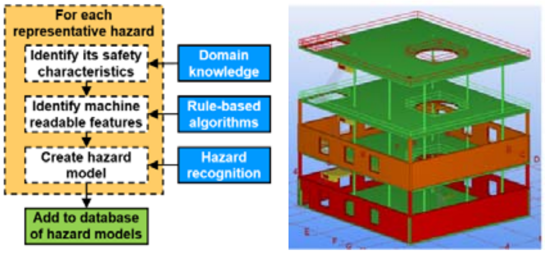

Figure 4. Rule-based safety checking (dashed lines indicate current manual practice) and result to automated rule checking that detects and mitigates fall hazards in BIM [20].

4.2 Near Real-time Leading Safety Performance Indicator Data Collection, Analysis and Visualization

As positioning sensors collect time-stamped location data, the spatio-temporal proximity of two (or more) resources can be found by cross-correlating data from both resources. User-defined proximity thresholds can be applied to define the terms of “near-miss”, “warning”, “alert”, and “collision”. Empirical data generated in this experiment, once analyzed automatically, creates valuable proximity graphs without any human interference. Mining such data further can lead to evaluation of truthfulness of safety best practices (e.g., rules established for work near dynamic hazards). Recorded site data can further be mined to result in personalized education and training [23]. The frequency of the proximity of workers can be quantified and mapped. See the location of fatal events of workers-on-foot with underground mining equipment in Figure 5.

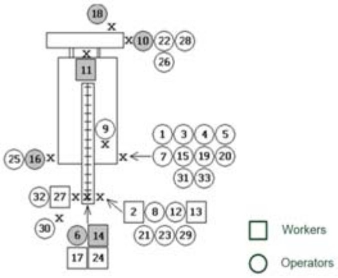

Figure 5. Number and location of fatalities around equipment recorded after the fact [27].

If needed, individual resources can be optimized, e.g. a worker can be taught to change his/her work behavior. Alternatively, a piece of equipment can be replaced with safer ones, if it is determined that it causes many near misses. Criteria on when to change will be set on leading indicators. The advantage of leading indicators (compared to lagging indicators) is that they can change the outcome of a process before it actually ends. The chance of improving the safety performance is subsequently high, as many incidents can be prevented if actions are taken rapidly enough. Thus, should a-priori safety thresholds or tolerable benchmarks be met, unfortunately, control or actions will be taken to resolve the issue immediately, if not automatically.

Such a scenario is novel as in the past, lagging indicators depended on incidents to occur to control a process after the fact. Lagging indicators offered no remedy since information was provided too late to have significant impact on changing the process (and safety performance). As important site safety metrics become measurable effortless and at low investment, immediate increase in safety performance while a process is running is possible.

Results to a real-world application are visualized in Figure 6. A construction site with many worker-on-foot and equipment near misses in and close to a ramp into an excavated pit is shown. Although the near miss data was collected in real-time and processed afterwards, timely information can be presented to the site safety management that then provides a second, safer entrance for workers-on-foot into the pit area or that orders placement of concrete barriers for a safe walking path for the workers-on-foot next to the traversing heavy equipment. After visualizing the proximity data, the contractor decided on installing a separate entry/exit into the pit. Even such alternatives (e.g., using potentially an unstable ladder) should be evaluated whether they are a good safety best practice.

Figure 6. Close proximity events visualization projected on satellite imagery [28].

5 Discussion and Conclusions

Safety in increasingly complex, large, and capital intensive construction projects is challenging, time consuming, and mostly a manual task for engineering and construction professionals. In such projects, communication of essential safety information among project stakeholders becomes key to save lives and cost. When technology is utilized to rapidly provide valuable information to decision makers, significant safety and efficiency improvements are envisioned to trigger tighter (safety and risk factor) integration of safety and construction process information. Several motivators have led this study on a right-time monitoring system for construction health and safety based on an intelligent safety indicator framework. Other approaches – based in safety culture and climate – exist as well [29].

