# Technology Alternatives for Workplace Safety Risk Mitigation in Construction: Exploratory Study

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**Abstract.** Safety performance in the construction industry has reached alarming levels and continues to be a primary source of concern to industry stakeholders. The construction industry is considered more hazardous than other major industries such as manufacturing. In the other industries, safety performance has been substantially improved and generally falls within acceptable levels. One noticeable difference between construction and other industries is that the rate of technology implementation in the other industries is significantly higher than in construction. High rates of technology implementation are expected to lead to improved safety and non-safety performance. The primary objective of the present study is to summarize the use of technology alternatives in the application of the hierarchy of controls using a preliminary, unstructured review of literature. The hierarchy of controls is a systematic method to reduce worker exposure to workplace hazards and mitigate potential safety risks on the jobsite. The result of the study indicated that there are several technological controls used to mitigate workplace safety hazards during construction. Although virtual reality and building information modelling (BIM) are more effective than others in mitigating workplace safety hazards, the other technologies such as wearable sensing devices, warning systems, drones, and robotics can play significant role in protecting and/or alerting workers from potential workplace safety hazards. It is expected that the present study will help industry practitioners improve their understanding of technological controls used to mitigate workplace hazards and motivate higher levels of technology adoption in construction.

**Keywords:** Hierarchy of controls, occupational safety, technology, building information modeling, virtual reality, wearable safety devices.

## 1 Introduction

Safety performance in the construction industry remains a primary concern and continues to frustrate industry stakeholders. Annual fatality and injury statistics from the Bureau of Labor Statistics (BLS) indicate that construction is one of the most hazardous industries in the US [1]. In 2016, 991 fatal work injuries were recorded in construction [1], which accounts for almost 20% of all US fatal injuries in that year. Given that the construction workforce comprises no more than 5% of the overall US workforce [2], safety performance in construction is considered poor especially compared with other major industries. In the other industries (e.g., manufacturing), technology implementation is maximized to prevent or reduce worker exposure to potential workplace hazards, thus improving work conditions and safety performance. High levels of technology implementation usually lead to improved safety performance [3]. Unfortunately, in the construction industry, the rate of technology implementation is still limited, although upward trends have been observed recently. Previous studies have concluded that technology implementation in the built environment can bring numerous advantages with respect to safety, schedule, cost, and quality throughout the facility life-cycle [4]. In particular, high levels of technology implementation found to particularly improve safety performance outcomes [5 and 6]. The challenge is that technology implementation in construction is still relatively low.

Fortunately, there are abundant safety technologies that project teams can implement throughout the facility life-cycle to improve workplace conditions, mitigate potential jobsite hazards, and enhance safety performance outcomes. However, the application of technology as it relates to safety management and risk mitigation plans has not been adequately studied and explained. The present study attempts to bridge this gap in knowledge by reviewing previous studies on the use of technology in safety management and risk mitigation plans.

## 2 Study Objective

The specific objective of the present study is to identify and summarize technologies that can be used to mitigate safety risks on the jobsite and improve workplace conditions as they relate to the hierarchy of safety controls. The research method adopted to identify safety technologies is a preliminary, unstructured review of literature on the topics of safety and technology, as used by Gent et al. [7]. The unstructured literature review conducted has limitations but is considered acceptable for a preliminary investigation. For future research on the topic, a more systematic review of literature supported by industry insight is recommended.

## 3 Hierarchy of Controls

The hierarchy of controls is a safety management system used in many industries to minimize or eliminate workplace safety risks. It is an effective means of determining what safety measures to implement and how to implement them effectively. Manuele defines the hierarchy of controls as "a systematic way of thinking and acting, considering steps in a ranked and sequential order, to choose the most effective means of eliminating or reducing hazards and the risk that derive from hazards" [8]. The hierarchy of controls is divided into five levels of safety controls—personal protective equipment (PPE), administrative controls, engineering controls, substitution, and elimination—as shown in Figure 1. The rationale behind the hierarchy is that some levels of safety control are more effective in mitigating workplace risks than others. Typically, high order levels at the top of the hierarchy, such as hazard elimination and substitution, are perceived as the most effective and reliable measures of safety control as opposed to levels that are low in the hierarchy such as PPE. Safety measures that are low in the hierarchy are considered reactive; reactive safety measures are usually less reliable and more expensive to implement onsite than proactive safety measures. Reactive safety measures typically require worker involvement in the activation of the system [9]. Accordingly, they are perceived as less effective at mitigating workplace risks than proactive measures. The five levels of safety control are described below in more detail.

