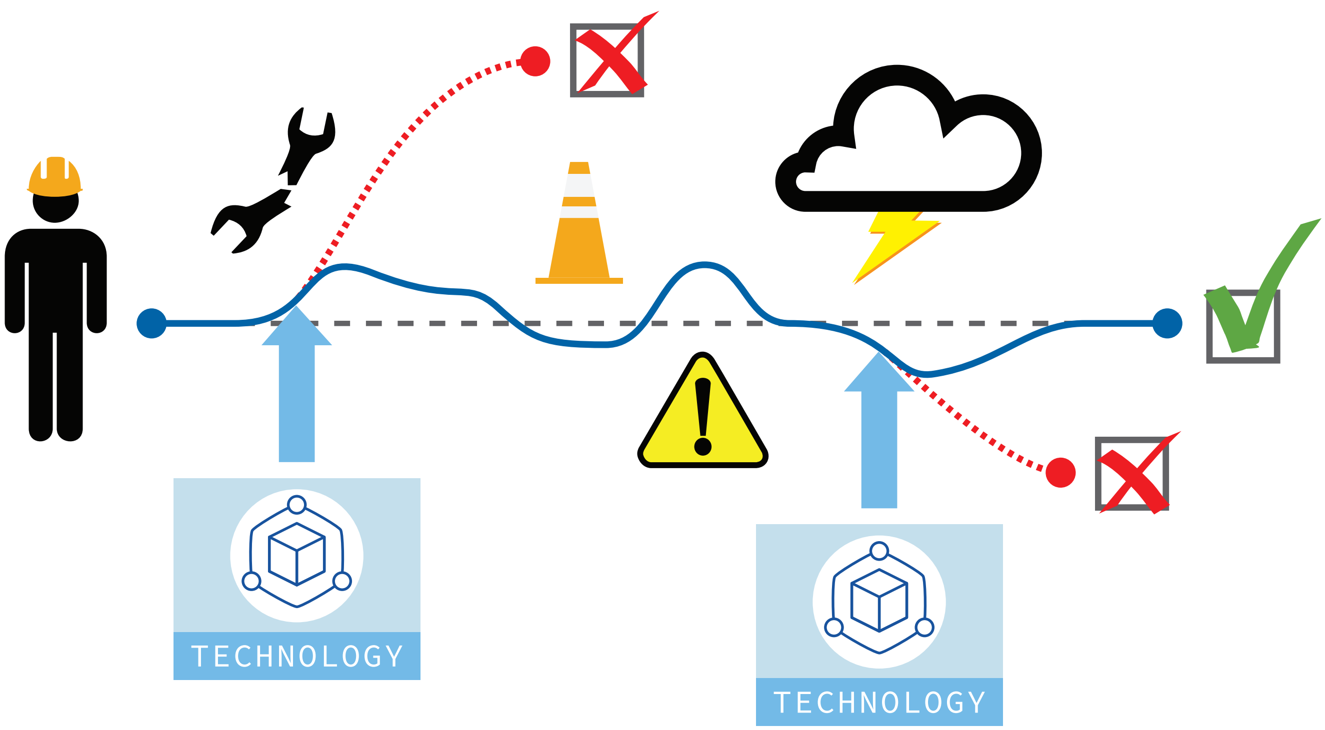
Guide to Technologies for Preventing Serious Injuries and Fatalities Related to Last-minute Work Changes



Final Report 382

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Guide to Technologies for Preventing Serious Injuries and Fatalities Related to Last-minute Work Changes

Prepared by

Construction Industry Institute

Research Team 382

Technologies to Prevent Serious Injuries and Fatalities
Related to Last-minute Work Changes

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Executive Summary

Unforeseen changes in work site conditions or work operations can be stressful, but especially in last-minute situations when workers are under time constraints. In some instances, the time pressure can lead to distractions, frustration, and poor decisions. For some work roles and settings, the consequences of a last-minute change only affect the quality or timeliness of the work. In the field, however, a poor safety decision made in response to a last-minute change could result in a serious injury or fatality (SIF). In fact, theories of incident causation suggest that the effects of last-minute changes on worker behavior and decision-making are likely contributors of SIF incidents.

The objective of pre-task planning is to prepare and account for the possibility of unforeseen circumstances. That way, when a last-minute change occurs, workers are able to safely and efficiently mitigate or adapt to the change, and prevent negative consequences that may result from the change. Using technology may provide an effective means to create this desired resiliency in last-minute situations. Given the present dramatic increase in the development and availability of new technologies for use in construction, the possibility of using technology to mitigate the safety impacts of last-minute changes is quite promising.

CII directed Research Team 382 (RT-382) to explore the idea of using technologies to prevent and/or mitigate the impacts of last-minute work changes that could lead to SIFs. By using a combination of literature reviews, industry surveys, multi-round team surveys, and focus group discussions, RT-382 investigated approaches to identifying and managing last-minute changes, evaluated the availability and capabilities of current technologies, and developed guidance for adopting and implementing technologies to positively influence safety performance in last-minute change situations. The findings from this research are revealing and point to a path forward for improved safety in construction, dedicated attention to last-minute changes, and future technology development.

RT-382 found that last-minute changes play a role in the majority of SIF incidents. In fact, a review of 179 fatality incidents that occurred in construction and industrial work settings since the year 2000 revealed that 73 (41%) included some type of change in work site conditions or work operations that contributed to the incident. Of these 73 cases that included a change, 52 of the changes (71%) could be classified as last-minute according to the team's definition. In addition, in approximately half of the 73 incidents, the last-minute change was highly connected to the affected worker rather than to a different worker or at a different location or time. When a last-minute change played a role in the fatality (73 cases), the change was most often related to equipment usage (36% of cases), a change in the planned work process/construction method (21%), and worker/equipment path of travel (8%). These results reveal that focusing on last-minute changes in worker-equipment proximity and in the planned work process or construction method will have the greatest impact on preventing SIFs that occur due to these changes. One potential means to prevent SIFs associated with last-minute changes is through the use of technology, and that is the focus of this research.

A wide range of commercially available technologies are applicable to the construction industry, and some have the potential to facilitate the anticipation of, monitoring for, or response to last-minute change. RT-382 created a catalog of 40 technologies that can potentially provide the desired ability to mitigate the safety impacts of last-minute changes. The team grouped these technologies into seven categories:

1. Sensing
2. Monitoring
3. Visualization
4. Site control and site access
5. Automation
6. Artificial intelligence (AI)
7. Communication and mobile computing

These technologies are in various stages of development. Their readiness can be evaluated via a technology readiness assessment (TRA). Conducting a TRA identifies the technology readiness level (TRL) for a technology, which can range from 1 (low) to 9 (high). For example, AI technologies are still being investigated and developed, so the research team gave AI a TRL of approximately 5. On the other hand, communication and mobile computing technologies are fully developed and used throughout the industry, so the team gave them a TRL equal to 9.

A technology is only suited to preventing SIFs if it can perform the functions needed to mitigate the safety impacts of last-minute changes, which include the following tasks:

- Monitoring the work site and operations
- Detecting the presence of a change
- Comprehend the potential impacts of that change
- Identifying options and selecting the best one
- Decide to take action
- Implementing the selected option

When RT-382 mapped the catalog of technologies to these functional requirements, it revealed that only two of these types of technologies could perform all of the functions: AI and site control and site access technologies. AI is the most promising technology for performing all of the functions; however, in its current state of development, AI is too limited. Current technologies that include AI capabilities cannot perform all of the required functions in real time under dynamic and changing construction site conditions. To make AI a viable technology for mitigating last-minute changes, substantial, consistent, organized, and standardized data collection is needed, along with further development of AI capabilities for real-time applications in dynamic environments like construction sites. It is not yet clear when AI technologies will be mature and diffused throughout the industry, but the construction industry needs to continue investing in the development of AI capabilities until they reach that next step.

From the perspective of RT-382, the following technology selection criteria were typically considered to be most important: technology effectiveness, cost, and ease of use. With respect to the specific technologies the team evaluated, sensors for worker physiological status met the selection criteria to the greatest extent, followed by sensors for monitoring surrounding site conditions and sensors for tracking worker location on a jobsite.

The success of a technology to mitigate last-minute changes on projects depends on its first being adopted by an organization. Technology readiness, coupled with technology effectiveness, drives selection, diffusion, and ultimately success in technology adoption. RT-382 developed a technology adoption protocol to provide a rigorous, objective means for selecting a technology that meets an organization's needs and addresses the safety impacts of last-minute changes. This adoption protocol includes three assessment checklists targeted at different stages of the decision-making process. Organizations are encouraged to use the adoption protocol to identify which technology best suits their needs and use cases, and which can effectively address last-minute changes.

When it applied the adoption protocol to existing work process-related technologies, RT-382 found that only cloud-based connected worker systems were able to prevent SIFs due to last-minute changes. RT-382 felt that only a cloud-based connected worker system has the ability to monitor site conditions and work operations, detect last-minute changes, comprehend safety hazards due to last-minute changes, project the safety risk, and send an alert – all in real time. None of the technologies assessed was deemed to be able to identify options for mitigating the impacts of last-minute changes, decide which option to select, and implement the selected option in real time.

In many cases, effectively mitigating the safety risk associated with last-minute change will require practitioners to integrate multiple existing technologies. For example, to utilize drones for real-time site monitoring, assessment, and action, the drone's video and mobility capabilities need to be complemented with a wireless or Bluetooth system for connectivity, along with AI to evaluate the data collected, make a decision about how to proceed, and then take the necessary action, all in real time.

When adopting a technology, consider the desired level of automation for the work operation. In some cases, an organization may feel comfortable using a technology to perform all of the required functions; however, in high-risk, uncertain, and complex operations, it may prefer to retain human involvement in making decisions and/or performing any actions. Humans working together with technology may provide the optimal balance of safety, efficiency, quality, reliability, and cost. Further research is needed to find this balance.

The industry needs to continue its investment in technological development, especially in robotics and AI. Most present systems lack the robust capabilities required for real-time monitoring, assessing, decision-making, and taking action. The industry would benefit from concerted efforts to develop technologies that perform the intended operations effectively and meet the needs of the industry, while also making the technologies readily accessible, both physically and economically, to all construction organizations.

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Chapter 1: Background and Motivation

Motivation for this research study came from the continuing desire to improve safety in the construction industry. Therefore, the overarching focus of the study is safety. As Figure 1 depicts, this study addresses safety from the perspectives of two specific topics – last-minute changes and technology. Thus, developing an understanding of all three topics (i.e., safety incidents, last-minute changes, and technology) within the context of the construction industry is an important starting point for the study.

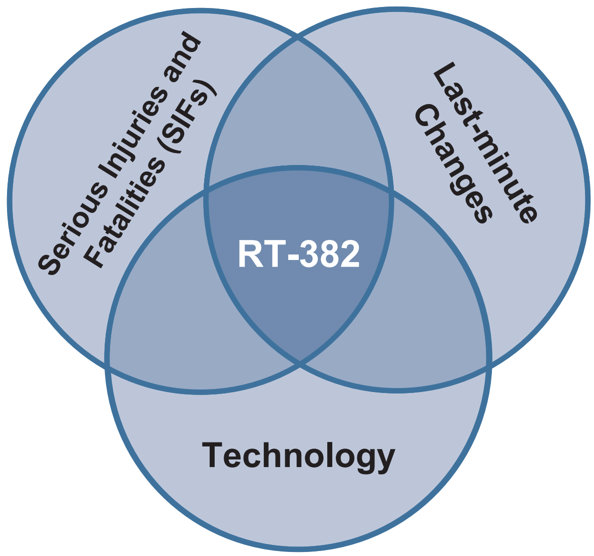

Figure 1. The Intersection of Topics Studied by RT-382

1.1 Safety in Construction

Construction site safety is both unconditionally important and painfully confounding. The safety of the construction workforce is paramount, and CII benchmarking efforts have long shown that members of the Institute lead the industry in safety performance. As a result, construction safety has improved markedly over the years. However, despite decades of research and the implementation of countless injury prevention strategies, serious injuries and fatalities (SIFs) continue to plague the construction industry. In its annual Census of Fatal Occupational Injuries, the Bureau of Labor Statistics revealed that the construction industry experienced approximately 1,000 fatalities in 2020, which amounted to 2.7 fatalities per calendar day – more than any other industry (BLS, 2021). It remains clear that, in addition to ensuring that it continues its efforts to improve safety, the construction industry needs to explore new ideas and actions to fully and confidently eliminate SIFs.

Researchers have explored reasons why SIF incidents occur on construction sites. Common theories center on human behavior and site conditions. For example, site conditions may appear that are unexpected or sudden, and which cannot be controlled in a timely and safe manner. With respect to human behavior, injury incidents may result from a mistake or error, absentmindedness or a distraction, ignorance about safety hazards or safe work procedures, poor risk management, high risk tolerance, or showing a low level of concern or even indifference to safety. Often this means putting other priorities (e.g., cost and schedule) ahead of safety (Gambatese et al., 2016). When humans are under pressure to perform, they become susceptible to risk discounting, a cognitive failure that can lead to poor risk management and ultimately result in injury or fatality incidents (Sigurdsson et al., 2013; Hasanzadeh et al., 2020).

Unanticipated changes have also been linked to SIFs, especially in times of pressure to complete the work. Importantly, research reveals that while the consequence surfaces on the work site (i.e., a worker injury or fatality), the change or behavior may originate elsewhere in the design and construction process, including during project management and planning prior to the execution of the work. Decisions made upstream may place field workers in dangerous site conditions or stressful situations. Pressure to perform the work amid the complex and dynamic conditions experienced on construction sites can magnify the possibility of risky decisions during the performance of the work. In fact, past CII studies (e.g., RT-284 and RT-321) have identified last-minute change and improvisation, especially in stressful situations, as key precursors of SIFs.

Research has developed best practices for anticipating and preventing worker injuries and fatalities. In addition to proper and consistent use of personal protective measures and meeting the OSHA requirements, previous CII research studies have reported that many safety practices are administrative:

- Tracking leading indicators (Hinze and Hallowell, 2013)
- Reporting near misses (Marks et al., 2014)
- Owner involvement in safety (Hinze and Huang, 2003)
- Pre-task planning (Hinze, 2002; Hallowell et al., 2014; Maloney et al., 2016)
- Designing for safety targets incorporating safety during the design process, upstream of construction (Hinze and Gambatese, 1996)
- Using precursor analysis in real time while monitoring the work being executed to identify anomalies that indicate the likelihood of an imminent injury or fatality incident (Hallowell et al., 2016a)

All of these practices and many more aid in preventing worker injuries and fatalities. All should be considered as a company provides a comprehensive safety program.

1.2 Work Changes on Construction Projects

Changes occur regularly on construction projects. Some changes are intentional and planned, while others are unanticipated and unintentional. Research has shown that both planned and unanticipated changes influence project success, and both can have positive and negative impacts. Analyses of changes, whether unexpected or planned, reveal four general descriptors of changes:

- **Agent** – Every change has an origin and is instituted by the agent of the change.
- **Indicator** – When the change occurs, the indicator of the change reveals that a change has occurred through observable differences in the surrounding conditions.
- **Effect** – The change effect is how the environment and work operations react to the change (i.e., what physical and operational differences are present due to the change).
- **Consequence** – The change consequence represents the overall impact on performance due to the change. Examples of change consequences include lower productivity and worker injuries or fatalities.

Past research has explored the nature of work changes, including changes that are unanticipated and changes that occur at the last minute. For example, Park and Peña-Mora defined two types of changes that commonly occur on construction projects (Park and Peña-Mora, 2003):

- **Unintended changes** happen when there is no control over managerial actions.
- **Managerial changes** arise when managerial decisions are needed to ensure the desired level of quality on the project.

Perhaps most closely related to last-minute changes, Sun et al. defined four types of changes in terms of change timing and severity (Sun et al., 2006):

1. **Gradual changes** occur over a long period of time.
2. **Radical changes** happen suddenly and dramatically.
3. **Anticipated changes** are planned.
4. **Emergent changes** are unanticipated and unplanned.

In a study by Hao et al., the researchers identified various types of changes, their impacts, and the actions taken during different stages of a project (Hao et al., 2008). The results (shown in Table 1 on the next page) provided essential information for the present study to consider; namely, that changes can occur in different phases of construction projects and that technologies could be applied during all phases to mitigate the impacts of these changes.