First, enhancing workplace safety and health – in particular providing effortless and accurate data collection and reporting valuable information – has large potential to transform the industry's current best practices.

Second, what is considered a complex human capability to capture, process, interpret, and assimilate safety information, is yet a challenging task if human-designed systems are to be replicated automatically and in real-time as intelligent prototypes. Improving performance and robustness of tracking site resources for data recording, establishing leading indicator data fusion and inference algorithms, and information sharing through immersive visualization platforms are few of important examples to improve the current standards-of-practice.

Third, no research to date has established a formal link between the impacts of pro-active hazard prevention, right-time data collection, real-time processing, and reporting of safety-relevant information to decision makers. The effective use of advanced right-time techniques in monitoring and reporting construction workplace safety and health performance indicators allow rapid acting based upon of never before recorded events.

For these above mentioned reasons, a novel system for right-time risk identification and monitoring coupled with intelligent data analysis and reporting techniques has been introduced. The strategic importance of considering the time-dimension of a leading indicator and action framework to improve early pro-active feedback, provide advanced learning, and better safety and health decision-making has been successfully implemented and tested on various application scenarios. The framework and early testing show promising results that at some point in the future may lead to autonomous intelligent prediction and avoidance of hazards in the construction workplace. New concepts to solve these problems will likely need to use an interdisciplinary approach and utilize or adapt various tools from sensing, data fusion, machine learning, behavioral factors, and virtual reality research.

References

[1] Census Bureau, 2007 Economic Census, www.census.gov (Last accessed July 10, 2009).

[2] Teizer, J., Caldas C.H., and Haas, C.T., Real-Time Three-Dimensional Occupancy Grid Modeling for the Detection and Tracking of Construction Resources, *Construction Engineering and Management*, ASCE, 133(11):880-888, 2007.

[3] Navon, R. and Sacks R., Assessing research issues in automated project performance control (APPC). *Automation in Construction*, Elsevier, 16(4):474–484, 2006.

[4] Dupre, D., Accidents at work in the EU 1998-1999, KS-NK-01-016-EN-I, Eurostat, Luxembourg, http://epp.eurostat.ec.europa.eu/cache/ITY_OFFPUB/KS-NK-01-016/EN/KS-NK-01-016-EN.PDF, p. 9, 2001.

[5] Teizer, J. and Melzner, J., Sicherheitstechnische Planung von Hoch- und Ingenieurbauprojekten mithilfe von Bauwerksinformationsmodellen (BIM), VDI-Bautechnik, Jahresausgabe 2015/16, *Der Bauingenieur*, Springer, Heidelberg, 128-135, 2015.

[6] OSHA, Accidental Reports and Statistics, U.S. Department of Labor, Occupational Safety & Health Administration (OSHA), Washington D.C., http://www.osha.gov. (Accessed January 26, 2010).

[7] HSE. HSE press release E234:03A, Health and Safety Executive, HM Government, http://www.hse.gov.uk/press/2003/e03234a.htm, 2003.

[8] LOSH. Fatal Workplace Accident Statistics, Ministry of Trade, Industry and Employment, Jerusalem, http://www.moit.gov.il/NR/exeres/0FE9A855-90F2-4C15-8793-BF4D05159D08.htm, 2015.

[9] Saurin, T. A., Formoso, C. T., and Cambraia, F. B., A Human Error Perspective of Safety Planning and Control, *12th Annual Conference on Lean Construction*, Elsinore, Denmark, 2014.

[10] Abdelhamid, T.S., and Everett, J.G., Identifying root causes of construction accidents, *Construction Engineering and Management*, 126(1):52-60, 2000.

[11] Mitropoulos, P., Abdelhamid, T.S., and Howell, G.A., Systems Model of Construction Accident Causation, *Construction Engineering and Management*, ASCE, 131(7):816-825, 2005.