### 3.1 Personal Protective Equipment (PPE)

PPE is the least effective level of safety control although its presence is indispensable in any safety management plan. PPEs are considered reactive safety measures and can be ineffective in some circumstances (e.g., workers may not use them or use them improperly). They are used to reduce severity of the injury if an accident occurs, as opposed to mitigating safety hazards on the jobsite. PPEs do not decrease worker exposure to hazard nor reduce severity of hazard on the jobsite. Accordingly, this type of safety control should not be used independently, and it is more effective when used in conjunction with other safety measures, such as engineering and administrative controls. Moreover, PPEs can be sometimes uncomfortable and may place physical burden on workers. All of the aforementioned reasons make PPEs the least effective level of safety control. Examples of PPEs include safety goggles, gloves, hard hats, high-visibility clothing, safety footwear, and ear plugs.

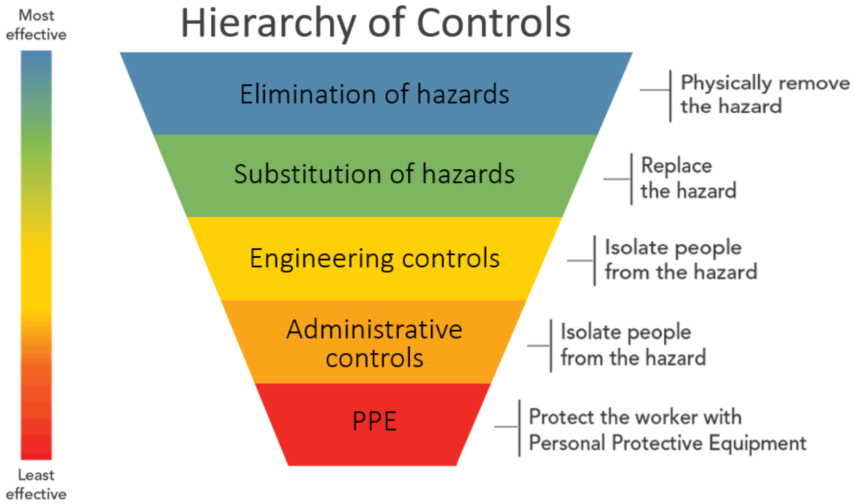


**Fig. 1.** Hierarchy of controls, adapted from [10].

### 3.2 Administrative Controls

Administrative safety controls are changes in work procedures and policies including written safety program, job rotation policy, safety rules and supervision, safety training and education, safety and health planning, and warning systems with the intent to improve employee awareness of potential workplace hazards and reduce potential severity of injuries if an accident occurs. Administrative controls are reactive measures and typically require worker involvement in the activation of the system [9]. A fall arrest system (a combination of PPE and administrative control) can be used during construction and maintenance of a roof to prevent roofers from falling to the ground level. However, if roofers do not use the system, or use it improperly, they can fall and be seriously injured. Moreover, even if the roofers use the system properly, they can still fall and be injured although the fall-protection gear will catch the roofers and prevent them from falling to the ground level. Administrative controls do not aim to remove hazards from the jobsite or isolate workers from the hazards; instead, the goal of their usage is either to improve risk perception of employees or to reduce severity of injuries when accidents occur. Typical examples of administrative controls are equipment safety standards, material safety data sheet (MSDS), frequent housekeeping, safety hazard warning signs and symbols, personal hygiene practices, pre-task planning, job hazard analysis, safety checklist, and OSHA 10-hour training.

### 3.3 Engineering Controls

Engineering controls are methods and practices integrated into the design of a product, or a process, to isolate workers from potential workplace hazards. They are considered reliable measures to prevent worker exposure to hazards if adequately designed, implemented, and maintained [11]. Even though engineering controls do not eliminate hazards from the jobsite, they can eliminate exposure to the hazards. That is, by isolating workers from potential workplace hazards, the risk of injuries will be substantially reduced or even eliminated in some cases. Building a temporary guardrail system around the entire perimeter of a building's rooftop is a form of engineering control that an employer can implement to protect workers from the risk of falling over the roof edges. Other common examples of engineering controls are safety nets and machine guarding.

### 3.4 Substitution of Hazards

Substitution of hazards is considered the second most effective method of safety control after hazard elimination. Substitution of hazards involves replacing a material, machine or a process, with an alternative that is either non-hazardous or less hazardous than the original material intended for use. Substitution of hazards is a reliable method to mitigate workplace hazards and oftentimes inexpensive to implement especially if considered early in the design process [10]. Specifying the use of non-toxic and low chemical-emitting materials [e.g., zero volatile organic compound (VOC) materials] for caulks, paints, carpets, sealants, adhesives, and other building materials is a typical example of hazard substitution.