Table 1. Summary of Construction Changes (Hao et al., 2008, modified)

Stage	Stakeholder	Types of Changes	Impacts	Actions
Specification	Owner, client, user, or architect	• Changes to requirements including specification, scope of projects, and design brief • Changes in codes and regulations	Changes in design and construction processes	Carefully provide detailed specification documents before bidding.
Design	Design or engineering consultant	• Incomplete or inconsistent drawings • Design error or defect • Design change • Omissions of site conditions and buildability	Rework of design and drawing; rework in construction; change orders	Better control of design versions, drawings; site investigation; consider buildability in design
Construction	Contractor or subcontractor	• As-builts not in conformity with as-designed • Quality defect • Unforeseen site conditions • Value engineering; materials or equipment not available • Inclement weather	Rework; change orders; changes in design	Quality control; site operational control; coordinated documents and drawings; daily logs

When changes occur, their timing is a concern to project success. In its guide on effective project management, the Project Management Institute describes the relationship between the cost of changes and project time (PMI, 2008). The cost of changes increases as the project progresses. Cost, in part, reflects the amount of work to be undertaken, which is a factor that influences worker safety (i.e., exposure of the workers to hazards). In addition, the degree of influence that stakeholders have, along with the risk that the stakeholder shoulders and the uncertainty to the project, decrease during later phases of the project. Given the positive influence that owners and clients can have on safety, a decrease in their influence over the course of the project can be a cause of concern for safety.

A realization of the increased cost of changes as a project progresses has motivated project stakeholders to dedicate additional attention during initial planning and design phases. The concept of Prevention through Design supports this intentional effort to modify the design to improve downstream outcomes, especially safety. In this case, the modifications (i.e., changes) are intentional and designed to benefit safety. Weinstein et al., for example, recognized the relationship between project schedule and the ability to influence safety to show how design changes can both reduce safety risk and increase worker productivity. Based on this relationship, if changes in the design are implemented early on, during conceptual and detailed design, fewer safety hazards will be present on the site (Weinstein et al., 2005). While RT-382 focused on unintentional change that could potentially negatively influence safety, an understanding of how change of any type is related to safety was important for the success of this study.

Zhang et al. emphasized that construction projects have a dynamic nature, which leads to many changes that occur regularly. Furthermore, when these changes occur, modifications to the safety plan may be required (Zhang et al., 2015). Another study indicated that last-minute changes requested by clients might trigger the need for demolishing parts of the project already constructed, or rework. Hence, given the negative effects that rework can have on safety, late design modifications require attention to safety associated with this additional work (Poon, 2007).

With respect to changes to work operations, Mitropoulos et al. mention that if a change happens suddenly, workers may not have adequate time to react to the change, and this could lead to an accident (Mitropoulos et al., 2005). Lastly, Khatib et al. pointed out that two-dimensional drawings cannot fully explain three-dimensional assemblies in the real world. Designs in 2D plans may look reasonable, but may not be physically feasible in the 3D real world. Therefore, a last-minute change may arise whenever alterations to the design are needed on the site (Khatib et al., 2007).

Past research reveals an inventory of types of changes that occur on construction projects, along with the common reasons for these changes. Additionally, there is clear evidence that changes influence safety. Any changes on the construction site will likely lead to changes in the working conditions and work operations, and this can result in injury and fatality incidents. Eliminating the changes results in eliminating the SIFs that occur due to change.

Questions remain, however, regarding the types and extent of *last-minute* changes that occur, and whether last-minute changes affect safety, especially in terms of SIFs. Importantly for improving safety performance in the construction industry, how can the industry effectively prevent or mitigate last-minute changes? Is technology part of the solution?

1.3 Technology in Construction

Historically, the construction industry has been slower than other industries to adopt new technologies. However, today the construction industry is expanding the use of technology. The Horizon 360 Subcommittee within CII's Technology & Innovation Committee has developed an extensive list of technologies, both currently used and in development, with the aim of accelerating their use in the construction industry. The technologies fit within a wide range of categories including advanced work packaging, modularization, project controls, risk management, safety, and supply chain management, among other topics. Some of the specific technologies that are being implemented in the field include robots for performing work, sensor for monitoring the work site and worker, telematics for monitoring equipment conditions and operator performance, exoskeletons for enabling heightened worker performance, and unmanned aerial systems (drones) for monitoring sites and tracking work progress. The list of technologies is extensive and continues to grow.

Although some technologies are fully developed and diffused throughout the industry, many technologies intended for use in construction are still being developed. These technologies are primarily being developed to support humans as they perform the construction work, monitor work performance, and search for ways to create more efficient, safe, and cost-effective work processes. Adopting a technology to support or replace human input can be a difficult and maybe unwanted change. In addition to the development of specific technologies, research has explored various aspects surrounding technology functional capabilities, readiness, and adoption factors. This study addressed each of these topics.

Technology is increasingly being leveraged to improve construction productivity and many other aspects of construction (Haas et al., 2010 and 2013). CII's Safety Committee for Business Advancement (SCBA), researchers, and other organizations across the industry foresee the adoption of new tools and technologies as a means to prevent SIFs. Whether the new technologies are used on the work site or in the project office, they are being designed to keep workers safe and reduce their exposure to hazards.

The safety technologies presently available typically either monitor the site and operations for potential hazards, reduce worker exposure to a hazard, and/or protect the worker from injury if an accident occurs. Examples of safety technologies include wearable sensors, augmented reality, proximity alarms on heavy equipment, and many more. Other technologies, such as a simple mobile phone, may not be have been designed specifically to promote safe construction, but they can positively influence safety through their use.

1.4 Value Proposition and Problem Statement

As mentioned above, SIFs continue to plague the industry and last-minute changes and projects' responses to them may be factors in the SIFs' occurrence. Nevertheless, the actual safety impacts of last-minute changes are an uncharted territory. Data on the extent to which SIFs are related to last-minute changes are not being captured, observed, and discussed. In-depth research on the topic provides an opportunity to bring the dangers of last-minute changes to the forefront of safety discussions, arming companies to mitigate these mostly undetected risks.

Technology has the potential to be the catalyst to improving safety efforts, equipping safety professionals and team with enhanced tools, capabilities, and methods to mitigate and prevent risks. However, technologies implemented to eliminate SIFs are only effective if they address the causes of incidents or protect the workers from injury when an incident occurs. Technologies should mitigate one or more aspects of last-minute change, which commonly occurs due to unanticipated human behavior or unexpected site conditions. Last-minute changes may occur in the site conditions, equipment, materials, and/or work process. These changes are often needed due to issues with the quality of work (i.e., rework), a lack of or deficient planning, unforeseen circumstances, and other significant impacts to critical work activities.

Given the time-restricted nature of last-minute decisions and the ever-present need to monitor work operations and site conditions for potential hazards, technology may provide an opportunity to prevent, or mitigate the impacts of, last-minute changes.

Technology development, especially with the advent of artificial intelligence, has progressed to a point where real-time monitoring, evaluation, decision-making, and action in the presence of last-minute change may be achieved, either partly or fully, through technology. Practical application of technology in this way is attractive. It can potentially help eliminate injuries and fatalities, and do so in an efficient, reliable, and cost-effective manner. However, given the lack of research on the topic, and the present state of the art in technology and its application to construction practice, the technologies that can be used to prevent injuries and fatalities due to last-minute changes require further exploration.

CII organized and chartered RT-382, a highly experienced team of researchers and industry practitioners, to investigate how technologies could be utilized to prevent and/or mitigate the impacts of last-minute changes that could lead to SIFs. The study's aims were to investigate current approaches to identifying and managing last-minute work changes, evaluate the availability and capabilities of current technologies, and develop guidance for adopting and implementing the technologies to positively impact safety performance. The overarching interest was to provide academically supported knowledge, guidance, and resources to CII membership that could lead to improved safety and project performance. Through this research, CII has the opportunity to evaluate and curate some of the industry's leading technologies to help companies invest in the right solutions for their businesses and their greatest assets – their employees. It is hoped that doing so will help further industry investments in construction safety technologies and, ultimately, prevent injuries and save lives.

This study was founded upon and leveraged prior research on topics such as safety technology adoption and development, risk assessment, safety best practices, and predictive analytics for safety performance. It gave special emphasis to technologies that directly supported the identification of, and response to, the types of last-minute changes and/or unplanned work that could potentially lead to SIFs. The guidance RT-382 developed is intended to target those technologies that provide the highest aggregated value with respect to safety, implementation effort, technology robustness, cost, industry readiness, and other common technology and work operation performance criteria.

With these parameters in mind, the researchers pursued this study to answer the following questions:

- What constitutes a critical last-minute work change that has safety implications? How are changes currently identified and managed by work crews?
- What technologies are currently available that benefit safety when a last-minute change occurs?
  - What are the features, cost, availability, and related characteristics of each technology?
  - What operational capabilities and safety benefit does each technology provide, and how do the capabilities map to the competencies and skills needed to perform construction work safely?
- What factors should be considered when assessing potential adoption and implementation of technology for safe work practices?
  - What should the technology adoption decision process consist of and how should it be structured?
  - Is the industry ready to absorb the technologies?
- What is the impact of technology implementation on safety performance? Are specific technologies available that are highly beneficial to project safety and that are particularly well-suited to expanded use and diffusion in the capital projects industry?

The researchers selected and designed a multi-step research process for the study that utilized a mixed-methods approach. (The general research design is depicted in Figure 2.) This research relied heavily on the experience and expertise of RT-382's members from industry as well as objective evaluations of SIF incidents and existing technologies available for use in the construction industry. Appendix A provides a more detailed description of the research methods.

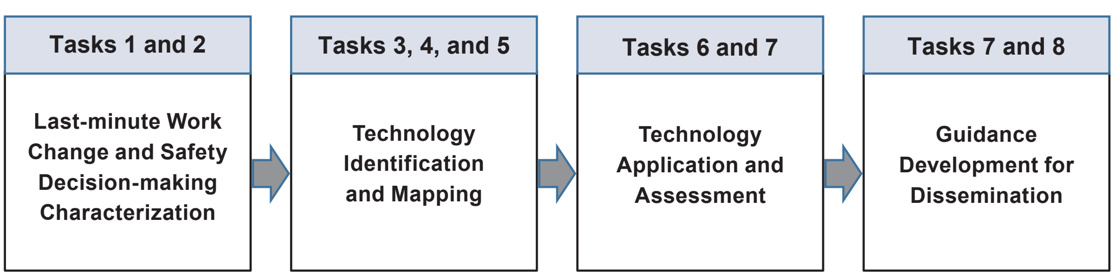

Figure 2. Research Study Process

1.5 Definitions of Key Terms

At the onset of the study, RT-382 established definitions of key terms to guide the study efforts, bound the study scope, and ensure that the study stayed consistent with the intent and nature of its topic. Using available literature and industry perspectives of change as a starting point, RT-382 developed the following definitions for the study:

- **Change** – An unexpected, unplanned, non-routine deviation in a condition, action, or process
- **Last-minute change** – A change that occurs or manifests at the work face when there is limited time available to plan for and address the change
- **Potential SIF-related last-minute change** – A last-minute change that could potentially cause a serious injury or fatality (SIF)

RT-382 also established the types of changes to be targeted in the research study. Specifically, the team chose to focus on **changes in the site conditions, scope of work, work process, and/or schedule that are deemed to be impactful to the safety of the workers and the ability of the workers to safely perform the contracted scope of work**. Examples of these changes include changes to the availability and quality of the resources (e.g., staff, materials, equipment, and structures), environmental conditions, physical site conditions, and the energy state of the site features and temporary works and equipment.

Based on these definitions, this study explored the potential technologies to mitigate or eliminate last-minute changes and improve safety performance when such changes do occur. It should be noted that within the broad spectrum of changes that may occur on projects, there are some types of changes that the research team chose to exclude from the focus of this study. Types of changes not included in the study are changes in a condition, action, or process that are anticipated or planned and/or that occur when there is sufficient time to observe and react to the change without interruption of the work. Examples of such changes are change orders and rework of nonconforming work.

Chapter 2: Current State of Technology in Practice

RT-382 gave considerable attention to technology and the technologies currently available for use in the construction industry. Technology can take many forms. For the purposes of the research study, the researchers considered technology to be physical systems designed to perform a specific purpose within the construction process. **Technology** is often interpreted to mean electronic and computer-related devices and equipment. Instead of limiting this study's breadth these types of technologies, RT-382 considered all types of technologies that showed potential value for mitigating the impacts of last-minute changes on SIFs.

2.1 Available Technologies

Many agents can contribute to last-minute changes, and last-minute changes have a variety of effects. Therefore, a multitude of potential technologies could be beneficial to addressing these changes, from anticipating changes caused by upstream planning and work packaging through sensing and managing changes when they actually occur in the field. Many technologies that can potentially prevent or mitigate last-minute changes can be found in archival literature and on the internet. A comprehensive keyword internet search, along with a review of academic literature on the topic, revealed a long list of technologies. In their search, the researchers uncovered 40 technologies that potentially apply to last-minute changes.

The researchers organized this list of identified technologies into seven categories: sensing, monitoring, visualization, site control and site access, automation, artificial intelligence (AI), and communication and mobile computing. Each category has specific functions that apply to last-minute changes and the prevention of SIFs in construction. For example, weather sensors in the sensing category can detect changes in the surrounding environmental conditions. Similarly, monitoring technologies are able to continuously monitor work site features to determine whether the features differ from what was expected or even represent safety hazards.

This chapter describes the technology categories in detail, and Appendix B provides a catalog of detailed information about all 40 identified technologies. This catalog describes and presents specific technologies that RT-382 identified for this research study. In some cases, the technologies were designed for a specific purpose separate from last-minute changes. The identification of technologies that are particularly effective at preventing or mitigating last-minute changes is a unique contribution of this research study.

Sensing: The main task of sensing technologies is to detect the physical conditions present on the site (e.g., temperature, wind speed, a worker's location). When these variables change, sensing technologies can detect the changes immediately. For example, when the surrounding temperature changes dramatically over a period of time (e.g., rising above 100°F), a weather sensor can detect this change and alert the project superintendent or other personnel that the work is being conducted in potentially hazardous temperatures.

A weather sensor may also be able to detect a strong gust of wind; workers can adequately prepare for strong wind after they receive an alert from the weather sensor. Sensors are available which can detect the presence and location of objects and people, movements in equipment or machinery, physiological conditions of workers, along with many other conditions. Ultimately, sensors provide the basis for most, if not all, of the technologies in these categories; every technology relies on one or more sensors in some way.

Monitoring: Technologies in this category use sensors to: (1) monitor the distance between workers, objects, and equipment, or (2) monitor the condition of an equipment operator. An example of technology in the first category is a system that monitors the perimeter around vehicles and equipment to determine whether a hazard is present. Such a monitoring system can identify pedestrians and objects in a detection zone around a piece of equipment, and in the back-up path of the equipment. The system can provide back-up views on a screen in the equipment cab, and emit an alarm when a person or object is detected in a dangerous location. With this technology, the operator can see whether there are any pedestrians or objects in the back-up path of the equipment, and the system can stop the equipment if an unanticipated pedestrian or object intrudes into that path.

Another example is a system within the cab of a piece of equipment that monitors the facial expressions, movements, and performance of the operator. If the technology senses that the operator is fatigued, distracted, or under the influence of alcohol or drugs, the system can take action to limit operation of the equipment. For all of the different types of monitoring technologies available, consider the possibility of normalization of deviance, alarm fatigue, and modification of the system to avoid detection.

Visualization: Visualization technologies present physical objects and conditions in three dimensions for monitoring, review, and analysis by humans. Visualization is performed using video and still cameras, laser scanning, and other types of imaging technologies. For example, a 3D model can be built by laser scanning and lidar or visually seen through virtual reality (VR) glasses. Starting with a 3D scanner, visualization systems utilize recorded point cloud data to generate a digital image of the scanned image. Building information modeling (BIM) then uses the point cloud data to support review, planning, clash detection, and other uses. The use of VR glasses enables users to view the model in three dimensions, which assists with visualizing the design. With these technologies, project personnel can review the design and construction setting, and fix problems immediately.

Site Control and Site Access: This category consists of technologies that monitor and control entry into a particular work area or exposure to an identified hazard. For example, the BIM-based fall hazard system developed by Zhang et al. can help prevent workers from walking near an opening in a floor or roof slab (Zhang et al., 2015). The program can automatically insert a task called “fall protection installation” in the project schedule when the program detects there is a hole or edge in the model. A “fall protection removal” task is also inserted in the schedule when the hole has been sealed or the permanent edge protection is in place, because fall protection can be removed. Another example of a site control/site access technology is the automated flagger assistance device (AFAD). An AFAD acts like a flagger to help control access through roadway work zones and active work areas using a stop/go signal and movable barrier arm. Work zone intrusion alert systems also fit within this category.

