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CLASSIFICATION OF CONSTRUCTION HAZARDS FOR A UNIVERSAL HAZARD IDENTIFICATION METHODOLOGY

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Abstract. Hazard identification in the construction industry is subject to a larger number of variables and unknowns than in other manufacturing industries making the hazard identification process more difficult and resulting in many injuries and fatalities. Moreover, previous research identified a research gap with regards to a universal hazard identification method. The results presented in this paper are a prerequisite for the development of such a method. Specifically, this paper proposes a novel classification of hazards in order to enable a more accurate hazard identification process which can take all possible hazards into consideration. Based on the theoretical framework, three hazard types are proposed in the research: self-induced hazards, peer-induced hazards, and global hazards. This classification is based on who is the source (who causes) the hazards in relation to who is affected by the hazards. Such classification was not identified in previous literature. This research also has practical implications. Such classification of hazards may influence safety experts to more actively focus on peer-induced hazards which are the hardest to identify. Finally, the outputs of the entire research should enable a more accurate and comprehensive hazard identification resulting in reduced injury and fatality rates in the construction industry.

Keywords: health and safety, construction hazards, hazard identification, hazard classification, self-induced hazards, peer-induced hazards, global hazards.

Introduction

The construction industry is an extremely hazardous industry, as evidenced by numerous statistical indicators and by the research interest in the topic. Annually, around 60,000 deaths occur on the construction sites, which is 18.7% of total work-related deaths (International Labor Organization, 2005). Considering that the construction industry employs around 6–10% of the workforce (Raheem & Hinze, 2014), this makes construction workers a lot more likely to suffer a fatal accident than the average across all industries. Such a high number of accidents and fatalities is not just a problem of undeveloped countries. The United States has had 971 fatal accidents in 2017 which makes for 20.7% percent of all fatalities (U.S. Bureau of Labor Statistics, 2018), while in the EU, the construction industry participates with 21% of the fatal accidents (Eurostat, 2015). Nonfatal injuries are also much more common for workers in the construction sector than the average across all industries, even when compared to other production industries, taking the third place in the EU (Eurostat, 2015). Those percentages are most certainly even higher when injury underreporting is taken into consideration, given that research dealing with underreporting of injuries (Al-Aubaidy et al., 2019) assumes that as much as 50% of the injuries on the construction site are not reported.

Due to this relatively poor safety performance, there is a lot of space for improvement. A myriad of research efforts has been undertaken in order to reduce accident and fatality rates in the construction industry, to understand the accident occurrence and to minimize the impact on the health and safety of construction workers. The number of publications regarding Health & Safety (H&S) has risen exponentially over the past two decades (Zhou et al., 2015), providing further evidence of the importance of the issue. The topics addressed by the researchers can roughly be divided into three "waves", as defined by Niu et al. (2019). The first wave focused on physical protection from hazards, such as the use of personal protective equipment, while the second wave tackled H&S through managerial approaches. They further propose Artificial

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Intelligence (AI) as the third wave. While their classification is valid, the author suggests a more lenient view of the third wave, specifically for it to include all applications of Information Technologies (IT) for H&S. This is primarily because a large number of different technologies have been researched for their ability to improve the levels of H&S on the construction sites through many different applications, as is evident from a recent comprehensive review paper by Martínez-Aires et al. (2018).

H&S improvement has an impact on numerous stakeholders and provides both ethical and financial benefits. Construction workers directly benefit from reduced risk for injuries and fatalities; contractors and owners from reduced construction costs (due to less lost work time, lower insurance premiums, healthcare bills, etc.); the construction industry from a better public perception of the industry leading to attracting better talent; and finally, the society also benefits from a healthy, safe and satisfied workforce.

The research presented in this paper aims to participate in the effort of reducing the number of accidents in the construction industry. This paper proposes a novel classification of hazards in order to subsequently enable a more accurate hazard identification process which can take all possible hazards into consideration. The proposed research is in line with current research efforts which aim to include IT in various aspects of H&S improvement.

Section 1 of the paper presents the research methods, previous research into construction hazards, specifics of hazard identification and risk quantification in the construction industry, and lays the theoretical framework for the remainder of the paper. The following section presents the need for a universal construction hazard identification method and introduces the issue addressed in the paper. Section 3 presents the new classification of construction hazards, and Section 4 shows the validation process. In section 5 the results and practical implications of the research are discussed, while, the final section concludes the paper and gives recommendations for further research.

1. Methodology and theoretical framework

The research presented in the paper is grounded in the previous research regarding H&S in the construction industry and construction hazards. Previous literature was analyzed to determine the state of the art in the field, to discover how hazards are currently identified, how risks are quantified in the construction industry, to establish the reasons for such high number of construction injuries and fatalities, and to gain knowledge and insight for proposing a universal hazard identification process. Based on the findings from the literature, a new framework for classifying hazards was proposed, discussed and validated with experts from H&S in the construction industry. The end goal is to mitigate the particularities of the construction industry which hinder efficient and comprehensive hazard identification and to enable identification of all potential construction hazards.

1.1. Construction hazards

Various researches use different definitions for the same terms, or even more confusingly the same definitions for different terms. With regards to H&S, the terms hazard and risk need to be defined in order to avoid potential confusion. The British Health & Safety Executive defines risk as "the likelihood that harm from a particular hazard will occur and the possible extent of the harm", while a hazard is something with the potential to cause harm (NNC Limited, 2003). A common element to almost all definitions of risk is that it comprises of two independent components: probability and severity (Cerić, 2014). Both components can (and need to) be quantified so that risks can be analysed, compared and ranked. This research describes hazards as potential outcomes of events which may cause ill effects to the safety and wellbeing of construction workers. Risk, on the other hand, is defined in this research as a quantified value containing the probability of a hazard's occurrence and the severity outcome of the hazard.

Hazards can be divided into types based on many different factors and characteristics, most commonly based on their frequency levels, severity levels and consequently risk levels. The simplest and most often overlooked classification is division based on the effects of the hazard if it occurs on the construction site. If a hazard occurs but does not cause injury or damages workers' health, then it is categorized as a near-miss. If it does cause adverse effects, then it is an accident. This categorization is important since near-misses are often overlooked by safety professionals, even though "learning from near-misses is a proactive way to prevent accidents from happening and enhance safety performance for construction projects" (Zhou et al., 2019).

Additional classifications were proposed by Abdelhamid and Everett (2000), who classify hazards based on causes of unsafe conditions. These conditions include: management action or inaction; unsafe acts of workers or co-workers; non-human related events; unsafe conditions which are natural parts of initial construction site conditions. Zhang (2014) has also categorized hazards based on the cause of the hazard. Potential hazard causes are (Zhang, 2014):

1. Unsafe work conditions – resulting from hazardous conditions at the construction site, such as the potential to fall, fire hazards and environmental hazards.
2. Activity-based hazards – resulting from performing construction activities.
3. Hazards caused by activity interaction – resulting from space conflict between two or more activities.