### 3.5 Elimination of Hazards

Elimination of hazards is a proactive method and widely recognized as the most effective means of preventing workplace injuries, illnesses, and fatalities. This method aims at removing the hazards physically from the jobsite, thus eliminating safety risks associated with a particular operation. Risk is the product of both frequency of exposure to hazard and severity of hazard [12], and, therefore, elimination of the hazards from the jobsite will likely result in minimal safety risks during work operation. The design of underfloor heating, ventilation, and air conditioning (HVAC) systems instead of typical overhead systems is one way to eliminate the risk of working at height. Eliminating the risk of working at height can minimize fall hazards during construction and maintenance operations, the leading cause of fatal work injuries in the US [1]. Nevertheless, the implementation of hazard elimination in construction is challenging, and several barriers that may inhibit construction stakeholders from implementing this method have been recognized. For more details about potential barriers, prospective readers are advised to review the SmartMarket Report [5].

## 4 Technological Controls for Workplace Safety Risk

### 4.1 Smart Personal Protective Equipment (PPE)

PPEs, which are considered reactive safety measures, are the least effective method to mitigate workplace safety hazards, as mentioned previously. However, they can become more effective, or even proactive in some cases, when wearable sensing devices (WSDs) and sensors are embedded in them. Physiological sensors such as temperature and heart rate detectors can be equipped in hard hats and safety vests to provide real-time health conditions of workers, and alert both workers and supervisors of potential safety risks such as fatigue and physical complaints. Locating techniques such as global position systems (GPS) and radio frequency identification (RFID) can also make PPEs more effective in mitigating workplace safety risks. Besides locating and tracking workers on the jobsite, RFID tags attached to PPEs can be used to detect unsafe worker behaviors such as the improper use of PPEs [13]. Furthermore, by incorporating GPS, RFID, and inertial measurement units (IMU) into some PPEs (e.g., smart boots and smart vests), employee location and motion can be tracked [14 and 15]. Tracking employee location and motion can detect situations when workers lose balance and fall, for example, thus providing immediate help to those workers. In all cases, the severity of hazard in the workplace is not reduced by using WSDs and other sensors. However, the integration of these technologies into PPEs improves awareness among workers and enhances interactive communication between workers and managers/supervisors. Improved awareness and enhanced interactive communication can maximize the usability and effectiveness of PPEs, thus improving worker safety on the jobsite. It should be mentioned that these technologies can be also considered administrative controls, but they are primarily categorized into this level of control in this study because they are encased into PPEs. That is, these WSDs and sensors integrated into PPEs may be used to serve a different function (e.g., sending real-time locations and warning signals) than the primary function of traditional PPEs

### 4.2 Administrative Controls through Technology

As mentioned previously, administrative controls are typically used to improve employee awareness of potential workplace hazards and reduce potential severity of injuries if an accident occurs. Recently, the incorporation of technology to enhance administrative safety controls has received substantial attention. With respect to training, technology has been utilized in multiple ways to enhance safety training programs. Teizer et al. developed interactive training methods using three-dimensional immersive data visualization tool to train workers on performing steel erection tasks safely in a virtual, indoor environment [16]. In addition, technology is frequently used to create real-time digital safety signage on construction jobsites. Digital safety signage is an effective method to warn workers of potential workplace hazards and remind them of necessary safety protection and precautions required in order to perform a task safely [17]. Moreover, safety warning systems can be applied to alert workers from potential workplace hazards. For example, heavy construction equipment can be linked into a proximity warning system to alert workers when they are in-close proximity to equipment by releasing visual and audible alarms. Work zone intrusion alert technology is another form of warning systems used on highway construction projects to alert workers from potential hazards resulting from a vehicle intrusion into the work zone [18]. Such alert can provide additional reaction time for construction workers to protect themselves and avoid potential risks. Quick response (QR) codes, also referred to as two-dimensional barcodes or matrix barcodes, are, in turn, used to improve worker safety through providing precaution information pertinent to a specific location on the construction jobsite. Smartphones or tablets enabled with a QR code reader are used to access information stored in a database using a designated URL. QR codes could be used to check if a worker obtained the required training to perform work at a specific location, list out the work operational procedures and safety issues associated with a specific task, and provide schematics of temporary structures to facilitate hazard identification [19].