Automation: Technologies in this category are highly automated robots that can perform construction-related work tasks on their own. The Spot® robot is an example of a technology in this category (Boston Dynamics, n.d.). This robot can walk around and within the construction site under the remote control of a human operator, collect site data through its audio and video capabilities, and inspect physical site conditions and assets. By using this technology, workers can maintain safe distances from dangerous conditions and forego completing hazardous tasks associated with site monitoring. Similarly, remote-controlled vehicles allow operators to control equipment from a distance, which means the operator can stay in a safe place and not be exposed to potential hazards. There are many other examples of automation, including brick-laying robots, autonomous drones, and autonomous material supply robots.

Artificial Intelligence: RT-382 identified that three subsets of this category were applicable to last-minute changes: machine vision, machine learning/deep learning, and natural language processing. The key function of AI is that it can learn by itself based upon previous experience or data (training), and then improve its algorithms to make predictions about future events, conditions, and impacts. Thus, technologies in this category may be the future of the construction industry because, owing to its ability to learn and modify its algorithms, AI can point out potential instances of last-minute changes and related safety hazards.

Communication and Mobile Computing: This category encompasses a broad number of different technologies, including mobile phones, tablets, and laptops, all of which are connected through wireless networks and internet resources. All of these technologies are regularly utilized on construction projects to perform a variety of tasks, and a wide variety of types are available. Communication and mobile computing technologies can also be used to communicate information about last-minute changes to project personnel so they can interpret and mitigate the changes. This category of technologies also includes cloud-computing technology that connects and integrates all of the other individual technologies into a complete system. Such integration of the process is critical to realizing the desired benefits of technology for all aspects of construction including addressing last-minute changes for safety.

The researchers identified two unique technologies in this category that are potentially applicable to the study topic: quick response (QR) codes and digital safety signage. These technologies can be used to provide information about current potential hazards on the site and suggest possible protection for workers. However, these technologies cannot detect any changes by themselves, which means they only present the information to humans. Therefore, this study will not focus on these technologies.

2.2 Technology Readiness Assessment

To be of value, a technology must fulfill its intended use. In some cases, the technology may already be developed to an extent that it can readily perform as desired, while in other cases the technology may need further development before it can be considered effective. As a result, another vital factor in evaluating a technology for potential adoption is its readiness for implementation. A **technology readiness assessment** provides objective processes and scales for evaluating a technology's readiness for widespread implementation. According to the U.S. Government Accountability Office, "A technology readiness assessment (TRA) is an evaluation of the maturity of critical elements of a product's technologies, often called critical technologies" (GAO, 2020).

In order to perform TRAs, the GAO established an evaluation standard called the **technology readiness level** (TRL). Technologies may have been developed for use in one industry, but they could also be attractive for use in another industry. As a technology is developed, tested, and validated, and its acceptance and use by an industry increase, its TRL also increases. Meanwhile, other organizations, such as the Bechtel Corporation, Federal Highway Administration, and the Office of Energy Efficiency and Renewable Energy, established similar standard TRA processes and TRLs for their particular industries. The existing TRA processes and lists of TRLs are similar in nature, in that they enable a TRL to be assigned to a technology for use when a potential user is deciding whether to adopt that technology. Figure 3 depicts a TRL scale developed by the National Aeronautics and Space Administration and the European Space Agency (ESA, 2008).

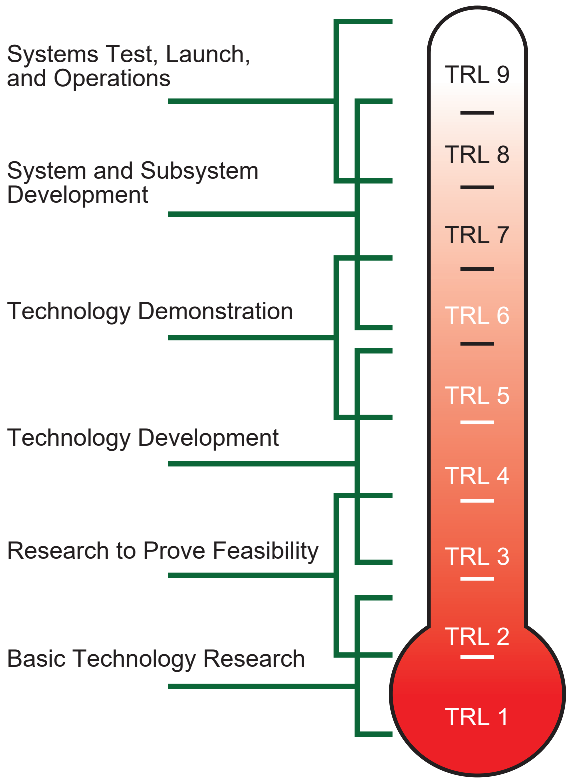

Figure 3. Technology Readiness Levels (ESA, 2008)

For this study, the researchers utilized the existing lists of TRLs mentioned above to create a set of TRLs applicable to, and simplified for, the construction industry. Table 2 (on the next two pages) gives RT-382's list of TRLs. Each level in the scale, from TRL 1 to TRL 9, contains a significant, identifiable change in the readiness status of the technology. The table may be used to determine the extent to which a technology is ready for use in the construction industry. The team developed this table content based on TRA resources developed by the Federal Highway Administration, U.S. Government Accountability Office, Office of Energy Efficiency and Renewable Energy, and the Bechtel Corporation.

Table 2. Technology Readiness Levels Adapted for this Study

Phase	Technology Readiness Level	Description and Requirements
Basic Research	TRL 1	Initial technology basic principles are qualitatively postulated and observed by initial scientific research. • Do basic scientific principles support the concept? • Has the technology development methodology or approach been developed?
	TRL 2	Potential practical applications and applicability are identified. The potential required procedure or material to reach the goal of using this technology is confirmed. • Are potential system applications identified? • Are system components and the user interface at least partly described? • Do preliminary analyses or experiments confirm that the application might meet the user's need?
	TRL 3	Initial development of the concepts, which include analytical and experimental proof, has started. • Are system performance metrics established? • Is system feasibility fully established? • Do experiments or modeling and simulation validate performance predictions of system capability? • Does the technology address a need or introduce an innovation in the field of construction?
Applied Research	TRL 4	Alpha prototype procedure or system has been tested in the lab within a controlled environment. Results can provide evidence to prove that the targets of the concepts are achievable. • Are end-user requirements documented? • Does a plausible draft integration plan exist, and is component compatibility demonstrated? • Were individual components successfully tested in a laboratory environment (a fully controlled test environment where a limited number of critical functions are tested)?
	TRL 5	Prototype procedure or system has been tested in a simulated environment. Results show that the target can be achieved in a relevant environment. • Are external and internal system interfaces documented? • Are target and minimum operational requirements developed? • Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?

Table 2. Technology Readiness Levels Adapted for this Study *(continued)*

Phase	Technology Readiness Level	Description and Requirements
Development	TRL 6	Prototype procedure or system has been piloted on multiple projects with confirmed positive effects (beta prototype system level). • Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? • Was the prototype tested in a realistic and relevant environment outside the laboratory? • Does the prototype satisfy all operational requirements when confronted with realistic problems?
	TRL 7	Concept of the prototype procedure or system has been accepted by enterprise-wide deployment (integrated pilot system level). • Are available components representative of production components? • Is the fully integrated prototype demonstrated in an operational environment (i.e., real-world conditions, including the user community)? • Are all interfaces tested individually under stressed and anomalous conditions?
	TRL 8	Actual procedure or system is qualified and completed through multiple deployments, proving the validation and positive impact of the technology (pre-commercial demonstration). • Are all system components form-, fit-, and function-compatible with each other and with the operational environment? • Is the technology proven in an operational environment (i.e., meets target performance measures)? • Was a rigorous test and evaluation process completed successfully? • Does the technology meet its stated purpose and functionality as designed?
Implementation	TRL 9	Actual procedure or system proves the effectiveness of the technology through successful operations in the operating environment. Technology is ready for full commercial deployment and has become a new proven, impactful, and sustainable enterprise standard. • Is the technology deployed in its intended operational environment? • Is information about the technology disseminated to the user community? • Is the technology adopted by the user community?

When evaluating a new technology using a TRA process, the Federal Highway Administration highlighted that "The TRL scale does not identify risks or challenges in technology development" (FHWA, 2017). This means that the TRL only focuses on the current readiness of the technology itself – not the challenge for the technology to advance to the next level, its potential market, or its expected impact. Therefore, for this study the team incorporated this limitation as it determined the TRLs for technologies based on their potential to mitigate the safety impacts of last-minute work changes.

RT-382 utilized its members' collective knowledge and experience associated with the technologies identified to conduct a TRA of each technology. Team members were given the overall list of technologies identified, along with the TRA process and standard described above. RT-382 members then conducted focus group discussions about each technology and its readiness for practical use, so each group could assign a TRL to each technology. (Appendix B presents the results for each technology in a technology catalog.)

Because most of the technologies the team identified were currently available for use or had undergone sufficient development to demonstrate their use, the assigned TRLs were fairly high, ranging from 6 to 9. While RT-382 did not provide TRLs for technologies within the artificial intelligence (AI) category, its members expected the TRLs for AI technologies to be lower than the TRLs for technologies in other categories. Following further discussion, RT-382 established a TRL of 5 for AI technologies. Similarly, team members expected the TRLs for the communication and mobile computing category to be high. The average TRLs for each technology category, based on the team's perspectives, were as follows:

- Sensing – 8.5
- Monitoring – 8.4
- Visualization – 8.5
- Site access and site control – 7.5
- Automation – 8.25
- Artificial intelligence – 5 (estimated)
- Communication and mobile computing – 9 (estimated)

In some cases, insufficient information was available for a technology, so the team assigned no TRL. Some technologies were added to the list after the assessment was complete and therefore also have no TRL.

It should be noted that TRLs are categorical. Therefore, slight differences in TRL values within a TRL level (e.g., between 8.4 and 8.5) do not necessarily indicate a difference in technology readiness. Also, technologies have different trajectories through the levels. That is, technologies will differ in the amount of time, effort, and resources required to progress from one level to the next. No set amount of time, effort, or resources is required or expected to move between levels.

2.3 Technology Capabilities and Their Applicability to Situational Awareness

One of the factors to consider in conducting a TRA to establish the TRL for a technology is whether that technology meets its intended purpose and functionality. A technology may be fully operable but not ready for implementation if the functions it performs do not meet the purpose for which it is needed. For this study, to eliminate the safety impacts associated with last-minute change, technologies must perform the functions associated with mitigating last-minute changes. Those functions can be viewed effectively through the concept of situational awareness.

Situational awareness is the human ability to perceive and comprehend the surrounding environment and then project its future status based on present conditions. Human limitations and tendencies can inhibit effective performance at each situational awareness level, including the identification and response to last-minute changes. A lack of training, limited physical ability, bias in assessing risk, a tendency to be forgetful, emotional impacts, and many other factors affect human abilities in this regard. While these factors affect human performance, technology – whether used alongside or in place of humans – may be able to overcome these deficiencies. As a result, the application of technology is an appealing potential alternative for performing the needed actions related to change, perhaps even offering greater effectiveness and confidence than humans. However, a question arises as to whether technologies possess the capabilities to master the physical and cognitive tasks currently performed by humans. RT-382 conducted analyses to answer this question.

The team began its assessment of **technology capabilities** by identifying and defining which capabilities were needed to perform the steps related to last-minute changes, whether with or without technology. The team identified three basic capabilities:

- **Practice** – the overall task or function that is to be performed. For example, monitor the surrounding environmental conditions or monitor the proximity of a worker on foot to an active piece of equipment.
- **Competency** – the knowledge needed to perform the task or function. For example, before the technology can assess whether the level of carbon monoxide in an enclosed space is above the permissible limit, it needs to know what level of carbon monoxide is permissible.
- **Skill** – the physical abilities needed to perform the task or function. Using the carbon monoxide example, the technology must be able to sample the air within the enclosed space.

As an example of these basic capabilities, Figure 4 illustrates the relationships among the capabilities of a stress watch. A person wears a stress watch to monitor their stress level, and the watch alert its user if that stress becomes elevated. RT-382 conducted similar assessments for the other technologies it identified, as well.

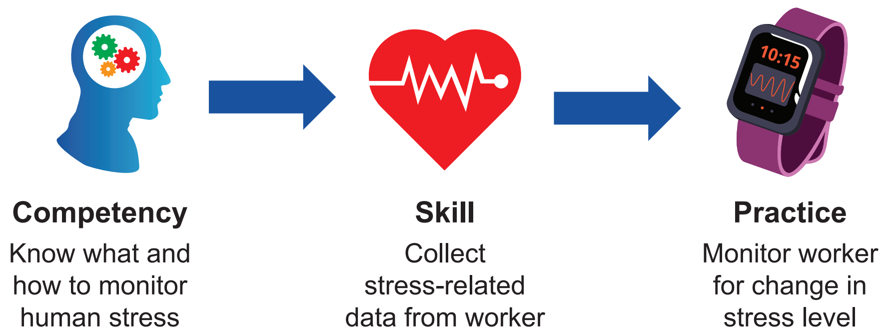

Figure 4. Example: Capabilities Needed and Provided by a Stress Watch

Construction workers continually comprehend and react to their environment as they go about performing their work. Possessing this ability is especially important amid complex and changing surroundings that present safety and health hazards. Construction work often requires field workers to perform their work next to hazards, such as live traffic or operating machinery, leading edges on elevated structures, and confined spaces. In all cases, when a change in the environment or operations occurs, workers progress through a common cognitive process with respect to the change. Figure 5 depicts this chronology related to a worker's interaction with change.

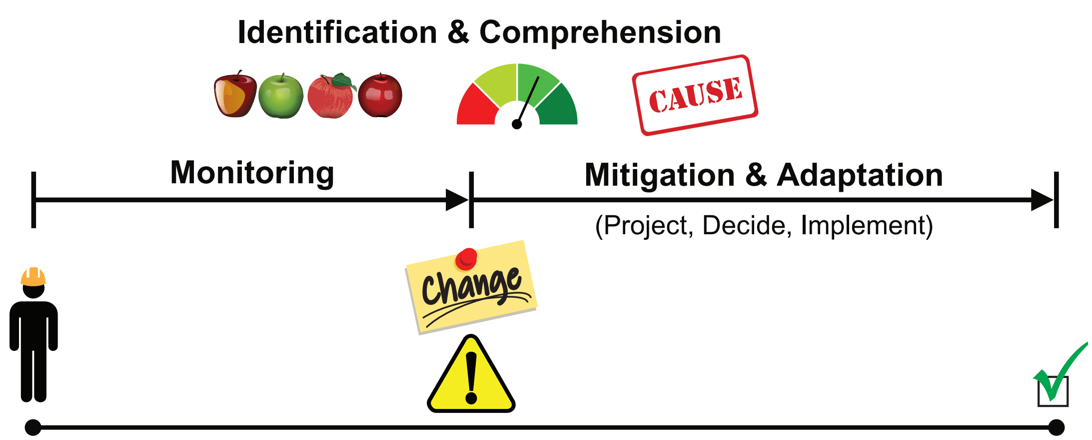

Figure 5. Change Chronology

The chronology begins with monitoring. Workers are continually monitoring their work environment and work operations for potential issues that may affect performance of the work. Then, when a change in the work environment or operations arises, the workers identify that something is different and seek to comprehend the change and its cause. The next step is determining whether and how to react. The workers project the potential outcome(s) of the change, decide whether to act and, if so, how to act. Finally, the workers then implement the selected action. Depending on the action selected, in some cases this last step constitutes mitigation of the last-minute change, while in other cases the workers adapt to the changed conditions (i.e., adaptation).

Situational awareness is an important skill for workers exposed to hazards. This skill is especially important when the workers are under stressful conditions that may distract from clear decision-making. Endsley and Smith and Hancock stated that “safety is optimized when situational awareness is maximized throughout the project network” (Endsley, 1995; Smith and Hancock, 1995). The ability to effectively perform the situational awareness process is vital to people who work on construction sites, and there are three levels to situational awareness:

1. **Detection** involves hazard recognition – detecting hazards in the surrounding environment.
2. **Comprehension** synthesizes disjointed stimuli through pattern recognition, interpretation, and evaluation.
3. **Projection** makes decisions amid uncertainty. It involves the ability to correctly forecast the future actions of the stimuli by extrapolating knowledge of past situations.

RT-382 conducted a more detailed analysis of each identified technology to determine the extent to which its capabilities can perform each of the different situational awareness levels. To perform this assessment, the researchers developed a table for each technology that identified the capability requirements (i.e., practice, competencies, and skills) for each situational awareness level (i.e., change identification, change comprehension, projection, and decision). Tables 3 and 4 on the next page give examples of these assessments for the stress watch and a proximity warning system, respectively.