Roberts (2013) proposed a categorization for uncertainties in projects which can also be applied to construction hazards. She divided the uncertainties into "known unknowns", the risks that are already identified, and "unknown unknowns", which are unidentified risks. Kim (2017) further divided "unknown unknowns" into knowable and unknowable. Applied to construction hazards, "known unknowns" are the hazards identified during the hazard identification process. These hazards may or may not cause accidents during construction, but at least safety managers can plan for them and if possible, mitigate or even eliminate them. "Unknown unknowns" are the remaining hazards, which have not been identified. These are especially dangerous since control measures cannot be planned and implemented if safety managers are unaware of the hazard's existence (Carter & Smith, 2006). Furthermore, "knowable unknown unknowns" are those hazards which were not identified but could have been, and "unknowable unknown unknowns" are those hazards which could not have been identified by any current hazard identification methods. The goal of this research is, among other things, to enable safety experts to identify as many hazards on the construction site as possible, since based on the research by Carter and Smith (2006), over 30% of hazards remain unidentified during the hazard identification process.

Furthermore, hazards can be classified based on whether they cause an injury or a professional illness, depending on if the consequence is immediate or develops over an extended period of time. Such classification is needed since H&S research focuses mostly on the safety aspect of Health and Safety while neglecting health issues of construction workers (Mihić et al., 2018). Another useful categorization of construction hazards is based on their energy source, specifically, on which energy being released causes the hazard to occur. Hazard energy sources are adapted from literature and presented in Table 1. Finally, this research proposes a new division of hazards into three types based on who is the source (who causes) the hazards in relation to who is affected by the hazards. The three hazard types are: self-induced hazards, peer-induced hazards, and global hazards. Such division was not identified in the reviewed literature.

1.2. Industry-specific hazard sources

Reasons for the poor safety performance of the construction industry might be found in its particularities when compared to other industry sectors. Construction sites are dynamic with extensive movement of workers, equipment and materials (Pinto et al., 2011), workers are exposed to weather, site conditions change through time (Rozenfeld et al., 2010), and a lot of factors possibly influencing workers' safety are unpredictable and uncontrollable. These particularities separate it from the manufacturing industry, which is mostly stationary with non-moving workers working indoors in controlled environments (Zhang, 2014). Another significant difference is that construction workers are frequently exposed to hazards posed by workers from other, unrelated workgroups (Sacks et al., 2009). Additional hazards stem from frequent work team rotations, high proportions of unskilled and temporary workers (Rozenfeld et al., 2010) and from the specific conditions of each construction site that cannot be generalized (Godfaurd & Abdulkadir, 2011). These particularities are inherent to the nature of the industry and cannot be easily eliminated or mitigated, presenting a challenge for safety professionals and requiring a combined effort from both the practitioners and researchers to tackle it.

The construction industry is also different from other production industries because construction has (in addition to accidents with severe consequences) a large number of low-severity – high-frequency accidents (Hallowell & Gambatese, 2009) and diverse hazard sources (Zhou et al., 2015). A hazard source uncommon in other production industries is workplace congestion. Since the workers are transient and the product is static, scheduling activities can often lead to overlapping workplaces for different construction worker teams which in turn cause congestion hazards. They manifest as spatial interference which can lead to collision incidents between workers, equipment and/or materials (Teizer et al., 2010).

Movement of workers through the construction site is also a specific hazard source since in the production industries workers usually have a defined workplace and the product moves through the production line. Hazards, when moving through the site, include hazards from other activities performed in the area, slips and falls on the same level, falls through openings in the floor and struck-by hazards. These hazards are also significant because approximately 20% of the accidents occur while the worker is moving through the construction site (Health and Safety Executive, 2016; Korea Occupational Safety and Health Agency, 2003). Related to collision accidents and spatial interference, another industry-specific hazard is the proximity of workers to heavy construction equipment (Teizer

Table 1. Energy sources, adapted from Chen et al. (2013)

Energy source	Definition	Energy source	Definition
Biological	Living organisms that can present a hazard	Motion	The change in position of objects or substances
Chemical	The energy present in chemicals	Pressure	Energy applied by a compressed or vacuum liquid or gas
Electrical	The presence and flow of an electric charge	Radiation	The energy emitted from radioactive materials
Gravity	The force caused by the attraction of all other masses to the mass of the earth	Sound	A vibrating-cause force the energy is transferred through the substance in waves
Mechanical	The energy of the components of a mechanical system	Temperature	The measurement of differences in the thermal energy

et al., 2008). In other production industries machinery is mostly static and workers have limited access to their moving parts, while in the construction industry most of the machinery is mobile and it occupies the same workplaces as the workers.

1.3. Hazard identification in the construction industry

These specific hazard sources and particularities of the construction industry contribute to a large number of unidentified hazards and make the hazard identification process more difficult than it is in other production industries. Safety planning in the construction industry typically consists of identifying all potential hazards and choosing the corresponding safety measures (Bansal, 2011). Unfortunately, safety planning, even though it has a key position in production planning, is often carried out separately from the project design and planning phases (Zhang et al., 2015b). This separation creates inefficiencies in safety planning and causes difficulties for safety engineers to analyze what safety measures are needed where and when to prevent potential accidents (Zhang et al., 2013), and to consequently potentially improve the safety performance at the construction site.

Hazard identification, as the first step in safety planning, is crucial since if hazards are not discovered during the preconstruction phase (making them "unknown unknowns," as they have already been defined), they cannot be eliminated, reduced or controlled and have the potential to cause accidents. A standard method for identifying hazards in the production industries is the Job Hazard Analysis (JHA). JHA is a proactive measure for safety assessments in industrial manufacturing settings (Rozenfeld et al., 2010), whose job is to identify hazards before they occur by focusing on the relationship between the worker, the task, the tools and the environment (U.S. Department of Labor, 2002). The procedure of conducting JHA consists of three steps (National Safety Council, 1997): 1) identifying all job steps of a given activity; 2) identifying potential hazards related to those job steps; and 3) proposing procedures to eliminate, reduce or control each of the hazards. The US Occupational Health and Safety Administration recommends performing JHA for construction activities to identify hazards faced by construction workers (Zhang et al., 2015a).

However, the differences between the construction industry and other production industries mentioned above make such hazard identification procedures difficult. Hazards are difficult to predict because even though the activities performed are similar or even the same, every construction project has its unique location, time schedule and work conditions. Moreover, the construction sites are dynamic and even if the hazards were accurately predicted for such precisely defined conditions, there is a significant probability that the conditions would change by the time the construction activity is scheduled to be performed. Furthermore, for effective safety planning, safety hazards should be identified through all stages of the project (Alizadehsalehi et al., 2018), not just once during the design phase. Researchers have therefore developed methods which could monitor the construction sites and help safety managers in identifying hazards which have occurred on the construction site even if those hazards were not foreseen by the safety plan. One of such research efforts was conducted by Alizadehsalehi et al. (2018) in which they have presented how the use of unmanned aerial vehicles could aid safety managers in monitoring safety performance and in identifying hazards when they occur on the site.