[12] CMD. The Construction (Design and Management) Regulations 2007, Office of Public Sector Information, National Archives, London, http://www.opsi.gov.uk/si/si2007/uksi_20070320_en_1.

[13] Lingard, H., Wakefield, R., and Blismas, N., If you cannot measure it, you cannot improve it: Measuring health and safety performance in the construction industry, *19th CIB World Building Congress*, Brisbane, Australia, 2013.

[14] Teizer, J. and Cheng, T., Proximity Hazard Indicator for Near Miss Location Recording and Mapping of Workers-on-Foot Interactions with Construction Equipment and Geo-Referenced Hazard Areas, *Automation in Construction*, Elsevier, 60: 58-73, 2015.

[15] Edirisinghe, R., Lingard, H., Blismas, N., and Wakefield, R., Would the time-delay of safety data matter? Real-time active safety system (RASS) for construction industry, *CIB W099 Achieving Sustainable Construction Health and Safety*, Lund, Sweden, 564-574, 2014a.

[16] Dyreborg, J., The causal relation between lead and lag indicators, *Safety Science*, Elsevier, 47:474-475, 2009.

[17] Teizer, J. Right-time vs. Real-time Pro-active Construction Safety and Health System Architecture, *Construction Innovation*, EmeraldInsight, 2016.

[18] Heinrich, H.W. *Industrial accident prevention, a scientific approach*, McGraw Hill, New York, 1931.

[19] Bellamy, L.J., Exploring the relationship between major hazard, fetal and non-fatal accidents through outcomes and causes, Safety Science, Elsevier, 71:93-103, 2015.

[20] Zhang, S., Teizer, J., Lee, J.-K., Eastman, C., and Venugopal, M., Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules, *Automation in Construction*, Elsevier, 29:183-195, 2013.

[21] Teizer, J., Allread, B.S., Fullerton, C.E., and Hinze, J., Autonomous Pro-Active Real-time Construction Worker and Equipment Operator Proximity Safety Alert System, *Automation in Construction*, Elsevier, 19(5): 630-640, 2010.

[22] Luo, X., Li, H., Huang, T., Rose, T. A field experiment of workers' responses to proximity warnings of static safety hazards on construction sites, *Safety Science*, Elsevier, 84: 216-224, 2016.

[23] Teizer, J., Cheng, T., and Fang, Y., Location Tracking and Data Visualization Technology to Advance Construction Ironworkers' Education and Training in Safety and Productivity, *Automation in Construction*, Elsevier, 35:53-68, 2013.

[24] Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C.M., and Teizer, J., BIM-based Fall Hazard Identification and Prevention in Construction Safety Planning, *Safety Science*, 72:31-45, 2015a.

[25] Zhang, S., Boukamp, F., and Teizer, J., Ontology-Based Semantic Modeling of Construction Safety Knowledge: Towards Automated Safety Planning for Job Hazard Analysis (JHA), *Automation in Construction*, Elsevier, 52:29-41, 2015b.

[26] Zhang, S., Teizer, J., Pradhananga, N., and Eastman, C., Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning, *Automation in Construction*, Elsevier, 60:74-86, 2015c.

[27] MSHA - Mining Safety and Health Administration, *Presentation at a Workshop on Underground Mining Safety*, West Virginia, September 15, 2010.

[28] Teizer, J., Golovina, O., Wang, D., and Pradhananga, N., Automated Collection, Identification, Localization, and Analysis of Worker-Related Proximity Hazard Events in Heavy Construction Equipment Operation, *32nd ISARC*, Oulu, Finland, 2015

[29] Edirisinghe, R., Zhang, R., Lingard, H., and Boukamp, F., The development of an automated multi-level safety climate benchmarking tool for construction projects, *CIB W099 Conference on Achieving Sustainable Construction Health and Safety*, Lund, Sweden, 258-269, 2014b.