RT-382 created similar tables for all of the identified technologies. These tables served two important purposes:

- Providing a detailed assessment of the potential for each technology to mitigate safety impacts due to last-minute changes
- Exposing the capabilities where that promise lies within the context of last-minute change

Table 3. Example: Mapping Technology Capabilities to Situational Awareness Levels for a Stress Watch

Technology Capability	*1. Change Identification*	*2. Change Comprehension*	*3. Projection*	*4. Decision*
Practice	Monitor worker's stress.	Determine whether stress is high or low.	Analyze risk.	Determine whether to alert worker.
Can it be performed at the last minute?	*Yes*	*Yes*	*Yes*	*Yes*
Competency	Know what and how to monitor stress.	Know what a high stress level is.	Information about worker, how stress level affects them	Know criteria for when worker should be notified.
Can it be performed at the last minute?	*No*	*No*	*No*	*No*
Skill	Collect stress-related data.	Consult computer program.	Run the computer algorithm.	Make a noise or vibrate the watch.
Can it be performed at the last minute?	*Yes*	*No*	*Yes*	*Yes*

Table 4. Example: Mapping Technology Capabilities to Situational Awareness Levels for a Proximity Warning System

Technology Capability	*1. Change Identification*	*2. Change Comprehension*	*3. Projection*	*4. Decision*
Practice	Detect whether worker is close to moving equipment.	Determine whether worker is in unsafe location.	Determine risk associated with distance between worker and equipment.	Determine whether to alert worker and/or equipment.
Can it be performed at the last minute?	*Yes*	*Yes*	*Yes*	*Yes*
Competency	Know how to measure distance between worker and equipment.	Know what constitutes an unsafe location.	Determine what will happen if distance between worker and equipment is unsafe.	Know criteria for when worker and equipment operator should be notified.
Can it be performed at the last minute?	*No*	*No*	*No*	*No*
Skill	Identify the radio frequency tag on the worker.	Identify size and location of unsafe zones, and worker location.	Conduct risk analysis.	Emit an audible alarm on both worker and equipment.
Can it be performed at the last minute?	*Yes*	*No*	*Yes*	*Yes*

RT-382 could then use these assessments to determine whether to pursue each technology further as part of the research scope. The tables also highlighted gaps in a technology's capabilities, where further development would be needed or other technologies could be integrated to increase the studied technology's readiness for implementation, and thus that technology's value to the user.

Returning to the stress watch example from Figure 4, Table 3 shows the technology capabilities required for a stress watch to perform the practice of monitoring a worker's stress level. The competency needed to perform this task is knowledge about what and how to monitor stress. Lastly, the skill needed is the ability to collect stress-related data. As the evaluation continues, it steps through other practices, competencies, and skill capabilities that are associated with change comprehension, projection, and decision. Table 4 applies the same analysis to consider the technology capabilities of a proximity warning system.

Each assessment includes a determination of whether the capability was applicable to last-minute changes (i.e., could the capability be performed at the last minute):

- In these two cases, the practice could be performed at the last minute to respond to a last-minute change.
- However, the competency required for each situational awareness level had to be programmed into the technology beforehand and thus could not be attained at the last minute.

The next chapter considers last-minute changes in greater depth.

Chapter 3: Last-minute Changes and Safety

Many of the technologies described in the previous chapter have been identified as a means to improve safety. In fact, innovation in the construction industry has resulted in the development of a variety of technologies that improve safety training, protect workers from hazards, remove workers from hazardous exposures, enhance hazard identification and risk assessment, and enable more efficient contractor coordination and work planning. For the present study, two questions remained to be explored: the extent to which last-minute changes are related to SIFs, and the ability of technologies to mitigate the impact of the last-minute changes that lead to SIFs.

To explore these questions, the researchers conducted detailed analyses of SIF incidents in the construction industry. The team's analyses employed reviews of fatality cases reported in the Fatality Assessment and Control Evaluation (FACE) Program overseen by the National Institute for Occupational Safety and Health and the accompanying state FACE Programs. To ensure that the cases reviewed for the study were representative of the current types of construction projects undertaken, construction work processes employed, and technologies utilized, the researchers limited these FACE Program cases to incidents that occurred after the year 2000. (This chapter provides a summary of the results of this analysis. Appendix C offers detailed descriptions of the FACE Program cases included in the analysis and the protocol used to conduct that analysis.)

It should be noted that the FACE Program targets cases involving confined spaces, electrocutions, machine-related incidents, falls from elevation, working youth, logging, deaths of foreign-born workers, and energy production. Therefore, the results may be skewed to favor fatality incidents associated with these types of projects and conditions. Also, while the incident cases involve fatalities, the incidents may also have resulted in serious injuries to other workers. RT-382 was not able to identify a similar database of solely serious injury incident reviews, either publicly or privately available, that contained sufficient detailed information to make similar judgments about whether last-minute change were associated with the cases.

3.1 Connection of Last-minute Changes to Safety

3.1.1 Change as a Cause of Fatalities

In its review of the FACE Program cases, the team attempted to determine whether each incident involved a change. In many cases, the level of detail in the FACE reports enabled the researchers to make such a determination; however, in some reports, the information was insufficient to tell whether the incident was caused by or involved a change. As Figure 6 shows, the team found that 41% of the 179 cases reviewed involved a change on the project (any type of change, not strictly last-minute changes). Another 28% were identified as not involving a change, and too little information was available in the rest of the cases (31%) for the team to determine whether the incident involved a change. The resulting percentages are conservative; if more detailed case information were available, the percentage of cases that involved a change could have been higher.

3.1.2 Characteristics of Changes in Fatality Incidents

Beyond considering the relationship between changes and safety, RT-382 assessed multiple other aspects related to the changes that were associated with each fatality incident. An analysis of fatality incidents that occurred because of a change (73 of the 179 cases reviewed) revealed details about the nature of these changes. Table 5 shows the prevalence of different change characteristics. (The case review rubric in Appendix A has the team's definitions for each characteristic.) As the table shows, a large percentage (52 of 73 cases, or 71%) of the changes was classified as last-minute. Additionally, many of the changes likely could not have been anticipated or recognized before the incident, but could have been avoided. These results, along with the findings of previous research related to worker pressure and improvisation, support RT-382's motivation to focus on last-minute changes and suggest that there is promise in being able to avoid the changes.

The team also focused on the origin of each change and its connectivity to the worker. For example, the connectivity would be high if the injured worker experienced the change directly. Low connectivity could occur based on physical distance, time difference, or other types of separation. When it reviewed the FACE Program cases, the team evaluated the level of connectivity of the workers involved in the incident. They used a simple scale of low, medium, or high connectivity. Figure 7 shows the results of this analysis. High connectivity between the affected worker and the change was present in approximately half (50.7%) of the 73 cases that involved a change.

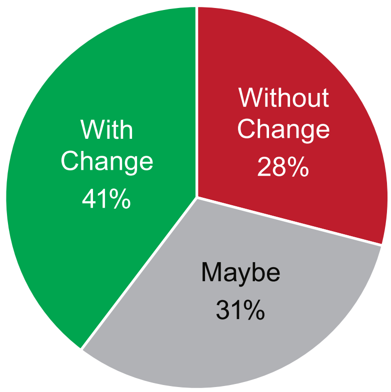

Figure 6. The Relationship between a Fatality Incident and Occurrence of a Change on FACE Program Cases (n = 179)

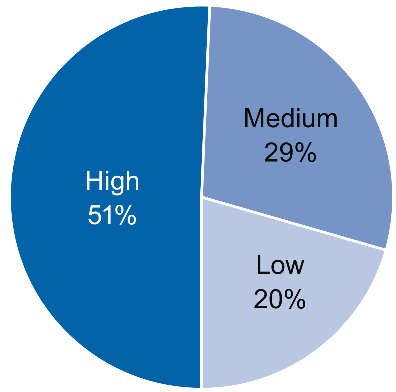

Figure 7. Connectivity between the Affected Worker and the Change

Table 5. Nature of FACE Program Cases that Originated from a Change (n = 73)

Change Characteristic	Percentage of Cases with Changes	
	With	**Without**
Potentially anticipated	28%	**72%**
Potentially recognizable	37%	**63%**
Potentially avoidable	**82%**	18%
Last-minute change	**71%**	29%

In their reflections on changes that had occurred in their companies and organizations or on their projects, RT-382 members identified multiple instances of change. The team categorized the types of these reported changes into the following broad categories:

- Health-mandated restrictions (e.g., COVID-19 social distancing)
- Material or component conditions (e.g., electrical circuit not terminated)
- Environmental conditions (e.g., unusually extreme weather)
- Equipment malfunction
- Personnel availability and capabilities (e.g., sudden workforce reduction)
- Delivery or supply interruption

The researchers' review of FACE Program cases revealed similar categories of change. Figure 8 shows the prevalent types of changes across the FACE Program cases that occurred as a result of a change. The figure includes both changes that were considered to be last-minute and other changes that did not occur at the last minute. As can be seen in the figure, for those cases in which the fatality was caused by a change (n = 73), the type of change was predominantly equipment-related. Equipment usage and worker/equipment path were factors in 32 of the 73 incidents (43.8%). A high percentage (20.5%) of the fatalities occurred due to a change to the planned work process (i.e., a change in the planned method of construction).

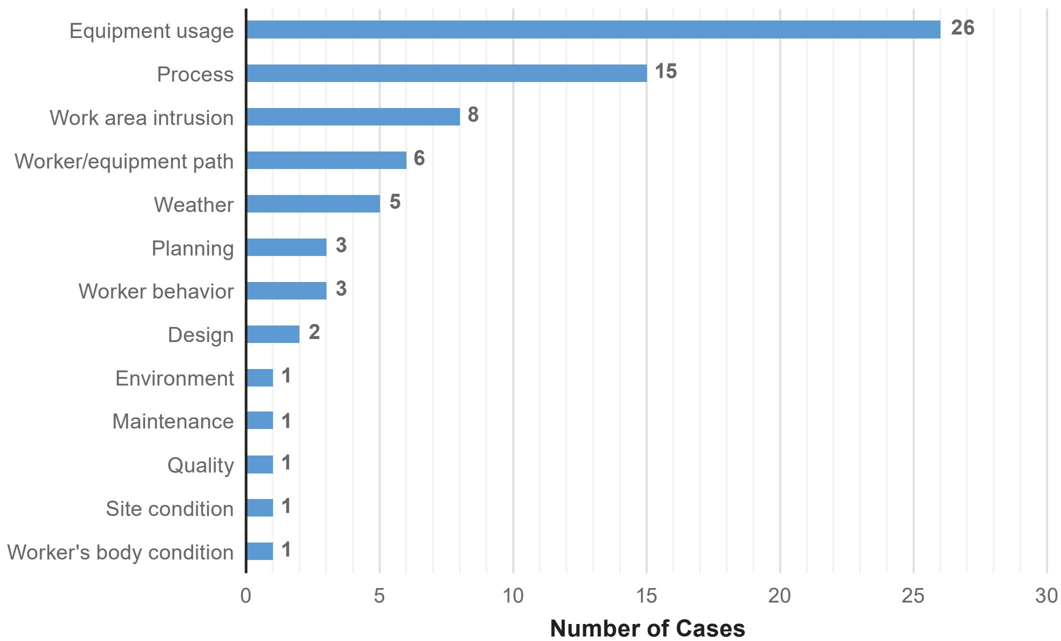

Figure 8. Types of Changes Related to Fatality Incidents

As the FACE Program cases reported, the impact of changes was ultimately one or more worker fatalities, and other impacts could result from changes. For changes that occurred in their organizations or projects, team members noted the following types of impacts, many with direct correlation to the causes of injury and fatality incidents:

- New, unexpected hazards
- Known hazard became uncontrolled
- Less time or resources for safety
- Training no longer adequate or applicable
- Work plan no longer effective
- Presence of less experienced or new employees
- Experienced workers overworked
- Delays caused schedule pressure
- Confusion or incorrect assumptions
- Different equipment needed
- Traditional methods of planning and communication were no longer possible

Prior research has investigated the connection between hazard energy type and worker injuries and fatalities (e.g., Albert et al., 2014). Energy was present in different forms, including gravity, electrical, mechanical, motion, biological, chemical, pressure, and temperature. The prevalence of injury/fatality incidents and of last-minute changes may vary depending on the type of energy associated with the incident. In addition, the applicability of technologies to the last-minute changes may correlate to the energy type. Thus, the research team explored the extent to which each type of energy was present in the FACE Program cases and related to the fatality incident. Table 6 shows the results of this analysis.

Table 6. Type of Energy Involved in a Fatality Incident
(Percentage of FACE Program Cases; n = 179)

Motion	50%	Mechanical	2%
Gravity	40%	Biological	1%
Chemical	4%	Pressure	1%
Electrical	2%	Temperature	1%

Of the 179 cases reviewed, the majority of cases (50%) involved motion (e.g., a change in physical position or location of an object or substance, such as traffic, mobile equipment, projectiles, and dust particles) and a large percentage (40%) were attributed to gravity (e.g., falls and dropped objects). It is important to note again that the FACE Program targets cases involving confined spaces, electrocutions, machine-related, falls from elevation, working youth, logging, deaths of foreign-born workers, and energy production. The prevalence of energy types associated with the fatality incidents will be affected, in part, by the characteristics of the fatality incidents targeted in the FACE Program.

3.2 Promising Opportunities for Eliminating SIFs Due to Last-minute Changes

An important consideration for this study was the extent to which the last-minute change that occurred could have been prevented and/or mitigated through the application of a technology. The use of technologies to mitigate the safety impacts of last-minute changes may not be possible if the technologies available are not related or applicable to the predominant types of last-minute changes that occur on construction projects. Furthermore, some technologies may be particularly effective simply because they can prevent or mitigate common types of changes and/or many different types of changes.

As part of their evaluations for the 73 FACE Program cases that involved a change, the researchers attempted to identify technologies that, if implemented, could have prevented the change. The team considered technologies it had identified during the previous study tasks. In many FACE Program cases (57.5%), the details of the case were insufficient to identify an applicable technology, or no technology on the developed list was related to the change. However, in 31 of the 73 cases (42.5%), a technology could be connected to the change. The technologies that were found to be most applicable were proximity warning systems (32.3% of the 31 cases with connection to a technology), autonomous vehicles/unmanned ground vehicles (22.6%), and work zone intrusion alert technologies (19.4%). These results are consistent with the high prevalence of changes related to equipment usage and worker/equipment path. Sensors that monitor weather conditions and provide alerts to the workers are another type of technology that could be connected to the changes that occurred in the FACE Program cases reviewed.

During the FACE Program case reviews, the researchers also considered the extent to which technology could perform the situational awareness levels associated with the identified change. As mentioned previously, the situational awareness levels describe the actions and decisions that are required when encountering a new situation. When tailored to decisions related to change, the levels can be expanded as follows:

- **Level 1 – Change Identification**: The ability to detect a change to the current state
- **Level 2 – Change Comprehension**: The synthesis of disjointed stimuli through recognizing, interpreting, and evaluating the change event
- **Level 3 – Projection**: The ability, based on previous experience and knowledge, to properly predict the future due to the change
- **Level 4 – Decision**: Making the decision to address or mitigate the change
  a. Decision to alert
  b. Decision about action to take
- **Level 5 – Implementation**: Undertaking the action selected

For each FACE Program case it reviewed, the team assigned a rating based on the technology's ability to perform each situational awareness level. The ratings ranged from 0 (not applicable) to 1 (very low applicability) to 5 (very high applicability). Figure 9 presents the results of the team's assessment of FACE Program cases involving a change (n = 31). The technologies applicable to the change predominantly had the ability to identify that a change had occurred and to emit an alert for the presence of a change. Proximity alert systems on heavy equipment are an example of a technology that can identify the presence of a change (i.e., a worker is too close to the equipment) and convey an alert (i.e., notify the equipment operator and possibly the worker). The technologies were able to make a decision to take action, but could actually undertake the action to a much lesser extent. For example, after the proximity alert system emits an alert, that system may not be capable of taking action to control the equipment to

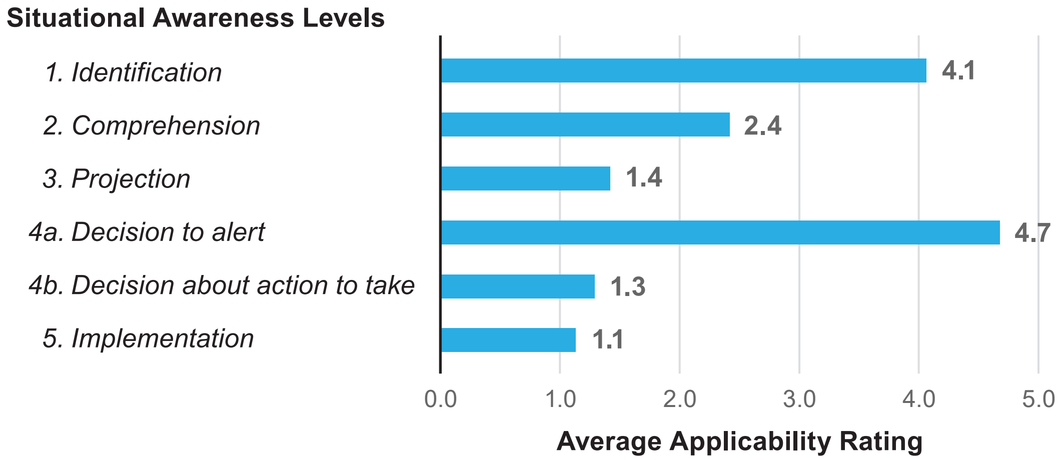

Figure 9. Technologies' Ability to Perform the Situational Awareness Steps Associated with a Change

avoid contact with the worker; the equipment operator must respond and take action. The third phase of this research study (Tasks 6 and 7) involved the selection and in-depth evaluation of promising technologies to mitigate the impacts of SIFs due to last-minute work changes. Initial study efforts were successful in providing a list of available technologies and their ability to address last-minute change, along with important considerations when deciding whether to adopt a technology for use in practice. RT-382 desired to identify one or two types of technologies to investigate further. To do so, the researchers conducted focus group assessments of the selection criteria and technology types using the Delphi method.