Perhaps the most significant barriers to efficient hazard identification are uniqueness of each construction process and frequent on-site changes. Given that each construction site is unique, a JHA would need to be performed for each activity for each construction site, and given the frequent changes on the construction site, JHA would need to be performed daily and not just once at the beginning of the project, perhaps even months before the activity is scheduled to be performed (Wang & Boukamp, 2011). Further complication arises from the fact that safety planning relies on manual efforts for identifying and preventing safety hazards (Kim & Cho, 2015). To identify the hazards, safety planners use 2D drawings and construction schedules to visualize the construction process and assess probable safety hazards (Bansal, 2011). Since this approach is manual and based on the knowledge and experience of the safety planner, the process is labor-intensive, time-consuming, inefficient and error-prone (Bansal, 2011; Kim & Cho, 2015; Zhang, 2014). These problems have prompted researchers (Rozenfeld et al., 2010; Zhang et al., 2015a) to explore how the JHA could be automated and applied to the construction industry. However, a review of previous research by Mihić et al. (2019) revealed that previous research efforts present methods to identify only small sets of specific hazards (fall hazards, collision hazards, crane-related hazards, etc.) and that a universal hazard identification methodology is needed.

1.4. Risk quantification

Researchers and practitioners have developed a large number of methods to quantify risk varying in complexity and application (Dharmapalan et al., 2014), most commonly in the form of a risk matrix. A risk matrix is a tool used to quantify risks by determining the intersection between the identified probability category (also sometimes called frequency or likelihood) and the identified severity category (sometimes called impact or consequence) (Cox, 2008). The matrix is, in fact, a table that has several categories of probability for its rows, and several categories of severity as columns, or vice versa. An example of a risk matrix is pictured in Figure 1. This method of quantification is far from being the only one used in the risk quantification process. Some more recent approaches for quantifying risk include using multi-attribute decision-making tools such as the analytic network process (Hatefi & Tamošaitienė,

Severity Likelihood	Insignificant (ex: no lost time at work)	Minor (ex: some lost time at work)	Moderate (ex: significant lost time at work)	Major (ex: unable to return to work)	Catastrophic (ex: death)
Rare (<3% chance)	Low	Low	Low	Moderate	Moderate
Unlikely (3%–10% chance)	Low	Moderate	Moderate	High	High
Moderate (10%–50% chance)	Low	Moderate	High	Extreme	Extreme
Likely (50%–90% chance)	Moderate	High	Extreme	Extreme	Extreme
Almost certain (>90% chance)	Moderate	High	Extreme	Extreme	Extreme

Figure 1. Example of a qualitative risk matrix (Collins et al., 2014)

Level of Consequence	Description		Level of Frequency	Description								
							5	5	10	15	20	25
1	Insignificant		1	Never			4	4	8	12	16	20
2	Minor		2	Unlikely		Probability	3	3	6	9	12	15
3	Moderate	×	3	Possible	=		2	2	4	6	8	10
4	Major		4	Likely			1	1	2	3	4	5
5	Catastrophic		5	Always				1	2	3	4	5
								Consequence				

Figure 2. Example of a quantitative risk matrix (Zolfagharian et al., 2014)

2019) and others even replace the core elements to quantifying risks. Gunduz and Laitinen (2018) have for example replaced the probability level (due to its inaccuracy) with levels of prevention and control which are easier to estimate and are more accurate.

Probability and severity categories and corresponding risk levels can be either descriptive and color coded (as described in Figure 1), or quantitative as presented in Figure 2. The number of each of the categories is dependent on how detailed the distribution needs to be and the table does not need to be symmetrical. Categories can also differ from one matrix to another, meaning that, for example, moderate severity can have different meanings in two different risk matrices.

Another essential factor to consider when calculating risk levels is exposure, and some risk quantification methods (Baradan & Usmen, 2006; Jannadi & Almishari, 2003) include the length of the exposure in the equation along with frequency and severity, where exposure is the amount of time a worker is exposed to the hazard. Naturally, the longer the worker is exposed, the higher are the chances of an accident occur.

Two other exposure types become relevant when we need to identify not just the hazards the workers expose themselves to (defined as self-induced hazards in this research), but also the hazards the workers are exposed to from activities performed by other workers (defined as peer-induced hazards). These exposure types are spatial exposure and temporal exposure (presented in Figure 3(a) and 3(b), respectively). For a worker to be exposed to a hazard caused by another activity, both activities need to take place at the same time or have a temporal overlap (temporal exposure), and the worker needs to be present in the hazard's radius of influence. Previous H&S research has identified that in the construction industry workers are exposed to such hazards, but only the research articles involving the "CHASTE" method (Rozenfeld et al., 2009, 2010; Sacks et al., 2009) take such hazards into consideration when identifying and quantifying hazards. This research also places considerable focus on peer-induced hazards.

2. Method for universal hazard identification

The previous section described the problems of hazard identification in the construction industry. These have presented obstacles for researchers in developing a comprehensive methodology designed to be able to identify all construction hazards that arise from constructing building elements. The classification of hazards presented in this paper is one of the prerequisites for the development of such a method and an accompanying tool for identifying hazards, named Hazard Integration System (System).

The basic premise of the Hazard Integration System, which is to be developed and detailed in subsequent research, is to enable hazard identification for every building element constructed at the construction site. The premise of the hazard identification process in the System is that all building elements are constructed by performing construction activities and performing construction activities causes construction hazards. Therefore, we can indirectly connect building elements with the hazards, through the construction activities which need to be performed in order to construct them. Figure 4 graphically presents such a connection. In the developed tool, BIM (Building Information Modelling) model will be used to query information on the building element types and materials and to facilitate the hazard identification process.

There is a large number of building elements and materials from which they can be constructed of (e.g., concrete wall, wooden wall, masonry wall, etc.; steel column, reinforced concrete column, etc.) and an even larger, but fortunately finite, number of unique construction activities. All combinations of building elements and materials they are constructed of can easily be cataloged and entered in a database, as well as the construction activities. Hazards stemming from performing activities can also be identified and attributed to the activities since workers, when performing work on the construction site also "produce" hazards. Those workers are in turn affected by the hazards. The interaction between building elements, activities, hazards and workers is presented in Figure 5.

Workers performing the activities do not necessarily endanger only themselves, but also other workers working in the same area at the same time, or perhaps even all workers at the construction site. Current methods like the JHA are equipped to identify only those hazards the workers expose themselves to, while other hazards remain unidentified. For this reason, the research presented in this paper presents a classification of construction hazards into three groups: self-induced hazards, peer-induced hazards, and global hazards.

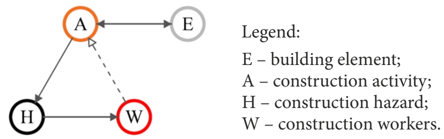


Figure 5. Interaction between building elements, activities, hazards and workers

The remainder of the section aims to visualize and graphically contextualize the interactions and interrelations between building model elements, activities, hazards, and workers. Figure 6 presents a model of a hypothetical situation on a construction site at one point in time. The Figure presents a snapshot of what building elements are being constructed, which activities are being carried out and by which construction worker groups. Hazards, which are a consequence of construction work and which affect construction workers, and their connections to workers and activities are also shown in the Figure 6.

A model of this interaction can be generated for any moment during the project's construction phase, in order to determine which hazards threaten which construction workers and which activity is the source of the hazard. The contents and the details of the model will be further explained in the following paragraphs.