### 4.3 Engineering Controls through Technology

Engineering controls aim to isolate workers from potential workplace hazards, thus reducing the risk of injuries. Advanced technologies have been increasingly adopted in the construction industry as effective engineering controls to mitigate workplace safety risks. Unmanned aerial vehicles (UAVs), also known as drones, are proven to improve monitoring and safety inspection processes on the jobsite [5, 20, and 21]. High-resolution images and videos captured by UAVs can provide accurate information of jobsite conditions, as well as detailed reports about onsite compliance with safety procedures. Moreover, the use of UAVs in structural inspection and condition assessment can eliminate the need for ironworkers to work in high risk situations or locations (e.g., bottom of a bridge), thus reducing worker exposure to potential workplace hazards, such as fall hazards. Similarly, robotic technology is another method used to provide effective engineering safety controls. Previous studies have also evaluated the effectiveness of automated flagger assistance devices (AFADs) as a potential technology to provide engineering safety controls in highway work zones [22]. The AFAD automates the traffic control flagging process—enabling a worker to remotely control the flag—thereby eliminating the need for a construction worker to work in close proximity to moving traffic. Furthermore, positive protection systems such as truck mounted attenuators (TMAs) and mobile barriers are utilized in highway work zones to reduce worker exposure to hazards and isolate them from potential risks resulting from moving traffic passing by.

### 4.4 Hazard Substitution and Elimination through Technology

Substitution and elimination of hazards are considered the most effective methods of safety control. These methods are oftentimes feasible only if implemented early in the design process. Clash detection and spatial collision are two potential sources of jobsite hazards that can be detected and eliminated during the design process. However, identifying and eliminating such kinds of collisions using traditional, two-dimensional (2D) drawings is challenging. To overcome potential challenges, technology, such as building information modelling (BIM), can be utilized using a simulation approach to visualize the physical characteristics of a workplace and identify potential collisions and other jobsite hazards [23]. The visualizing of design can assist project teams to identify potential safety hazards early in the project lifecycle, before start of construction, especially those hazards that are not readily detectable in 2D drawings [24]. Shen and Marks conducted real-life experiment and concluded that even experienced practitioners with many years of experience may not be able to detect a high percentage of jobsite hazards unless they use visualization tools such as 4D-BIM [25]. Likewise, virtual reality models can be used to reduce jobsite hazards and improve workplace conditions. Both BIM and virtual reality models are versatile and can be shared with different project entities to enhance team interaction and communication [26]. Enhanced team interaction and communication are critical factors to maintain high levels of jobsite safety.

Figure 2 illustrates technology alternatives organized in a hierarchy based on their level of risk mitigation effectiveness. Technologies at the top of the pyramid are more effective than those at the bottom in terms of mitigating workplace safety risks.

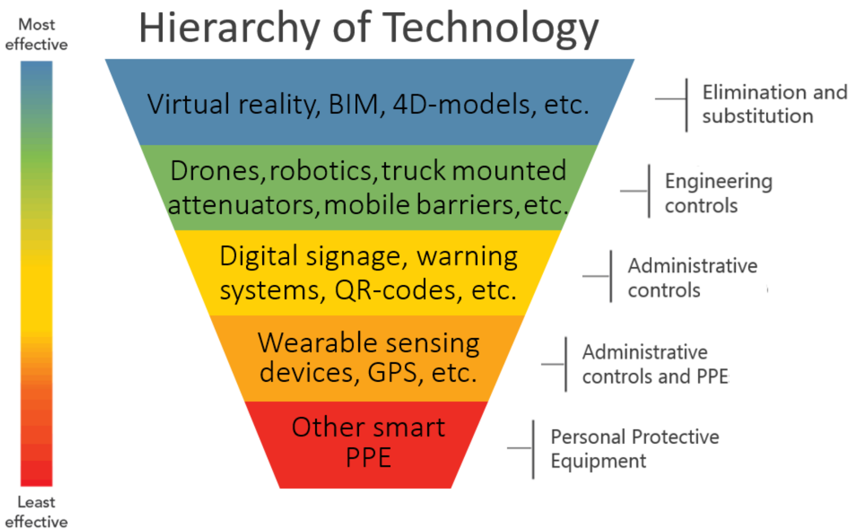


**Fig. 2.** Technology alternative organized in a hierarchy based on level of risk mitigation effectiveness.

## 5 Summary and Conclusions

Current statistics indicate that safety performance is construction is poor and that safety management in the industry lags considerably behind other major industries. Previous studies suggest that introducing innovative technology into safety management practices provides substantial potential for improving construction safety performance. One way that technology implementation could improve safety management in construction is through utilizing technologies as a safety control in phases that hold high impacts on performance outcomes – that is, applying technology as part of the risk mitigation plan to improve safety. The present study explored the potential alignment between safety technology and effective safety management protocols using the hierarchy of controls. Findings from this study suggest that although PPEs could be digitalized using technologies such as sensors and their effectiveness could be improved, the most effective technological controls for eliminating workplace safety hazards in construction are virtual reality and BIM. These results provide valuable information to industry practitioners about technological controls used in practice to improve workplace conditions and safety performance. Future research should conduct a systematic review of existing literature on the topic to identify other potential technologies used for safety management and determine their level of effectiveness using the hierarchy of controls. Such research can be facilitated using a panel of experts with industry insight.

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