The team conducted two Delphi studies, as described in the research methodology provided in Appendix A. The surveys focused on the following selection criteria:

- **Cost** – The initial purchase and long-term operation and maintenance costs of the technology
- **Extent of development** – The extent to which the technology is currently fully developed and ready for use
- **Extent of current use** – The extent to which the technology is currently used throughout the construction industry
- **Effectiveness** – The effectiveness of the technology in eliminating and/or mitigating changes that could lead to a serious injury or fatality (SIF)
- **Level of automation** – The extent to which the technology can perform the desired task and decision-making in place of a human
- **Ease of use** – The extent to which the technology can be implemented with current worker capabilities and resources
- **Type of control** – The type of safety control based on the hierarchy of controls: Elimination, Substitution, Engineering, Administrative, or PPE

The surveys used a scale of 1 to 5 to rate the importance of the selection criteria, where 1 was not important and 5 was extremely important. Table 7 shows the results of all three rounds of the Delphi survey. The table shows the median ratings for each selection criterion in terms of its importance to the selection of technologies for implementation in practice. **The experts placed the greatest importance on technology effectiveness, followed by cost and ease of use.** The group did not reach consensus on the importance of extent of development and type of control as selection criteria.

Table 7. Importance of Technology Selection Criteria

Selection Criteria	Importance Rating (median)	Group reached consensus?
Effectiveness	5	Yes
Cost	4	Yes
Ease of use	4	Yes
Extent of current use	3	Yes
Level of automation	3	Yes
Extent of development	3	No
Type of control	3.5	No

The team conducted a second Delphi study to correlate types of technologies with each of the seven technology selection criteria. The team followed a three-round process similar to one it had used for the first Delphi study, using a scale of 0 (not applicable) to 1 (low applicability) to 5 (very high applicability). Table 8 shows the results of the two Delphi studies.

The ratings were quite consistent across the different types of technologies, with the median selection criteria ratings ranging from 2 to 4 for each technology. With regard to which selection criteria are predominantly addressed by the technologies, ease of use and extent of development received the highest ratings (median rating = 4 for both criteria). Level of automation was also rated highly for all of the technologies (median rating = 3.83). (Chapter 5 of this report gives further information about levels of automation.)

Table 8. Relationships between Technology Selection Criteria and Technology Types in the Delphi Studies

Technology Selection Criteria	Delphi Study 1: Selection Criteria Importance Rating (median)	Delphi Study 2: Applicability of Selection Criterion to Technology Type (median rating)						
		Sensors for monitoring surrounding site conditions	Sensors for tracking worker location on a jobsite	Sensors for assessing worker physiological status	Telematic systems for reporting vehicle/ equipment conditions and use	Telematic systems for reporting operator conditions and actions while operating equipment	Work area monitoring and alert systems	**Average technology rating**
Effectiveness	5	4	4	4	3	4	3	**3.7**
Cost	4	3	3	3	3	3	3	**3.0**
Ease of use	4	4	4	4	4	4	4	**4.0**
Type of control	3.5*	2	2	2	2	2	2	**2.0**
Extent of current use	3	2	2	3	3	2	2	**2.3**
Level of automation	3	4	4	4	4	3	4	**3.8**
Extent of development	3*	4	4	4	4	4	4	**4.0**
** Weighted average *(selection criteria with consensus only)*		13.2	13.2	13.8	12.8	12.6	12.2	
** Weighted average *(all selection criteria)*		12.1	12.1	12.6	11.9	11.7	11.4	

* Consensus was not reached among panelists.

** Weighted average = $\frac{\Sigma(\text{Selection criteria important rating}) \times (\text{Technology rating})}{\text{Number of selection criteria}}$

Worker-Equipment Proximity Alert Technologies

One promising category of technologies was ones that monitor the proximity of humans to hazards associated with moving equipment. The results described above indicate that a high percentage of worker fatalities are related to changes associated with equipment usage and worker-equipment path. Worker-equipment proximity technologies are readily available and have been implemented successfully in some sectors of the construction industry. RT-382 identified seven example types of technologies within this category that have applicability to mitigating the impacts of last-minute changes. Table 9 shows the features and capabilities of each of these seven types of technologies. All of the technologies have been developed and are commercially available. Some of the technologies are presently being implemented in the industry, either as a feature on new equipment or as an add-on to existing equipment.

RT-382 conducted in-depth evaluations of each of the seven technologies using an online survey of experienced equipment operators, as described in Appendix A. The survey results revealed that the respondents are not currently using most worker-equipment proximity technologies. For all of the technologies except the parking package with 360° camera, more respondents indicated that they currently do not use the technology than those who indicated they use the technology. However, for all of the technologies, the majority of respondents indicated that they planned to use the technology in the future.

Table 9. Example Worker-Equipment Proximity Alert Technologies

Type of Technology	Features	Capabilities
Real-time Proactive Radio Frequency Warning and Alert Technology	Wearable device for workers and monitoring device installed on equipment to warn the operator and worker if the worker is close to the equipment.	Detects the RFID tag on both the personal protection unit (PPU) and the equipment protection unit (EPU). If the two tags are within a specified distance apart, the system will alert both the worker who wears the PPU and the operator of the equipment.
Blind Spot Assist	A device installed on heavy equipment to warn the operator if there is an object in the blind spot of the equipment.	Notifies equipment operator that there is an object in the blind spot of the equipment.
Equipment Anti-Collision System	A device installed on heavy equipment to warn the operator if there is another piece of equipment or object that is in the equipment's path.	Notifies the equipment operator that there is an object close to the moving equipment or the moving equipment is approaching objects.
Parking Package with 360° Camera	An assist system that includes multiple cameras on the equipment to allow the operator to see the physical environment surrounding the equipment when performing specific maneuvers.	Provides a visual screen showing the physical environment surrounding the equipment to the equipment operator.
Active Brake Assist	An assist system that is installed on heavy equipment to stop the equipment when it is about to hit an object or worker.	Monitors the space in front of the equipment and stops the equipment when the equipment may strike a worker or object.
Reflective Material Sensor	An assist system that can be installed on equipment to let the operator know that there is a worker(s) or objects close to, or in the path of, the equipment.	Monitors the surrounding area for the presence of reflective apparel/tape and provides an alert to the operator when the equipment may strike a worker or object.
Computer Vision-based System	An assist system that includes multiple cameras on heavy equipment to allow the operator to see the physical environment surrounding the equipment.	Provides a visual screen that shows the environment surrounding the equipment to the operator.

When asked their opinions about the technologies' effectiveness at detecting last-minute changes in proximity of workers to equipment, the respondents predominantly gave the technologies high marks. Using a scale from 0 = not effective to 5 = extremely effective, the median rating for all technologies was 4.0 (very effective), except for computer vision-based system which received a median rating of 3.0 (moderately effective). The respondents also provided input on the drawbacks and barriers that limit the effectiveness and applicability of the technologies. Figure 10 below shows their responses for each technology with respect to different drawbacks or barriers. Purchase cost is viewed as the greatest drawback or barrier to technology use.

The survey asked participants about which important factors to consider when deciding whether to adopt a technology. The most commonly cited factors were technology reliability, proven technology effectiveness, and complexity of technology. Technology brand and technical attributes and features included were the least cited factors. Figure 11 at right shows the results.

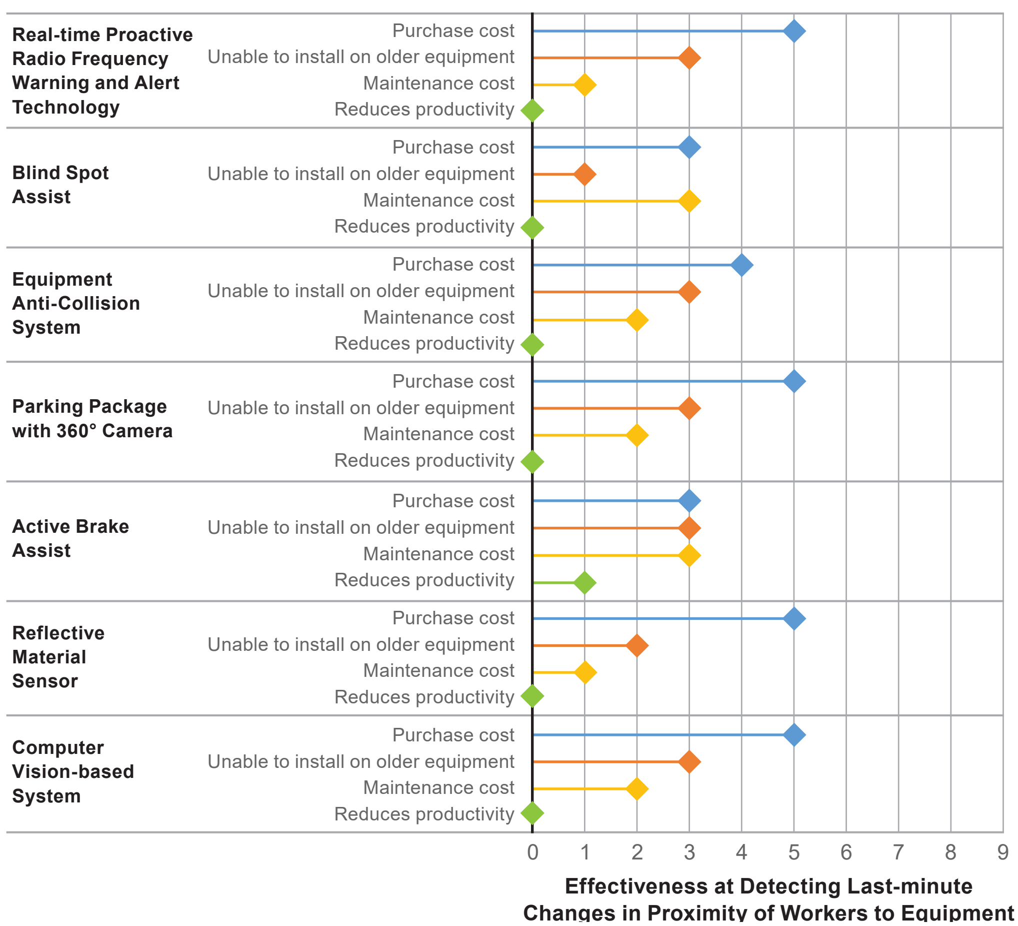

Figure 10. Equipment Operator Perspectives of Drawbacks and Barriers to Using Technology to Detect Last-minute Changes in Proximity of Workers to Equipment

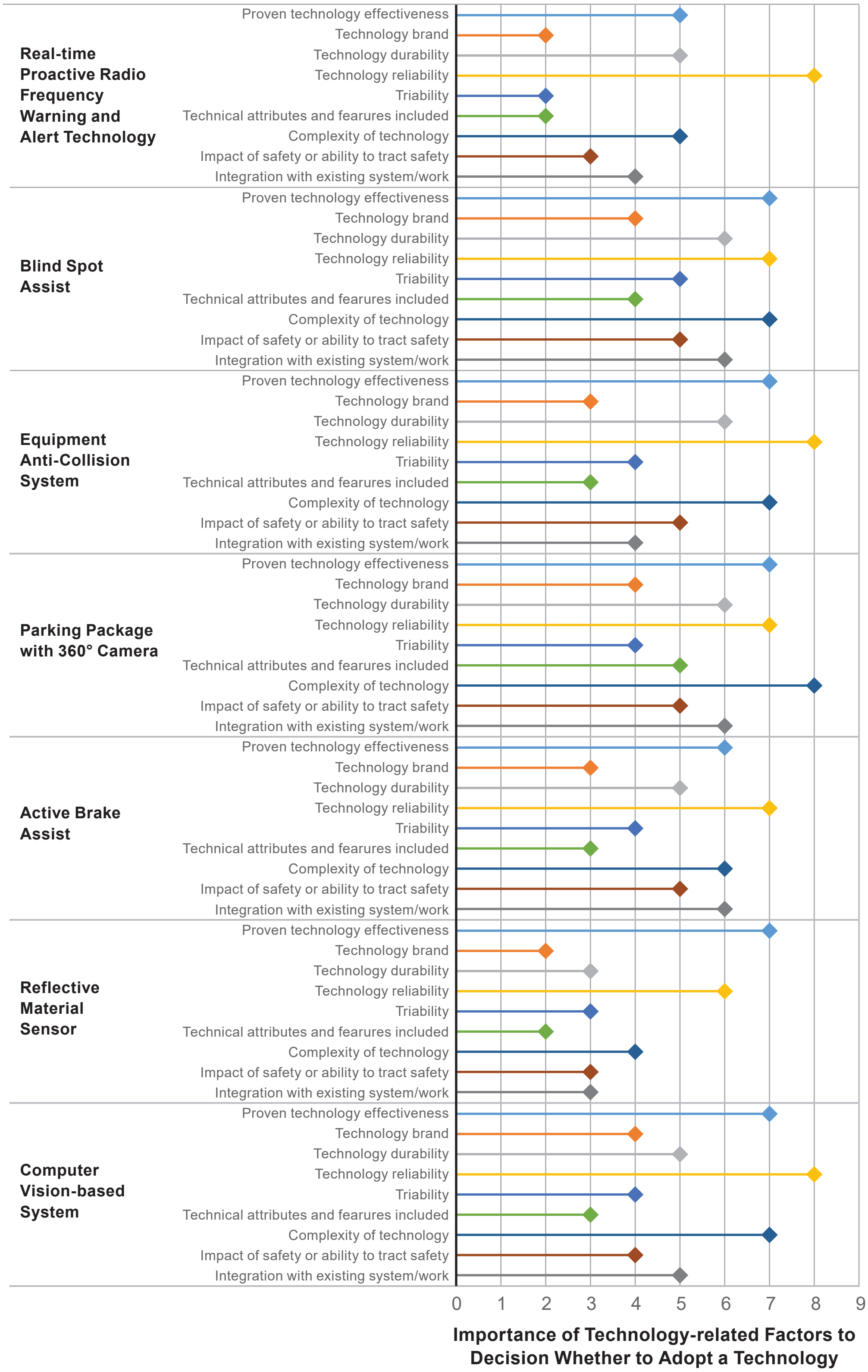

Figure 11. Equipment Operator Perspectives of Technology-related Factors to Consider When Deciding Whether to Adopt a Technology

Similarly, with respect to which user-related factors to consider when deciding whether to adopt a technology, ease of use was the factor most commonly cited. Other user-related factors (e.g., training required, level of individual innovativeness, and technical capabilities of users) were identified less often as important factors to consider. Figure 12 shows the details.