The notation in indexes next to the letter shown in the model is used to numerically show the connection between the model elements. The building model elements have only one number in the index (E_i), while the activities that are connected to the elements have the same first index number and the other describes each individual activity needed for the elements construction (A_{ij}).

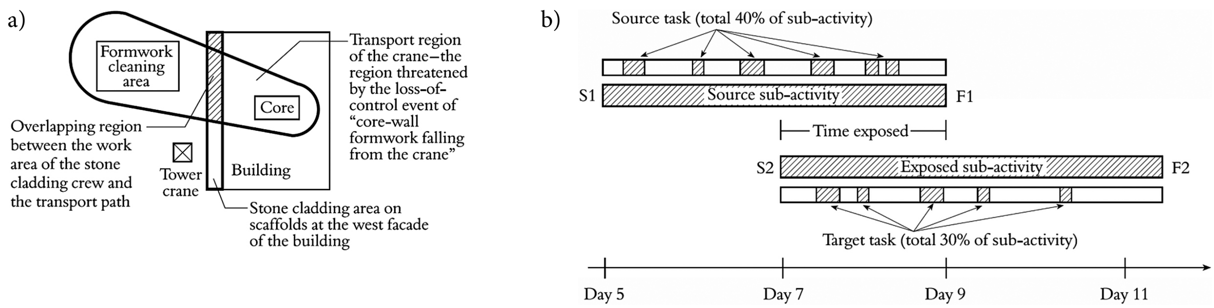


Figure 3. (a) Spatial overlap leading to spatial exposure; (b) Temporal overlap leading to temporal exposure (Rozenfeld et al., 2009)

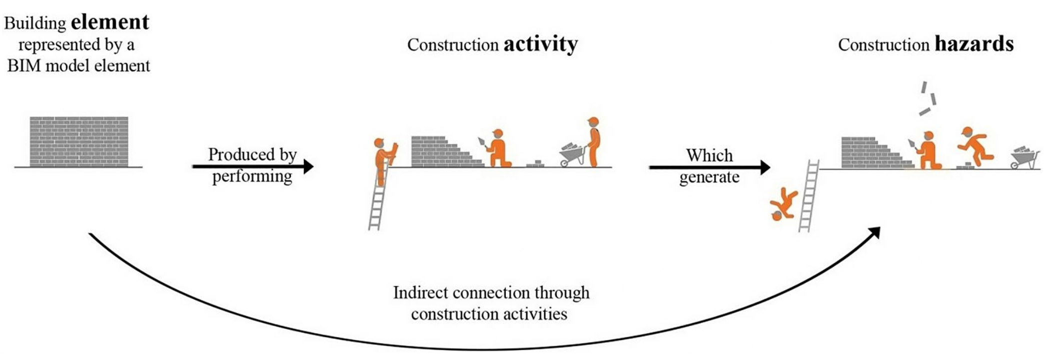
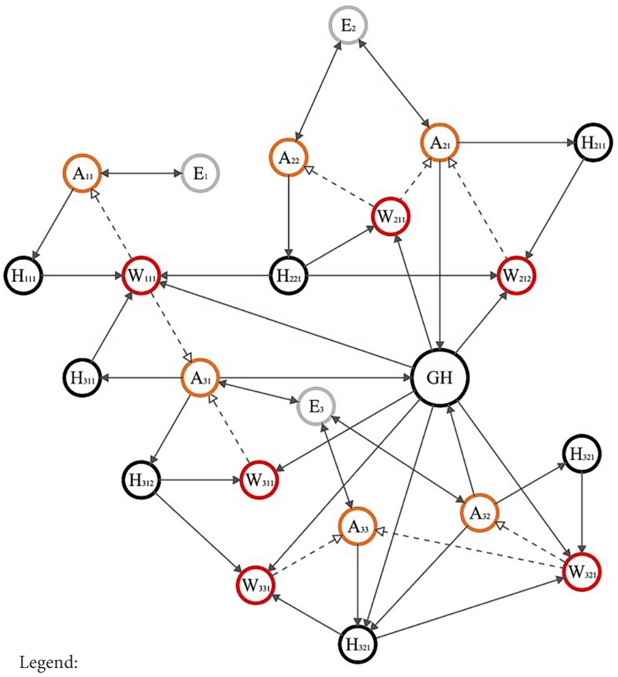


Figure 4. Indirect connection of building elements and construction hazards through construction activities



Legend:

– Grey circles with the letter E: building model elements;
– Orange circles with the letter A: construction activities needed to construct the building model element;
– Black circles with the letter H: hazards which are caused by the activities;
– Black circle with the letters GH: global hazards caused by the activities;
– Red circles with the letter W: workgroups which perform the construction activities;
– ←——→ Connects the building model element with the construction activities needed for its completion;
– ——→ Connects the construction activity with the hazards the activity causes;
– ——→ Connects the hazards to the worker groups which are affected by the hazard;
– - - - -▹ Connects the worker groups to the activities they perform.

Figure 6. Element-Activity-Hazard-Worker interaction model

The second index (j), incrementally rises if more activities are needed for element construction. Similarly, the hazards have three numbers in the index (H_{ijk}) and are connected to the activity in the same way as the activity is to the element. The first two indexes connect the hazard to the activity and the third index (k) is used if an activity causes more hazards. The workgroups (W_{ijm}) follow exactly the same numeration logic as do the hazards. They do, however, use a different index (m) to differentiate them from the hazards, since not all hazards posed by the activity affect the workers of the same activity.

There are also some general modelling rules to consider. While the same activity can be used to construct two elements, to avoid confusion, the activity is repeated for each element. For example, if we have the construction of two cast-in-place columns each would have its own activity and accompanying hazards and workgroups. Other rules are as follows:

– Each element is connected to at least one activity;
– No activity is connected to more than one element;
– Each activity is connected to at least one group of construction workers;
– It is highly unlikely that an activity would pose no hazards. Therefore, all activities are connected to at least one hazard;
– Each group of construction workers performs at least one construction activity;
– Workers can perform more than one activity at a time. For example, connecting the rebar for both the beams and slabs;
– Construction workers are unlikely not to be affected by any of the hazards. Therefore, they are connected to at least one hazard.

3. Classification of construction hazards

Three different hazard types are defined in and used by this research. These are self-induced hazards, peer-induced hazards and global hazards. The difference between the hazard types is in who is the source of (who causes) the hazard in relation to who is affected by the hazard. A worker may expose himself to harm, he may be exposed to harm from other workers in his immediate vicinity, or the hazard is so widespread it potentially harms anyone on the construction site. The previous section has already mentioned these hazard types, presented a hypothetical situation on the construction site and explained the notations of the elements. This section will offer additional information on the hazard types, as well as some practical and graphical examples for each of the hazard types.

3.1. Self-induced hazards

Self-induced hazards are the simplest hazard type defined in this research. This type of hazard originates from the activity performed by the workers who are affected by the hazard. The hazard generation process is as follows. Construction activities produce hazards when performed. Workers (one worker or a workgroup) perform the activities, and therefore they themselves produce hazards. If they are exposed to the hazard from the activity which they perform, they are exposing themselves to hazards. This exposure type is called self-exposure and results in self-induced hazards. Self-induced hazards will be graphically illustrated in the model presented in Figure 7.