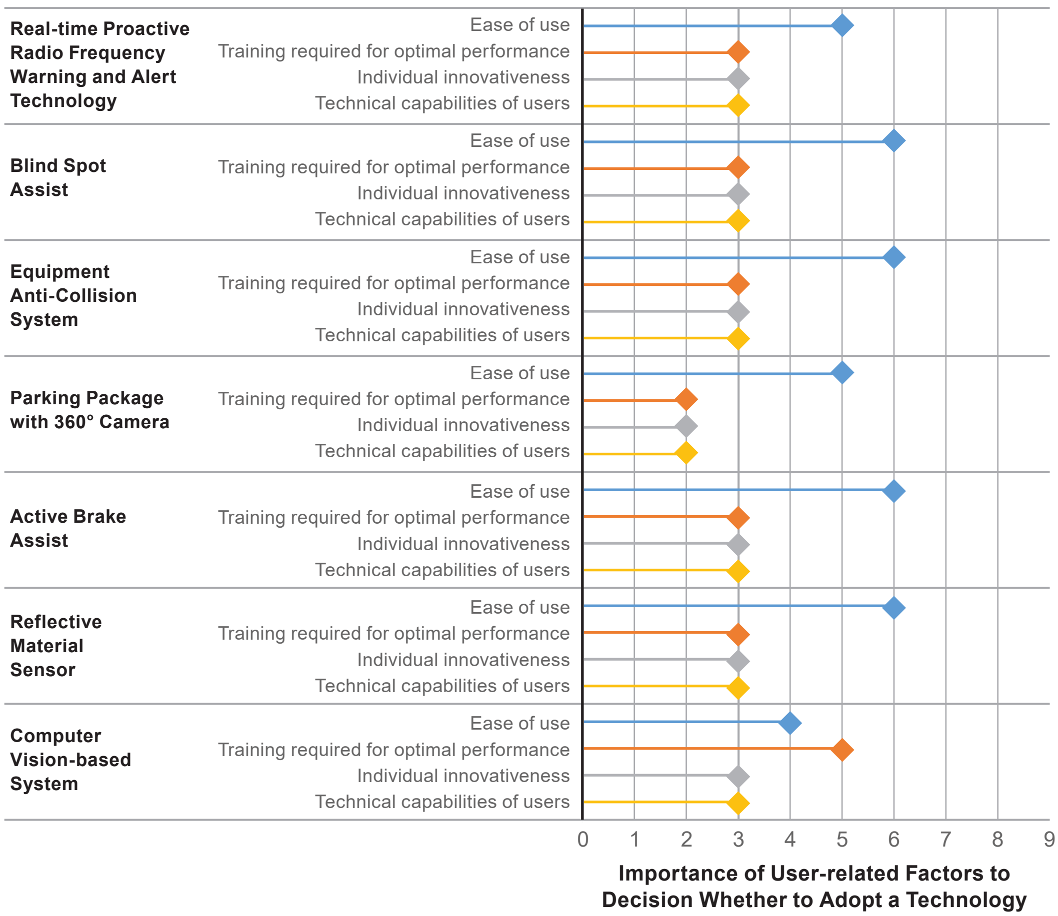

Figure 12. Equipment Operator Perspectives of User-related Factors to Consider When Deciding Whether to Adopt a Technology

Work Process Change Monitoring Technologies

The second target category of technologies identified by RT-382 as promising consists of intelligent ("smart construction") technologies that monitor and mitigate changes in the planned work process. As described above, the review of fatality cases revealed that many fatalities occur due to a last-minute change in the planned work process. This target category includes technologies that can monitor the work process, identify a change to the planned process, interpret whether the change poses a safety risk to the workers, and alert the workers of the potential risk. Performing all of these functions is challenging, especially in real time. Artificial intelligence technologies combined with augmented reality, machine vision, and site monitoring systems could perform the needed functionality. At present, such technologies are aspirational; further research and development of existing AI technologies are needed. However, these systems show significant promise for addressing the last-minute changes that lead to SIFs.

Most of the technologies designed for this use case are either still in development or used by only a small number of companies. The technologies are typically not commonplace on construction project sites. Therefore, experience with using these technologies in practice is quite limited throughout the industry. Given these limiting conditions, RT-382 chose to explore these technologies through in-depth presentations by, and team discussions with, the technology manufacturers. While these efforts were fruitful in providing additional information about the technologies, the team could not established the timeframes until their maturity with a high level of confidence. The research process associated with this effort is described in Appendix A. The following list exemplifies technologies that RT-382 evaluated for monitoring work process changes:

- **Digital Transformation Ecosystem** – Creates a Digital Transformation Ecosystem that includes an integration hub, workflow automation, collaboration and engagement, and data security. Uses multiple video cameras located around a site to integrate data from different locations on the site, and then uses the data to alert project personnel of potential concerns and impacts to efficiency.
- **Drone Program** – A drone (remote piloted aircraft system) program used for a variety of operations, including bluff measurements, 3D modeling with geomatics, inspections at height, and collecting thermal imagery of sites. Future goals of the program are remote operations, AI, drone automation, and performing simple operational tasks.
- **AI Site Risk Prediction System** – Contains many functions, such as monitoring workers, PPE use, workers working at height, trench issues, and other site conditions. Uses data collected and analyzed through site monitoring and machine learning to predict potential risks in the future.
- **BIM-based AI Prediction System** – Analyzes a project during each construction phase and predicts likely outcomes and safety risks. Can provide data to create a prioritized action list, project performance summary, and improvement suggestions. Can identify high-risk conditions with different contributing factors, such as fall risks, water risks, and other risk issues. Simplifies the data input, which helps people input real-time data easily. With more data or observations collected, the technology can provide better and more accurate data to the project.

- **AI Site Risk Ranking System** – Analyzes the project scope, location, and schedule and then provides risk rankings from the highest to the lowest risk to the project. Contains a risk engine that can identify specific risks and hazards in the project tasks and provide recommendations for each identified risk and hazard to keep workers safe. Can analyze inputted data and offer improvements to the project. The technology is intended to support frontline supervisors and safety leadership members on construction sites. Customer data is required to make predictions for future projects. After the customer data is input, a model is created that provides predictions and recommendations for potential risks and hazards in the project.

For each technology listed above, following its manufacturer presented at a team meeting, the academics asked the industry members of RT-382 to complete a brief online survey regarding that technology and its application to last-minute changes. A copy of the survey questionnaire is provided in Appendix A.

Responses to the technology surveys revealed that most technologies do not yet have the capabilities to perform all of the steps in the process to mitigate last-minute changes. The technologies can monitor and collect data from sites and present the data to humans for interpretation and analysis, but humans are then required to take action to mitigate the changes. In some cases, the technology can suggest actions to take.

As an example, Figures 13 to 16 summarize the survey responses for the Digital Transformation Ecosystem technology. The figures show the extent to which the factors would be a concern for the technology using a scale from 0 to 5 where 0 indicates that the factor is not a concern, 1 is a factor of minimal concern, and 5 represents significant concern with the factor.

Among the technology-related factors of concern (in Figure 13), team members were most concerned about technology effectiveness and the ability of the technology to impact safety or track safety performance. Similarly, among external-related factors of concern (shown in Figure 15), direct competitors adopting similar technology and use in remote locations received high ratings. The responses for the other technologies presented and evaluated were similar. Technology effectiveness was commonly the highest rated concern among all technologies, while technology brand was rated as the least concern for all technologies.

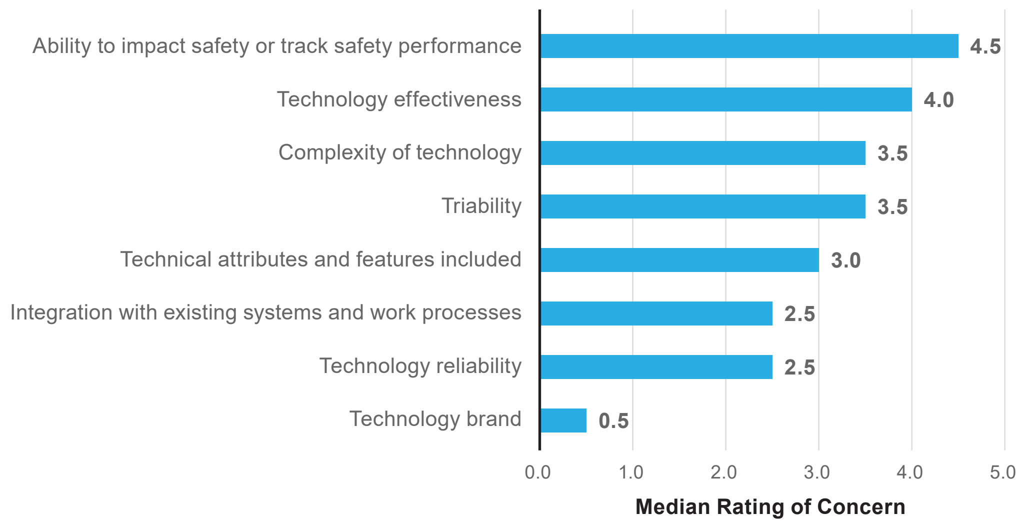

Figure 13. Example: Technology-related Factors of Concern for Digital Transformation Ecosystem

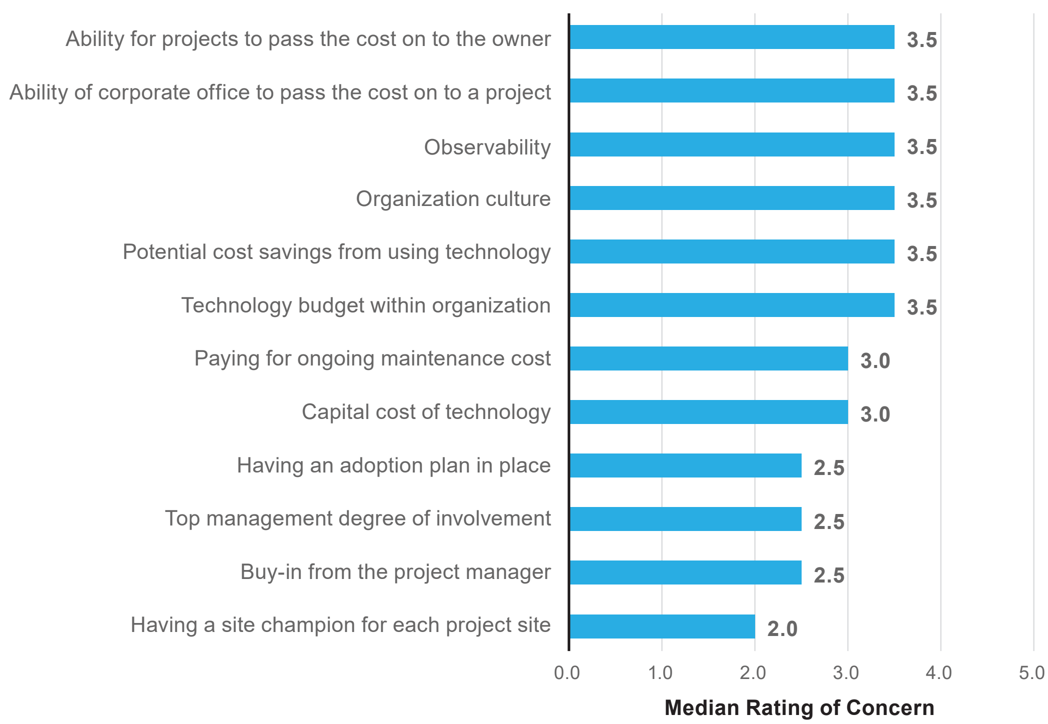

Figure 14. Example: Organization-related Factors of Concern for Digital Transformation Ecosystem

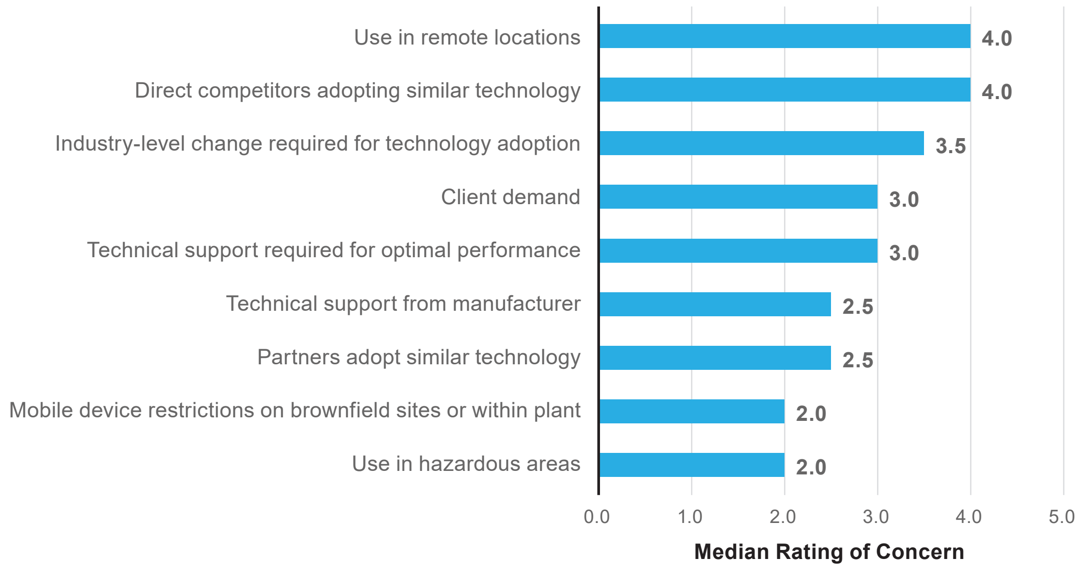

Figure 15. Example: External-related Factors of Concern for Digital Transformation Ecosystem

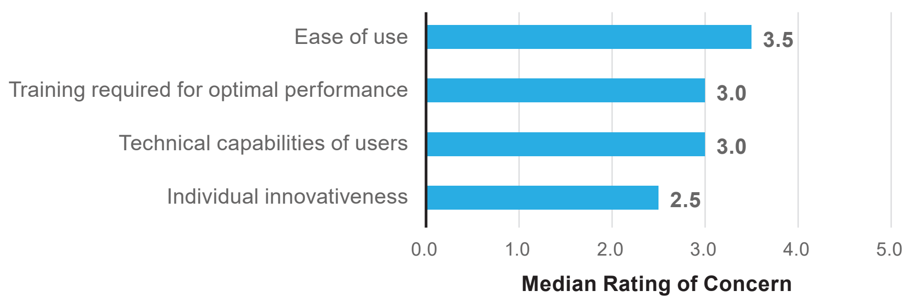

Figure 16. Example: User-related Factors of Concern for Digital Transformation Ecosystem

Chapter 4: Adopting Technologies for Last-minute Changes

The success of a technology is based in part on whether it meets the needs and desires of the organization for its targeted use. Prior to acquiring and implementing a technology, organizations commonly undertake a review process to ensure that adoption of the technology will be beneficial. Technology adoption protocols provide rigorous, objective processes to conduct comprehensive evaluations of technologies and support decision-making regarding adoption of the technology. The protocols commonly rely on the assessment of technology adoption factors, which are key aspects related to the technologies that influence their value to the organization and their likely acceptance and diffusion throughout the organization.

RT-382 worked to develop an adoption protocol that organizations could implement to assess technologies for mitigating the safety impacts associated with last-minute changes. Part of this research process included the identification and valuation of applicable technology adoption factors. Descriptions of the technology adoption factors and protocol are provided below.

4.1 Technology Adoption Factors

Technology adoption factors are indicators evaluated to inform the decision whether to adopt a technology. Adoption factors are typically confirmed by an organization, which then uses them whenever it considers whether to adopt a particular technology.

To identify adoption factors for technologies applicable to last-minute changes, RT-382 began by conducting a literature review to document existing recommended adoption factors. Past research has revealed effective factors. For example, Nnaji et al. summarized 26 key adoption predictors for safety-related technologies using responses from 257 construction practitioners. Those researchers then used statistical methods to identify that 12 out of the 26 predictors were highly influential in the construction industry, with relative importance index (RII) values greater than or equal to 0.8. Table 10 (on the next page) shows the adoption predictors developed by that study (Nnaji et al., 2019).

Table 10. Safety Technology Adoption Predictors (n = 257)
(Adapted from Nnaji et al., 2019)

Key Safety Technology Adoption Predictors	Category	Median Rating	RII*
Technology reliability (technology consistently meets performance requirements)	Technology	5	0.87
Proven technology effectiveness (technical attributes meeting the stated performance requirements)	Technology	4	0.84
Technology durability	Technology	4	0.84
Technical attributes and features	Individual	4	0.84
Level of training required for optimum performance	Individual	4	0.83
Level of technical support required for optimum performance	Individual	4	0.83
Level of complexity of technology	Individual	4	0.83
Level of technical support available by manufacturer	Individual	4	0.82
Client demand	External	4	0.80
Triability (end-user can try technology prior to adopting)	Technology	4	0.80
Observability (end-user can observe performance prior to adoption)	Technology	4	0.80
Organization culture (receptive to change or not)	Organization	4	0.80
Competitive advantage derived from using technology	Organization	4	0.79
Versatility (technology can be utilized for more than one task)	Technology	4	0.79
Potential cost savings from using technology	Organization	4	0.78
Peer influence (how quick users will be able to influence colleagues)	Individual	4	0.78
Top management degree of involvement (championing or opposing technology adoption)	Organization	4	0.78
Level of compatibility with current processes	Organization	4	0.77
Government policy and regulations regarding technology	External	4	0.76
Industry-level change required for technology adoption	External	4	0.76
Potential level of resistance from employees toward technology adoption	Individual	4	0.76
Capital cost of technology	Organization	4	0.74
Direct competitors adopting similar technology	External	3	0.70
Technology budget within organization	Organization	3	0.69
Partners adopt similar technology	External	3	0.67
Technology brand and reputation in the market	Technology	3	0.66

Rating scale:
1 = No Importance, 2 = Low Importance, 3 = Moderate Importance, 4 = High Importance, 5 = Extreme Importance

* RII = Relative Importance Index

Starting with the technology adoption factors that had been identified in prior research, RT-382's academics asked its industry members to give their opinions about the importance of each factor. Specifically, team members were asked to rate each technology adoption factor with respect to its importance in the decision whether to adopt a new safety technology in their organizations. (The rating scale they used is defined beneath Table 10.) The process for rating the factors was implemented during focus group discussions among RT-382 members. In addition, the researchers asked the industry members of the team to add and rate any adoption factors that their organization considered but that were missing from the list.