Figure 7 presented above depicts a model of an interaction between building elements (E), construction activities (A), construction hazards (H) and construction workers (W). It is a hypothetical situation on a construction site at one moment in time, not meant to represent any particular construction works. The model in the Figure is modeled using the same model elements and modeling rules as described in the previous section.

Self-induced hazards are circled in the model along with the activity which causes the hazard to appear in the first place and with the workgroup affected by the hazard. We can see from the model that the element E_1, requires activity A_{11} to be performed. The activity produces a hazard (H_{111}) and is performed by workgroup W_{111}. The workers are affected by this hazard which is produced by the activity they themselves are performing, making the hazard self-induced.

This hazard type is the simplest to identify and to predict since it only involves the activity being performed and

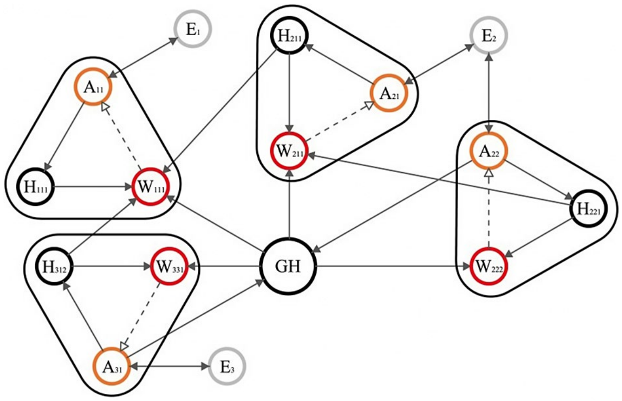


Figure 7. Self-induced hazards

the workers performing the activity. They are the simplest to identify in the context of this research and its requirements, as well. To identify the self-induced hazard the System will require only the existence of a correctly modelled BIM model. Self-induced hazards can even be identified without the construction schedule. Moreover, they do not even require the spatial information from BIM models, since only the element type and material information are needed to determine the construction activities required to construct the element, and by extension which hazards are produced by the activity.

Spatial and temporal information are needed for more complex hazard types described later in the section when the System needs to check if an overlap exists in time and place between the activity posing the hazard and the location of workers potentially exposed to the hazard during the time when the hazard is present. Spatial and temporal information is not needed for self-induced hazards since the workers produce the hazards themselves and the hazard location in time and place is precisely the same as the workers'.

Examples of self-induced hazards include:

– Falls from heights and into depths;
– Injury from inappropriate tool handling;
– Burns from touching hot objects;
– Lacerations from cutting wooden elements.

3.2. Peer-induced hazards

The most complex hazard types defined by the research are peer-induced hazards. Each construction site is a complex environment with a large number of activities being simultaneously performed by a large number of workers. Each workgroup is well informed about the tasks they perform and the schedule and locations of these tasks. They are, on the other hand, not informed about the schedule and location of other workgroups. Similarly, the workers are educated about the hazards they are exposed to while performing the construction activities (self-induced hazards) through safety training programs and other safety-related documents but are often not as informed about the hazards they pose to other workers, and about the hazards other workers pose to them.

Peer-induced hazards are the second type of hazards defined by this research to which the workers are exposed. The difference from the previously defined self-induced hazards is in the source of the hazard. In this case, the hazards are produced not by the construction workers themselves but by their peers (other construction workers) who are performing other construction activities on the same or on another building element. These other workers may be endangering themselves, but are also endangering all other workers present in the hazard zone of the activity. An example of such a hazard follows. A group of carpenters is assembling formwork for a cast-in-place reinforced concrete wall. A potential hazard for this activity is the formwork overturning and falling if not properly anchored. They themselves are exposed to the (self-induced) hazard, but they also expose a group of construction workers preparing rebar for the adjacent wall. A graphical representation of peer-induced hazards is shown in Figure 8.

This Figure presents the same interaction between the building elements, activities, hazards and workers as the previous one, but focuses on peer-induced hazards. All instances of peer-induced hazards are circled in the Figure, along with the activity which caused the hazard and the workers affected by it. A total of three peer-induced hazards are shown in the Figure. For example, workgroup W_{211} is exposed to a hazard (H_{221}) posed by their peers (W_{222}) who are performing an activity on the same building element (E_2), while workgroup W_{111} is exposed to two peer-induced hazards (H_{221} and H_{312}) produced by workers performing activities on other building elements. The model also shows that workgroups may be exposed to more than one peer-induced hazard and from multiple sources. Also note that a hazard can be both self-induced and peer-induced at the same time, as demonstrated in the hypothetical example above.

Hazard identification of the peer-induced hazards is much more complicated than for the self-induced hazards, especially if the hazard identification is made manually by a safety expert. This person would need to have a detailed understanding of the construction plan and construction sequence for each construction site, in addition to safety-

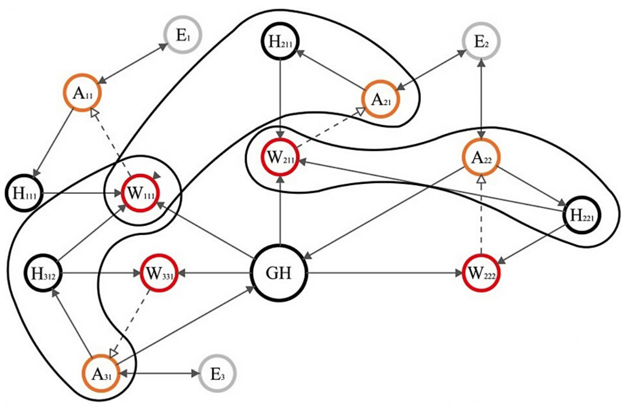


Figure 8. Peer-induced hazards

related knowledge to recognize which construction activities occur at the same time and which workgroup affects other workers and in what way. Hazard identification is generally a time intensive, and error prone process (Kim & Cho, 2015; Zhang, 2014) made even harder when identifying peer-induced hazards. Automated hazard identification of peer-induced hazards is also more complicated than for self-induced hazards. An essential prerequisite, in addition to those required for self-induced hazards, is the existence of an accurate and up-to-date construction schedule.

Examples of peer-induced hazards include:
- Fall of an object from height;
- Formwork collapse;
- Cutting/impaling on protruding rebar;
- Tripping on tools, material or waste;
- Getting hit by flying material or object.

3.3. Global hazards

Global hazards are a special type of peer-induced hazards in whose case the area of influence is so large that it is not practical to assign a particular area of the hazard's influence. Instead, the entire construction site is viewed as the hazard zone. These hazards affect all construction workers and other personnel who are present on the construction site at the time of the hazard. An example of how a group of construction workers might cause global hazards is when an activity requires crane lifting operations. The crane transports the material over possibly a large area of the site, thus having a large area of influence and potentially exposing a large number of construction workers. It would be infeasible (and impossible due to the dynamic conditions on the site) to calculate the exact path of every lift and the precise positions of workers in those moments. Therefore, all construction workers are considered to be affected by the hazard.

An example of global hazards is shown in the model in Figure 9, similarly as with previous hazard types. It is evident from the model that all the workers are exposed to global hazards and are connected in the same way as they are connected to self-induced and peer-induced hazards.