Table 11 (on the following pages) presents the results of the assessment:

- The importance factors ranged from 1 to 5.
- The following factors received the highest rating (5 = extremely important):
  - Triability
  - Impact on safety
  - Organization culture
  - Degree of involvement by top management
  - Presence of a site champion
  - Buy-in from project manager
  - Client demand
  - Adopted by direct competitors
  - Presence of mobile device restrictions
  - Use in hazardous areas
  - Ease of use
- For the 10 factors in the Technology category, the mean rating was 3.7 (with a range from 2 to 5).
- The mean rating for the 15 factors in the Organization category was 3.7 (with a range from 1 to 5).
- The mean rating for the 13 factors in the External category was 3.5 (with a range from 2 to 5).
- For the five factors in the Individual category, the mean rating was 3.2 (with a range from 1 to 5).
- A team member added one adoption factor to the list – "Multiple technologies competing for attention" – categorized it under Organization and assigned it a rating of 3.

Table 11. Importance of Technology Adoption Factors

	Technology Adoption Factors	Average Rating
Technology	Does the product improve safety or track safety performance?	5
	Triability (Can the user test it out before adopting it? Does the user believe in it?)	5
	Technology reliability (Is it reliable in all locations, including hazardous and non-hazardous situations?)	4.5
	Does the product integrate with my existing systems/work processes?	4
	Technology brand	4
	Proven technology effectiveness (Does it improve the end product and/or the user's ability to perform the work?)	3.5
	Complexity of technology	3
	Technical attributes and features included	3
	Technology durability	3*
	Versatility	2
Organization	Buy-in from the Project Manager	5
	Having a Site Champion for each project site	5
	Organization culture	5
	Top management degree of involvement (Executive support; consistent messaging from executive sponsor)	5
	Capital cost of technology (High initial cost? Commodity prices available?)	4
	Corporate office will not pick up the budget unless they can pass the cost on to a project	4
	Paying for ongoing maintenance cost (Which department or business unit will cover the cost of ongoing maintenance and support of the product and/or infrastructure?)	4
	Potential cost savings from using technology (Tight margins? Difficult to turn a profit or invest in technology?)	4
	Projects will not pick up the budget unless they can pass the cost on to the owner	4
	Technology budget within organization	4
	Having an adoption plan in place (Do not throw technology at them and just expect it to be adopted on its own.)	3
	Observability (Can it be observed before adoption? Does the user believe in it?)	3
	Level of compatibility with current processes	2
	Worker involvement in selection (Were any user-level people involved in the evaluation and selection? Let them have a voice so it does not feel like a top-down decision being pushed upon them.)	2
	Competitive advantage	1

Table 11. Importance of Technology Adoption Factors *(continued)*

	Technology Adoption Factors	Average Rating
External	Client demand	5
	Direct competitors adopting similar technology	5
	Hazardous areas	5
	Mobile device restrictions on brownfield sites or within a plant	5
	Industry-level change required for technology adoption	4.5
	Technical support required for optimum performance	4
	Partners adopt similar technology	3.5
	Remote locations	3
	Technical support from manufacturer (Available? Helpful?)	3
	Extreme weather environment	2
	Government policy and regulations regarding technology	2
	International sanctions	2
	Type of contracting method (e.g., Lump Sum contract)	2
Individual	Ease of use (e.g., complex, heavy, cumbersome, limited visibility, mobility)	5
	Individual innovativeness (“Old school” mindsets; resistance to change)	4
	Technical capabilities of users	3
	Training required for optimum performance	3
	Peer influence	1
Other: Please list other adoption factors considered by your organization		
Org.	Multiple technologies competing for attention	3

* Technology dependent; also first cost

Following its initial assessment of the importance of each adoption factor, RT-382 further investigated the importance of specific factors used to select technologies for implementation. The process began with the academics preparing a short online survey for other team members to complete individually. The survey asked the industry members to rank the importance of 13 selection factors starting with 1 as the highest priority, 2 as the second-highest priority, and so forth down to 13. The 13 factors listed were ones that had been highly rated in the prior adoption factor assessment along with additional important considerations identified by RT-382 related to the study topic, such as the level of automation provided and the type of hazard control.

The results of the survey of specific factors are shown in Table 12 below. It should be noted that a lower average rank indicates higher priority. The highest priority was given to technology cost (average ranking = 4.3 out of 13). Also highly ranked were potential impact on safety (average ranking = 4.4), ability to identify a change (average ranking = 4.7), and ease of use (average ranking = 5.7).

Table 12. Average Priority Ranking of Technology Selection Criteria

Technology Selection Criteria	Average Rank*
Cost	4.3
Magnitude of potential impact on injury (frequency and severity reduction)	4.4
Ability to identify a change	4.7
Easy to use (limited training required)	5.7
Type of incident prevented (e.g., SIF)	5.9
Ability to comprehend a change	6.1
Extent of development	7.0
Extent of current use	7.0
Applicability to last-minute changes	7.1
Ability to project the risk associated with a change	7.9
Level of automation	9.6
Ability to make a decision after a change is detected	10.4
Type of control (PPE, administrative, engineering, substitution, or elimination)	10.9

* Ranking: 1 = highest priority, 2 = second-highest priority, and so forth. A lower value indicates higher priority.

Based on the results of the initial survey, which polled each member individually, the academics decided to give further attention to whether some selection criteria were required while others might be simply desirable. To perform the assessment, RT-382 members were randomly assigned into four breakout groups during a focus group discussion meeting. Each breakout group was asked to discuss and rank each of the 13 selection criteria in terms of its importance, and place the criteria into “must have” and “good to have” categories. The teams were also asked to suggest, rank, and categorize other criteria for the list. Following discussion about the criteria in the small groups, RT-382 conducted a full group discussion about each group’s rankings. The results of the assessments are provided in Table 13 on the next page. All groups identified applicability to last-minute change as a “must-have.”

Table 13. Ranking and Categorization of Technology Selection Criteria

Rank	Group 1		Group 2		Group 3		Group 4	
	Must have	*Good to have*	*Must have*	*Good to have*	*Must have*	*Good to have*	*Must have*	*Good to have*
1	Applicability to last-minute change	Cost	Easy to use		Magnitude of potential impact on injury	Cost	Applicability to last-minute change	Cost
2	Applicable to serious injury and fatality	Easy to use	Applicability to last-minute change		Ability to identify a change	Extent of development	Type of incident prevented; applicability to SIF	Magnitude of potential impact on safety
3	Available today	Make the work more productive	Ability to identify a change		Type of incident prevented	Type of control		Ease of use
4		Higher on the hierarchy of controls	Cost		Ability to comprehend a change			Extent of development
5		Availability at the job location			Applicability to last-minute change			Extent of current use
6								Level of automation
7								Type of control on the hierarchy

Other comments from Group 4:

> "We considered the ability to identify change as the primary determinant of effectiveness. It seems like most technologies either identify that a change has occurred and inform people (e.g., sensors) or remove the people from the environment (e.g., dog robot), but none are available to actually measure and make decisions (e.g., AI)."

> "We thought that the ability to identify, comprehend, and make a decision about change (the situational awareness levels) was all a subset of effectiveness. I would suggest we remove those sub-questions and just use 'effectiveness' and document how and why they are effective/ineffective."

4.2 Technology Adoption Protocol

Similar to the way it developed technology adoption factors, RT-382 worked to develop an adoption protocol that organizations can use to support decision-making when they consider whether to adopt a technology. The aim was to develop a rigorous protocol applicable to the characteristics of last-minute changes and safety, and the steps associated with mitigating the safety impacts associated with last-minute changes.

RT-382 began by conducting a literature search to identify examples of adoption protocols that have been developed to date. The team chose an initial model of a protocol by Nnaji et al. as its starting point. The model protocol included a two-step process: a high-level feasibility evaluation of the technology was conducted, followed by a detailed technology assessment. The detailed assessment focused on four topic areas: organization (business case), individual (technology users), technology (features and functions), and environment (external drivers) (Nnaji et al., 2018).

Building on this initial model, the researchers performed additional literature review and conducted focus group discussions during team meetings to confirm the model and tailor it to the technologies applicable to last-minute changes. As a result of these efforts, the team amended the model protocol in several ways:

- Based on previous literature, the team added a fifth topic area focused on evaluating the technology vendor (Sepasgozar and Bernold, 2013).
- Questions within the vendor topic area focused on vendor support, capabilities, and services provided: does the vendor guarantee technology performance, provide a warranty, offer training, and support implementation needs?
- The team also added an assessment of the technology by pilot-testing it in the field. This actual use of the technology confirms its applicability to last-minute changes: can it respond to last-minute changes in a timely manner, and to what extent can it perform all situational awareness steps?

Figure 17 depicts the final adoption protocol. Successful results for all three evaluation steps would suggest that a technology can be adopted.

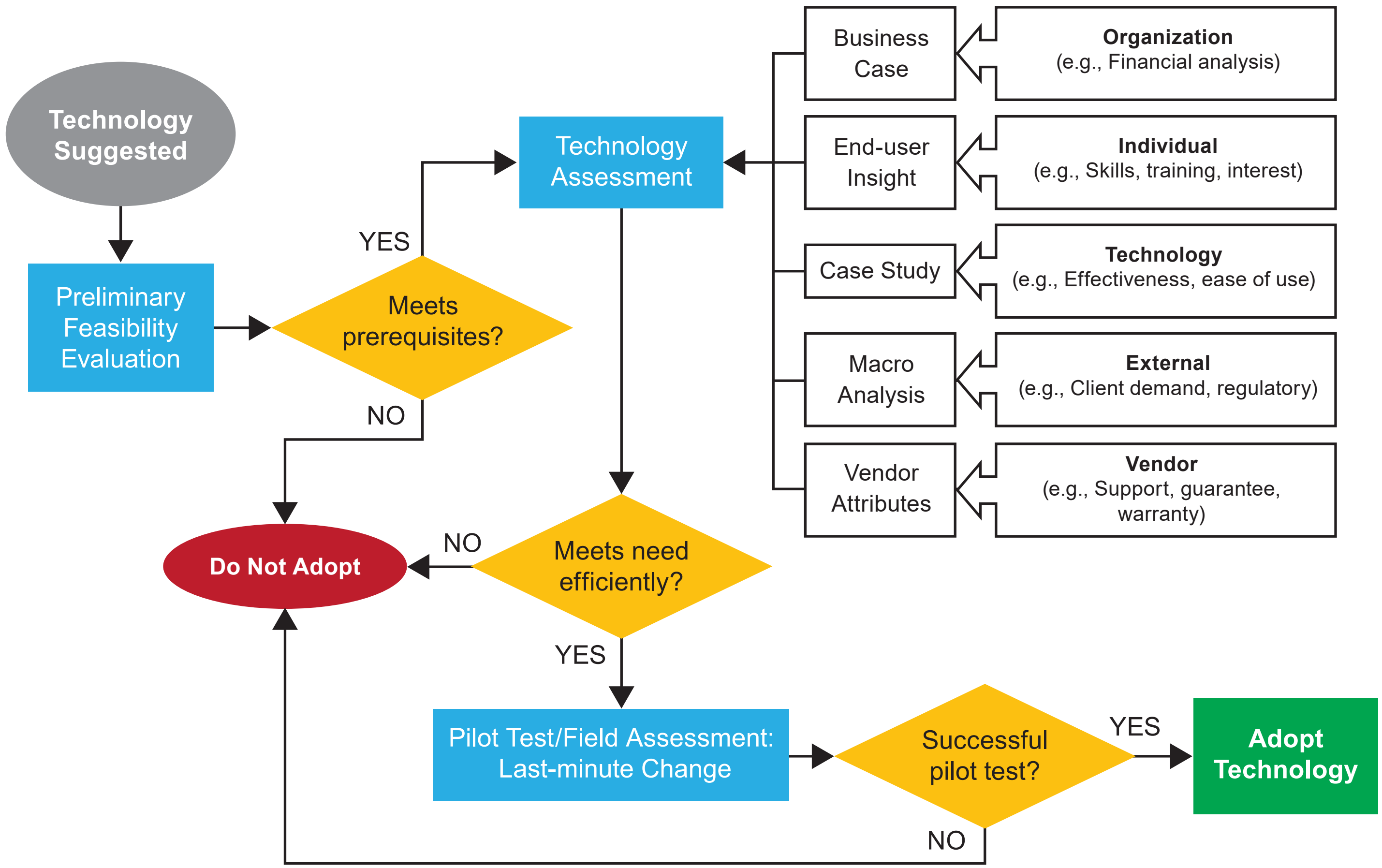

Figure 17. Technology Adoption Protocol to Mitigate Safety Impacts of Last-minute Changes

After a technology has been identified and suggested, the adoption protocol contains three levels of assessment: Preliminary Feasibility Evaluation, Technology Assessment, and Pilot Test/Field Assessment. For each level of assessment, RT-382 developed a checklist of questions. Summary descriptions of the three assessments and corresponding checklists follow. Appendix C describes the research process that developed these checklists, including final versions of the checklists.

1. *Preliminary Feasibility Evaluation*: The research team designed the Preliminary Feasibility Evaluation, as the first assessment conducted, to be a high-level appraisal of the technology after it has initially been identified and suggested as a possibility. This assessment focuses on an initial judgment of whether the technology has the potential to prevent or mitigate last-minute changes, followed by general questions regarding its cost, ease of use, reliability, scalability across the organization, and applicability. The checklist questions ask for a simple Yes/No answer. If the answer to any question is "No," subsequent adoption protocol assessments can be skipped and this technology can be omitted from consideration for adoption.

2. *Technology Assessment*: The assessment checklist for this in-depth assessment of the technology contains 44 questions organized into five parts: organization factors, individual user factors, technology factors, external factors, and vendor factors. Some questions require a simple Yes/No answer, while others ask for a score based on an ordinal scale from –3 to +3 (for Yes/No answers, the researchers arbitrarily chose to assign a value of +3 to Yes responses and a value of –3 to No responses):

   - A negative value on this scale indicates that a technology has a negative impact for that adoption factor.
   - A positive value is associated with that technology's positive impact on the adoption factor.
   - Greater score magnitudes (both positive and negative) indicate greater impacts on the adoption factor.
   - A score of zero indicates no or neutral impact.

   A summary analysis table is provided with this checklist to support analyzing responses to the questions. After answering all of the questions, the **technology evaluator** (the person(s) conducting the technology evaluation) will use this table to determine whether to proceed to the next assessment level. The table uses the number of negative, neutral, positive, and "I don't know" (IDK) answers, along with the total negative and total positive scores, to perform this evaluation:

   - If the total number of IDK factors is high, the evaluation is not valid. The assessment should be conducted again after more information about the technology has been evaluated.
   - If the total assessment score (positive score + negative score) is high, the evaluation proceeds to the Pilot Test, Field Application, and Demonstration

Assessment for further consideration and possible adoption of the technology.

- If the total assessment score is low or negative, the technology should not be adopted.

3. *Pilot Test, Field Application, and Demonstration Assessment*: The last assessment in the protocol involves a pilot test or demonstration of the technology in the field. The assessment assumes that the evaluator would be able to implement the technology in the intended use case(s) conditions and observe how it performs. This assessment checklist includes initial general questions about the technology that can be answered more accurately following the pilot test (e.g., ease of use, readiness, level of automation, and integration with other technologies).

   The checklist then asks questions directed at whether the technology can perform the necessary steps to mitigate last-minute changes: monitor the site conditions and work operations, detect the presence of a last-minute change, alert affected workers, determine potential options to mitigate the last-minute change, select an option, determine whether to implement the selected option, and finally, implement the option. The checklist uses simple Yes/No questions. If the technology can successfully perform all of the intended steps to a desired level, the technology would be adopted, since it has successfully passed all of the assessments in the technology adoption protocol.