This hazard type is also caused by workers performing construction activities, in the same way as the other two hazard types. The activities which produce the hazard, specifically in this case the activities A_{22} and A_{31}, are connected to the hazard in the model in the same way that they are connected to their respective self- and peer-induced hazards.

The model shows only one global hazard instead of two different global hazards. This could be used as a general modelling rule, since if every global hazard is connected to every construction worker workgroup, a larger model may be cluttered with connection arrows to and from the global hazards. A simpler solution would then be to list all the global hazards in a legend next to the model.

It is common for global hazards to have high severity but extremely low probability scores, such as an explosion

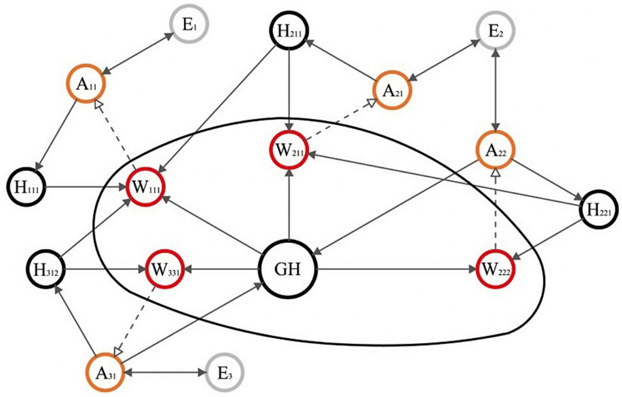


Figure 9. Global hazards

on the construction site or crane collapse, in which case the risk is negligible. The other possible combination is high severity with low to medium probability in the cases of soil collapse and falling objects from a crane. Those risks are significant but are also almost always anticipated in construction safety plans. Manual hazard allocation of global hazards to construction workers is somewhat simplified since spatial exposure is not a requirement. Moreover, hazard identification itself is more straightforward than in the case of the peer-induced hazards because global hazards are similar between various construction sites and safety personnel is well-equipped for their identification. The construction schedule is necessary to identify global hazards for the same reasons as is the case for peer-induced hazards.

Semantically, global hazards can be either peer-induced or self-induced, depending on if the cause of the hazard is an activity performed by the workers themselves. The distinction will be illustrated in the previous example of reinforced concrete formwork construction. Construction workers assembling the formwork require the formwork elements to be delivered to them by crane from the storage area. While the crane transports the formwork elements, all construction workers are exposed to the potential hazard of fall of an object carried by a crane, including those formwork workers. Therefore, since they require the formwork to be delivered, they expose themselves to hazards, as well as other workers, such as the workers placing rebar on the adjacent wall. Such semantic distinctions, however, are not important and this hazard type will always be assigned as a global hazard, whose source can be traced to the activity which caused it.

Examples of global construction hazards include:
- Scaffold collapse;
- Crane failure and collapse;
- Fall of object carried by a crane;
- Fire;
- Explosion.

3.4. Specific global hazard types

During the course of the research, two specific hazard subtypes of global hazards were identified: the global hazard source hazard and general construction hazard. These hazards are not global in a sense described in the previous subsection. Their "globality" is manifested differently. The global source hazard is global in the sense that a large number of activities can cause the hazard. It is known who is exposed to the hazard, but it is not known precisely which activity will cause the hazard to occur. Therefore, the hazard has a global source. An example of such hazard is an object falling from a scaffold and injuring a worker underneath and the electrocution hazard.

Additionally, general construction hazards were identified as hazards to which all workers are exposed just by working on the construction site. They may be self- or peer-induced, but they are so widespread that virtually anyone can be affected by them. All activities on the construction site can cause these hazards and it would be unfeasible to assign the hazards to every activity. For that reason, such general hazards will be added automatically to every construction activity and to every construction workgroup. A general construction hazard, for example, is a worker injuring himself with power tools. A tripping hazard or a worker hitting his head on something are excellent examples of hazards which are both global source and general construction hazards.

4. Validation

A short validation process of these intermediate research results presented in the paper was carried out to see whether the proposed classification of the hazards is applicable to the problem of hazard identification. Depending on the type of research, data which needs to be gathered, sample size and on other variables, there are numerous validation methods. Since the research is still in the conceptual phase, methods such as proof of concept cannot be administered, and based on the data that needed to be acquired, a combination of an interview with relevant experts and an administered questionnaire was chosen as the most suitable method. Validation of these intermediate research results presented in the paper is a part of the complete validation of the entire research.

Validation using expert opinions requires that respondents are qualified to judge the presented research. To do so, minimal qualifications need to be prescribed, and all respondents need to satisfy the requirements to be qualified as experts. They were required either to hold a position of an H&S expert in a large construction company or to have authored more than five site safety plans for complex construction sites. Two groups of experts were chosen to take part in the validation phase. Those groups include Health and Safety Coordinators and Health and Safety Experts employed in large construction companies. In total, ten respondents took part in the research. Their positions, profiles, and work experience are shown in Table 2. All Health and Safety Experts are safety engineers (as is prescribed by law as a requirement for that position), six out of seven H&S Coordinators are civil engineers and one is a mechanical engineer.

Table 2. Profiles of the respondents

Respondent	Position	Years of experience
#1	Health and safety coordinator	5–10
#2	Health and safety expert	5–10
#3	Health and safety coordinator	11–20
#4	Health and safety coordinator	11–20
#5	Health and safety expert	5–10
#6	Health and safety expert	>20
#7	Health and safety coordinator	5–10
#8	Health and safety coordinator	<5
#9	Health and safety coordinator	<5
#10	Health and safety coordinator	5–10

To prepare the respondents for the interview, a short research summary was created for them to read and the first part of the interview was the introduction to the research. If the respondents had read the summary beforehand, the research was still briefly explained, and if they had not read the summary, the research was explained in more detail. Moreover, if the respondents had questions or required further clarification at any point of the interview or the questionnaire, answers and clarifications were provided. This introduction lasted around 15 to 30 minutes, depending on the number of questions and whether or not a more detailed description of the research was needed. After the introduction, a questionnaire was administered to the respondents. The entire questionnaire in the validation process consisted of 44 questions divided into 10 subgroups. Only a small subset of three questions pertained directly to the results presented in this paper. The interviews were held in Croatian and were not audio recorded since the respondents' answers were immediately written down on printed-out questionnaires. Most of the interviews (seven of them) were held one-on-one, and only one interview was conducted with three respondents simultaneously.

The questions related to the research presented in this paper were as follows:

- Do you consider that construction hazards can be connected to the building's structural elements through construction activities?
- Is the classification of hazards into self-induced, peer-induced and global hazards clear to you?
- Do you consider that this classification is appropriate for use by the System?

The questions were of the "Yes/No" type and all the respondents answered "Yes" to all the questions. The questions and number of "Yes" or "No" responses to the questions is are presented in Table 3 This means that the respondents consider the connection between building model elements and hazards through the activities possible, that they understand the proposed division of hazards into self-induced, peer-induced and global, and that they consider that this classification is appropriate to be

Table 3. Results of the validation process

Question	Number of "Yes" answers	Number of "No" answers
Do you consider that construction hazards can be connected to the building's structural elements through construction activities?	10	0
Is the classification of hazards into self-induced, peer-induced and global hazards clear to you?	10	0
Do you consider that this classification is appropriate for use by the System?	10	0

used by the System. Through additional semi-structured discussion, after the questionnaire had been administered, the respondents commended the research and its approach to hazard identification and classification.

5. Discussion and practical implications

Review of the recent research in the field of construction H&S had revealed that despite numerous research regarding the implementation of Information Technologies in H&S some research gaps still exist. Given that most research is focused on identifying one or a few hazards types, one of such gaps is a universal hazard identification methodology, capable of identifying all hazards resulting from conducting work on construction sites. Understanding that this is an ambitious endeavor, extensive prerequisite research needed to be conducted. This paper, explored one of those prerequisites, specifically the possibilities of classifying construction hazards based on the source of the hazard in relation to the person affected by the hazard. As a result, three hazard types are proposed: self-induced hazards, peer-induced hazards, and global hazards.

The names of the hazard types are somewhat self-explanatory. Self-induced hazards are those where workers endanger themselves, peer-induced hazards are those where workers endanger other workers, and global hazards are those hazards which are present on the entire construction site. There are, however, cases in which the line between hazard types is a bit blurred. The same hazard can affect a group of workers performing the activity and another group of workers performing another activity nearby. In that case, the hazard is both self-induced and peer-induced, depending on from whose point of view are we looking from. The same can be said for a hazard which is both self-induced and global. An additional problem for the proposed classification are hazards which are so general that either a large number of activities may cause them or that the workers are exposed to them by merely being on the construction site. Since it is not simple or straightforward enough to determine the exact source or the victim of those hazards, they are for the time being classified as subtypes of global hazards and their identification will be a topic of further research.

The idea of such classification expands upon the research by Rozenfeld et al. (2009), where the authors took time and location of construction workers into consideration when calculating risk from "loss-of-control" events. In their research, the authors have identified that workers do not potentially endanger only themselves, but also to other workers who happen to be located in the hazard's radius of influence, during the time the hazard might occur. Their concept of temporal and spatial exposure is used to classify whether a hazard is affecting only the workers conducting the activity, or also workers in the vicinity of the hazard. Further research will use the proposed classification in the process of assigning construction hazards to workers.

Besides contributing to the existing construction H&S literature, the classification might prompt other researchers to explore identification and mitigation strategies for each of the hazard types or to focus research efforts on peer-induced hazards which are harder to identify than the two other types. This research will hopefully have practical implications. The results of this research are a prerequisite to a possible update of the JHA process. With peer-induced and global hazards in mind, the practitioners could also better plan for the complex interaction of workers and processes at the construction sites which often cause hazards which are not present in other manufacturing industries.

Conclusions

The construction industry is different from other production industries in many aspects, one of which is hazard identification. The paper presented some differences between construction and other production industries and has given potential reasons for such a high injury and fatality rates in construction, most prominent of which might be that identifying hazards is much more difficult on the construction sites than it is in industrial settings. Additionally, traditional methods used to identify hazards are manual, based on the knowledge and experience of the safety experts, and the newly researched methods are mostly focused on identifying specific hazard types. Since hazard identification is the first and most important step in making the workplace safer, this research aims to address the lack of a universal method for identifying construction hazards and presents one of the prerequisites for such a method. It was established that to be able to identify all hazards faced by the construction workers, the hazards needed to be classified based on the source of (who causes) the hazards and who is affected by the said hazard.

Therefore, the result of the paper is the classification of construction hazards into three types: self-induced hazards, peer-induced hazards, and global hazards. Self-induced hazards are the ones where workers endanger themselves, peer-induced hazards are the ones where the workers are endangered by workers of other workgroups, and global hazards are those hazards which endanger all personnel on the construction site. Such classification is necessary to enable identifying construction hazards through the interrelation between building elements, activities, hazards and workers. If implemented, the research has the potential to significantly improve the rate of identified hazards and to reduce the number of accidents and consequently injuries and fatalities on the construction sites.

As it was already mentioned, the development of the hazard classification is only one of the conditions that need to be met in order to develop the universal hazard identification methodology. Further research is required to develop the database containing the construction hazards and activities and to develop the Hazard Integration System itself.

Disclosure statement

The author does not have any competing financial, professional, or personal interests from other parties.

References

Abdelhamid, T. S., & Everett, J. G. (2000). Identifying root causes of construction accidents. *Journal of Construction Engineering and Management*, *126*(1), 52–60. https://doi.org/10.1061/(ASCE)0733-9364(2000)126:1(52)

Al-Aubaidy, N. A., Caldas, C. H., & Mulva, S. P. (2019). Assessment of underreporting factors on construction safety incidents in US construction projects. *International Journal of Construction Management*. https://doi.org/10.1080/15623599.2019.1613211

Alizadehsalehi, S., Yitmen, I., Celik, T., & Arditi, D. (2018). The effectiveness of an integrated BIM/UAV model in managing safety on construction sites. *International Journal of Occupational Safety and Ergonomics*, 1–16. https://doi.org/10.1080/10803548.2018.1504487

Bansal, V. K. (2011). Application of geographic information systems in construction safety planning. *International Journal of Project Management*, *29*(1), 66–77. https://doi.org/10.1016/j.ijproman.2010.01.007

Baradan, S., & Usmen, M. A. (2006). Comparative injury and fatality risk analysis of building trades. *Journal of Construction Engineering and Management*, *132*(5), 533–539. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:5(533)

Carter, G., & Smith, S. D. (2006). Safety hazard identification on construction projects. *Journal of Construction Engineering and Management*, *132*(2), 197–205. https://doi.org/10.1061/(ASCE)0733-9364(2006)132:2(197)

Cerić, A. (2014). Upravljanje rizicima. In *Hrvatski Graditeljski Forum*, Zagreb, Croatia.

Chen, A., Golparvar-Fard, M., & Kleiner, B. (2013). Design and development of SAVES: A construction safety training augmented virtuality environment for hazard recognition and severity identification. In *ASCE International Workshop on Computing in Civil Engineering* (pp. 841–848). American Society of Civil Engineers. https://doi.org/10.1061/9780784413029.105

Collins, R., Zhang, S., Kim, K., & Teizer, J. (2014). Integration of safety risk factors in BIM for scaffolding construction. In *2014 International Conference on Computing in Civil and Building Engineering* (pp. 307–314). American Society of Civil Engineers. https://doi.org/10.1061/9780784413616.039

Cox, L. A. (2008). What's wrong with risk matrices? *Risk Analysis*, *28*(2), 497–512. https://doi.org/10.1111/j.1539-6924.2008.01030.x

Dharmapalan, V., Gambatese, J., Fradella, J., & Moghaddam Vahed, A. (2014). Quantification and assessment of safety risk in the design of multistory buildings. *Journal of Construction Engineering and Management*, *141*(4), 04014090. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000952

Eurostat. (2015). *Accidents at work statistics*. http://ec.europa.eu/eurostat/statistics-explained/index.php/Accidents_at_work_statistics

Godfaurd, J., & Abdulkadir, G. (2011). Integrating BIM and planning software for health and safety site induction. In *COBRA 2011, The Royal Institution of Chartered Surveyors International Research Conference* (pp. 1043–1053), Manchester, UK.

Gunduz, M., & Laitinen, H. (2018). Construction safety risk assessment with introduced control levels. *Journal of Civil Engineering and Management*, *24*(1), 11–18. https://doi.org/10.3846/jcem.2018.284

Hallowell, M., & Gambatese, J. (2009). Activity-based safety risk quantification for concrete formwork construction. *Journal of Construction Engineering and Management*, *135*(10), 990–998. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000071

Hatefi, S. M., & Tamošaitienė, J. (2019). An integrated fuzzy DEMATEL-fuzzy ANP model for evaluating construction projects by considering interrelationships among risk factors. *Journal of Civil Engineering and Management*, *25*(2), 114–131. https://doi.org/10.3846/jcem.2019.8280

Health and Safety Executive. (2016). *Health and safety statistics for the construction sector in Great Britain*. http://www.hse.gov.uk/statistics/industry/construction/index.htm

International Labor Organization. (2005). *World day for safety and health at work 2005: a background paper*. http://www.ilo.org/public/english/bureau/inf/dowload/sh_background.pdf

Jannadi, O., & Almishari, S. (2003). Risk assessment in construction. *Journal of Construction Engineering and Management*, *129*(5), 492–500. https://doi.org/10.1061/(ASCE)0733-9364(2003)129:5(492)

Kim, K., & Cho, Y. (2015). BIM-based planning of temporary structures for construction safety. In *2015 International Workshop on Computing in Civil Engineering 2015* (pp. 436–444). American Society of Civil Engineers. https://doi.org/10.1061/9780784479247.054

Kim, S. D. (2017). Characterization of unknown unknowns using separation principles in case study on Deepwater Horizon oil spill. *Journal of Risk Research*, *20*(1), 151–168. https://doi.org/10.1080/13669877.2014.983949

Korea Occupational Safety and Health Agency. (2003). *Annual report: Fatal accident cases, 2001–2003*.

Martínez-Aires, M. D., López-Alonso, M., & Martínez-Rojas, M. (2018). Building information modeling and safety management: A systematic review. *Safety Science*, *101*, 11–18. https://doi.org/10.1016/j.ssci.2017.08.015

Mihić, M., Cerić, A., & Završki, I. (2018). Developing construction hazard database for automated hazard identification process. *Technical Gazette*, *25*(6), 1761–1769. https://doi.org/10.17559/TV-20180417105624

Mihić, M., Vukomanović, M., & Završki, I. (2019). Review of previous applications of innovative information technologies in construction health and safety. *Organization*, *Technology and Management in Construction*, *11*(1), 16. https://doi.org/10.2478/otmcj-2019-0004

National Safety Council. (1997). *Sample JHA*.

Niu, Y., Lu, W., Xue, F., Liu, D., Chen, K., Fang, D., & Anumba, C. (2019). Towards the "third wave": An SCO-enabled occupational health and safety management system for construction. *Safety Science*, *111*, 213–223. https://doi.org/10.1016/j.ssci.2018.07.013

NNC Limited. (2003). The development of a knowledge based system to deliver health and safety information to designers in the construction industry. In *Research report 173* (pp. 89). Norwich, UK: Health & Safety Executive.

Pinto, A., Nunes, I. L., & Ribeiro, R. A. (2011). Occupational risk assessment in construction industry – overview and reflection. *Safety Science*, *49*(5), 616–624. https://doi.org/10.1016/j.ssci.2011.01.003

Raheem, A. A., & Hinze, J. W. (2014). Disparity between construction safety standards: A global analysis. *Safety Science*, *70*, 276–287. https://doi.org/10.1016/j.ssci.2014.06.012

Roberts, J. (2013). Organizational ignorance: Towards a managerial perspective on the unknown. *Management Learning*, *44*(3), 215–236. https://doi.org/10.1177/1350507612443208

Rozenfeld, O., Sacks, R., & Rosenfeld, Y. (2009). 'CHASTE': construction hazard assessment with spatial and temporal exposure. *Construction Management and Economics*, *27*(7), 625–638. https://doi.org/10.1080/01446190903002771

Rozenfeld, O., Sacks, R., Rosenfeld, Y., & Baum, H. (2010). Construction job safety analysis. *Safety Science*, *48*(4), 491–498. https://doi.org/10.1016/j.ssci.2009.12.017

Sacks, R., Rozenfeld, O., & Rosenfeld, Y. (2009). Spatial and temporal exposure to safety hazards in construction. *Journal of Construction Engineering and Management*, *135*(8), 726–736. https://doi.org/10.1061/(ASCE)0733-9364(2009)135:8(726)

Teizer, J., Allread, B. S., Fullerton, C. E., & Hinze, J. (2010). Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Automation in Construction*, *19*(5), 630–640. https://doi.org/10.1016/j.autcon.2010.02.009

Teizer, J., Venugopal, M., & Walia, A. (2008). Ultrawideband for automated real-time three-dimensional location sensing for workforce, equipment, and material positioning and tracking. *Transportation Research Record: Journal of the Transportation Research Board*, *2081*, 56–64. https://doi.org/10.3141/2081-06

U.S. Bureau of Labor Statistics. (2018). *National census of fatal occupational injuries in 2017*.

U.S. Department of Labor. (2002). *Job hazard analysis*. Washington, DC.

Wang, H.-H., & Boukamp, F. (2011). Ontology-based representation and reasoning framework for supporting job hazard analysis. *Journal of Computing in Civil Engineering*, *25*(6), 442–456. https://doi.org/10.1061/(ASCE)CP.1943-5487.0000125

Zhang, S. (2014). *Integrating safety and BIM: automated construction hazard identification and prevention* (PhD thesis). Georgia Institute of Technology.

Zhang, S., Teizer, J., Lee, J.-K., Eastman, C. M., & Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction*, *29*, 183–195. https://doi.org/10.1016/j.autcon.2012.05.006

Zhang, S., Boukamp, F., & Teizer, J. (2015a). Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA). *Automation in Construction*, *52*, 29–41. https://doi.org/10.1016/j.autcon.2015.02.005

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., & Teizer, J. (2015b). BIM-based fall hazard identification and prevention in construction safety planning. *Safety Science*, *72*, 31–45. https://doi.org/10.1016/j.ssci.2014.08.001

Zhou, Z., Goh, Y. M., & Li, Q. (2015). Overview and analysis of safety management studies in the construction industry. *Safety Science*, *72*, 337–350. https://doi.org/10.1016/j.ssci.2014.10.006

Zhou, Z., Li, C., Mi, C., & Qian, L. (2019). Exploring the potential use of near-miss information to improve construction safety performance. *Sustainability*, *11*(5), 1264. https://doi.org/10.3390/su11051264

Zolfagharian, S., Irizarry, J., Ressang, A., Nourbakhsh, M., & Gheisari, M. (2014). Automated safety planning approach for residential construction sites in Malaysia. *International Journal of Construction Management*, *14*(3), 134–147. https://doi.org/10.1080/15623599.2014.926190