   RT-382 performed an evaluation of the pilot test assessment checklist during a team meeting in which multiple technologies were presented and demonstrated. During a visit to the Oracle Industries Innovation Lab, RT-382 was introduced to different technologies then being developed and, in some cases, was given the opportunity to operate them in a laboratory setting. RT-382 observed the following technologies during the lab visit:

   - Site monitoring
     - AI-based site monitoring, data analytics, and risk prediction system
     - Cloud-based connected worker system
   - Wearables
     - Exoskeleton suit
     - Worker location monitoring system attached to a hard hat
   - Robotics
     - Remote-controlled site monitoring robot
     - Remote-controlled overhead concrete drilling robot
   - Virtual reality
     - Construction safety training system
     - BIM-based system for immersive and collaborative design reviews

After being introduced to the technologies, RT-382 completed the pilot test assessment checklist for each: a total of 40 completed checklist assessments for eight technologies. The participants did not offer the team any recommendations for modifications to the pilot test assessment checklist. Their responses did, however, provide insights into the technologies evaluated.

All of the participants deemed all of the technologies ready to use. The average TRL given to each technology ranged from 7.6 to 8.6, with an average of 8.1 per technology. In terms of ease of use, the majority of participants indicated that every technology was easy to use.

While the technologies were designed for different intended purposes, the assessment asked whether every technology could perform each of the steps associated with situational awareness to mitigate last-minute changes. The cloud-based connected worker system and remote-controlled site monitoring were the robot technologies that a majority of participants deemed able to detect a last-minute change; however, only the cloud-based connected worker system was identified as being able to prevent SIFs due to last-minute changes. In fact, the participants felt that only the cloud-based connected worker system had the ability to monitor site conditions and work operations, detect last-minute changes, comprehend safety hazards due to last-minute changes, project the safety risk, and send an alert. None of the technologies was deemed to be able to identify options for mitigating the impacts of last-minute changes, decide which option to select, and implement the selected option.

Chapter 5: Guidance for Future Technology Development and Application

As Chapter 2 described, this study afforded RT-382 a comprehensive perspective of the current state of technologies in the construction industry. The findings reveal a state of practice in which technologies are currently being used to successfully benefit construction, including construction safety. However, taking advantage of present technologies to effectively meet the desired use cases requires some special considerations associated with technology and the human-technology interaction. This chapter describes issues of concern that should be taken into consideration when seeking and adopting technologies to mitigate the safety impacts of last-minute changes, and it provides guidance for the industry to address the concerns.

5.1 Smart Construction Technologies: Artificial Intelligence

Technology has the potential to positively mitigate last-minute changes. In many of the fatality cases studied, the presence of one or more of the technologies identified could have prevented a last-minute change from occurring or mitigated the effects of the change. A variety of technologies exist that could have been implemented. The functional capabilities of the technologies include sensing/monitoring, visualization, communication and mobile computing, automation, site access/site control, and artificial intelligence. Selecting an appropriate technology requires an understanding of the functional abilities of the technology and the capabilities needed to prevent or mitigate change. For example, AI is required for some hardware to reach its potential (e.g., anything with a camera needs computer vision and anything that makes forecasts needs some form of predictive engine such as machine learning). Unfortunately, the development of the AI seems to lag that of the hardware.

Table 14 on the next page presents how the present functional abilities of the different technology categories relate to the steps associated with mitigating last-minute changes. Sensing/monitoring technologies, for example, are designed to monitor the site, identify and comprehend when a change occurs, and issue a notification or warning if the change is potentially hazardous. However, sensing/monitoring technologies at their current level of development typically cannot decide what action to take and when to take the action to mitigate the impacts of the change, nor implement the selected action(s). Some site control/site access technologies are designed with the ability to decide what action to take and whether to implement the action.

For example, an automated flagger assistance device (AFAD) is programmed to change the color of a traffic signal (i.e., red, yellow, or green) and raise or lower a gate arm to allow traffic to enter a work area or prevent access. These abilities have made AFADs quite valuable for controlling access and therefore maintaining safety for motorists, equipment operators, and workers on foot. Other AI technologies provide the decision and implementation functionality, and as a result are quite promising. However, because they lack AI capabilities, many technologies cannot perform all of the functions required to mitigate the safety impacts of last-minute changes.

Table 14. Applicability of Technologies to Mitigation of Last-minute Change

	Situational Awareness Process				
			Mitigate		
Technology Category	**Monitor**	**Identify/ Comprehend**	*Alert*	*Decide*	*Implement*
1. *Communication/ mobile computing*	X				
2. *Sensing/monitoring*	X	X	X		
3. *Visualization*	X	X	X		
4. *Automation*	X	X	X		
5. *Site control/site access*	X	X	X	X	X
6. *Artificial intelligence*	X	X	X	X	X

X = current technology can perform the function on its own.

It is clear from the detailed investigations into multiple types of technologies that AI-based technologies, while quite promising, are limited in their current state. Many "smart" construction technologies aim to improve safety through continuous monitoring followed by assessments of the collected data to determine the presence of potential safety hazards. If hazards are identified, the technology sends an alert to a project manager, superintendent, worker, or other responsible party. Smart construction technologies also typically enable users to review and monitor the collected data themselves to identify trends and instances that could potentially lead to an injury or fatality incident. However, while AI-based technologies can also potentially seamlessly determine what action(s) to take, decide to take the action, and implement the action to mitigate the hazards, the ability to do so with the current level of AI development is relatively absent.

AI-based technologies that have been trained to autonomously mitigate hazards without human assistance are presently not available. The dynamic nature of construction sites and operations, along with the many different conditions, features, and actions that exist on sites, make it difficult to effectively utilize AI capabilities for these actions given current AI technology development. Further development and training of AI technology are needed to fully realize the breadth of possible benefits that AI can bring to the process of mitigating safety impacts of last-minute changes in real time. Until advancements in AI capabilities are attained, use of current AI-based technologies for last-minute changes requires assistance from humans. Organizations should expect that adopting current technology will not completely replace the need for human involvement. The need for humans to assist technology, or technology to assist humans, should be expected at this point in time.

5.2 Cross-technology Integration

Within the list of promising technology categories it identified, RT-382 observed many technologies that relate to construction safety and last-minute changes. Often implemented as single applications, the technologies provide an incomplete solution. That is, these technologies are limited in what they can perform and the extent to which they can communicate and integrate with other technologies. In these cases, multiple applications need to be connected to address an end-to-end business process.

For example, a "siloed" robotic tool may be implemented to eliminate the need for workers to traverse hazardous areas. The robot may not be able to communicate critical information to workers and/or supervisors to track and analyze compliance and changed site conditions. Additionally, the technology may not have the ability to integrate with other technologies that can provide such capabilities. The solution is an integrated safety analytics system that can extract and aggregate data from the robot to allow for meaningful action.

Furthermore, for those technologies that have the ability to share data and connect with other systems, RT-382 observed disconnected processes that require additional technologies or implementation efforts. Consider a hypothetical example: Company A buys sensors to detect gas leaks, each with its own separate low-tech alert. Company B buys sensors and an integrated internet of things ("IoT") management solution to detect gas leaks, monitor all sensors remotely in one user interface, dispatch alerts with a uniform system, and track human capital in relation to hazardous areas – tying in certifications, roles, and organization structures. The technology solution adopted by Company B enables cross-integration of the technologies and provides a seamless and effective system.

These observations allowed RT-382 to understand the importance of integration – both in the form of integrative technologies and processes. Furthermore, by making related data accessible for point solutions, the complete system can be leveraged in new and different ways. To enable data sharing, these point solutions need a common integration platform to tie into. Organizations intending to adopt technologies to mitigate the safety impacts of last-minute change should consider the need for cross-integration of the technologies.

5.3 Practical Considerations: Levels of Automation

One of the critical factors when deciding whether to adopt a technology, especially a technology that will be used to monitor worker safety in time-critical situations such as last-minute changes, is the functions that the technology can effectively and confidently provide. An important question arises as to which parts of the situational awareness process should be performed by a technology. Depending on the level of development of the technology and confidence in its performance, an ability such as decision-making under uncertainty may be better provided by a human. In other cases, use of a technology may be desired simply to provide redundancy alongside a human, or to fill gaps due to human limitations and training.

The concept of levels of automation provides a framework to describe the desired functions of technology. Sheridan and Verplanck defined 10 levels of technology functions to create the levels of automation shown in Table 15 (Sheridan and Verplanck, 1978). At each level, different tasks (e.g., data collection, decision, performance, and notification) are performed either by a human or by a computer or technology. At the lowest level, Level 1, a human performs all of the functions without any assistance from a computer or technology. As the level increases, more tasks are performed by the computer or technology with fewer tasks performed by a human. At the highest level, Level 10, the computer or technology performs all tasks associated with an operation, and no involvement from a human is needed.

Liu translated the levels of automation (LOA) to work performed in the construction industry. Given the difficulty in applying technology to many aspects of construction, Liu converted the 10 levels into five levels based on the characteristics of the construction industry (Liu, 2019). The five levels of construction automation are also shown in Table 15.

Organizations endeavoring to adopt a technology should consider the desired level of automation for the particular technology use case. This consideration is especially important when adopting technologies for safety purposes such as in the case of last-minute changes. In some cases, an organization may choose to not adopt a technology, or not utilize certain features of a technology, if it sees greater benefit and reliability of a human performing the functions. When a technology is adopted, an organization may also choose to retain human involvement for redundancy, especially if reliability of the technology is not proven or is low. On the other hand, in circumstances where human involvement is required for an operation, an organization may choose to increase redundancy by augmenting limited human abilities with the presence of a technology. Greater redundancy provided by the combination of humans and technologies may be desired in conditions and operations that are high-risk, critical, unique, and/or new to the organization.

Table 15. Levels of Automation (LOA) Analysis and Conversion to Construction (Liu, 2019)

LOA	**Description** *(Sheridan and Verplanck 1978)*	**Data Collection**	**Decision**			**Perform**	**Notify**	**Constr. LOA**	**Description**
			Alt.	*Sel.*	*App.*				
1	Human does the whole job up to the point of turning it over to the computer to implement	H*	H	H	H	H	N/A	1	Construction workers do the whole job with assistance of human-controlled machine
2	Computer helps by determining the options	C**	both	H	H	H	N/A	2	Sensors embedded to collect data for human to analyze
3	Computer helps to determine options and suggests an option, which human need not follow	C	C	H	H	H	N/A	3	Intelligent automated system; system assists human workers on data analysis and decision-making
4	Computer selects action and human may or may not do it	C	C	both	H	H	N/A		
5	Computer selects action and implements it if human approves	C	C	C	H	H	N/A		
6	Computer selects action, and informs human in plenty of time to stop it	C	C	C	C	both	N/A	4	Highly intelligent automated system; system makes decisions and performs the work. Provides performance report and system warning to human workers when necessary.
7	Computer does whole job and necessarily tells human what it did	C	C	C	C	C	If necessary		
8	Computer does whole job and tells human what it did only if human explicitly asks	C	C	C	C	C	C needs to ask H		
9	Computer does whole job and decides what the human should be told	C	C	C	C	C	C decides to tell H		
10	Computer does the whole job if it decides it should be done, and if so, tells human, if it decides that the human should be told	C	C	C	C	C	C decides not to tell	5	Highly intelligent automated system; system makes decisions and performs the work without notifying human workers.

* H represent human-controlled process; ** C represents computer-centered process

5.4 Practical Considerations: A Technology's Readiness and Its Effectiveness

The present level of development of AI technologies (and some technologies in other categories) limits their readiness for widespread implementation. As described above, when assessing opportunities for implementation, consider what level of automation is desired and feasible. What provides an acceptable factor of safety? Automation, for example, may be desirable, but present industry culture, regulations, and common practice may not accept allowing fully autonomous robots to make independent decisions without human input. However, these robots may become more acceptable once further development has improved their accuracy in decision-making and consistent demonstrations of error-free functioning have proven their effectiveness.

Consequently, in addition to evaluating a technology's technical readiness, potential users must also consider its ability to function effectively without concern for failure. Both readiness and effectiveness are key factors associated with technology. Figure 18 illustrates how readiness and effectiveness can be used to evaluate technologies. The figure depicts potential technology effectiveness – some technologies may still be in development and not ready for implementation. For this study, potential technology effectiveness would be interpreted as the ability of the technology to mitigate the impacts of an unanticipated, last-minute work change that could lead to a SIF.

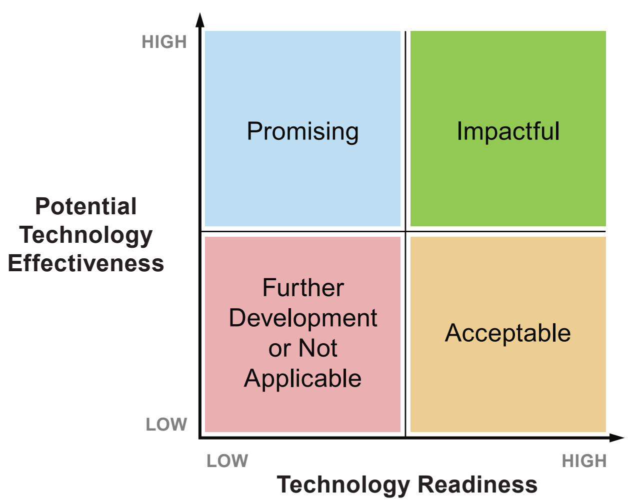

Figure 18. The Relationship between Technology Readiness and Effectiveness

As the figure shows, the relationship between readiness and effectiveness can be separated into four quadrants: Promising, Impactful, Acceptable, and Further Development or Not Promising. One promising technology is AI, which is still being developed but has the potential to be highly effective because it could provide every function required to mitigate change. Most present technologies the team identified fit in the Impactful or Acceptable quadrants, depending on their level of effectiveness.

Chapter 6: Conclusions and Recommendations

The research performed by Research Team 382 has afforded a detailed awareness of unanticipated, last-minute work changes in construction and their relationships to safety and technologies. The foundational knowledge developed by the study team provides a detailed and exhaustive understanding of the study topic for the industry. The knowledge also supports and guides practical implementation of the research results and future research on the topic. The following conclusions can be drawn from the study, and the team has recommendations for implementing the findings in practice and for future research.

6.1 Conclusions

It is clear from both objective and anecdotal evidence, plus the personal experiences of the research team, that unanticipated, last-minute work changes occur in construction. The origins of these changes are broadly distributed across different aspects of construction throughout the industry. In many cases, the changes are revealed through visual, auditory, or other types of physical cues. However, sometimes no indicator of the change is present and/or conspicuous. The effect or reaction to last-minute changes, especially if the change is unanticipated, is often a sudden movement or decision by a worker to prevent unwanted consequences. Unfortunately, the ability to mitigate the effects of the last-minute change may be minimal, and its unwanted consequences may include a serious injury or fatality (SIF). In other cases, a worker who is under pressure to complete the work may elect to take an ill-advised action that could lead to an injury or fatality.

Addressing last-minute changes to prevent SIFs requires attention and action associated with at least one of the descriptors of change – agent, indicator, effect, and consequence:

- Pre-planning should be in-place to expose potential origins (agents) of changes in work operations.
- Continuous monitoring (via humans and/or technology) is needed to observe and interpret site and operational conditions, and to be on the alert for differences in observable conditions (indicators).
- Protective measures are needed to ensure that workers are not injured by the effect of the change.
- In addition, effective training and motivation should be provided, so that workers make good decisions and take actions in response to the change that result in safe work performance (consequence).

Based on the team's review of fatality incidents in construction, a large percentage of incidents can be attributed to a changes in site conditions, work operations, or other aspects of a project. These changes typically cannot be anticipated, recognized, or avoided. However, with proper planning, resources, training, and/or technology, the changes can be eliminated or the effects of the changes mitigated.

In addition, most changes occur at the last minute. The actual change that occurs is typically closely connected to the worker, rather than distant in terms of time, space, or human interface. The most common types of changes associated with worker fatalities involve interface and interaction between workers and equipment (e.g., worker or equipment path, work area intrusion, and equipment usage), unanticipated changes in the planned work process, and unforeseen weather conditions are the.

To improve safety performance in the industry, this study suggests, organizations should increase priority on minimizing unexpected work changes, especially last-minute work changes in the proximity of workers to equipment and changes to the planned work process. These two types of last-minute changes were found to be related to a high percentage (64.3%) of fatality incidents in the construction industry. Increased attention to these types of last-minute work changes should lead to fewer SIFs.

Organizations can address safety related to last-minute changes by preventing the changes from occurring and/or mitigating the impacts of the changes when they do occur. People-related and process controls (e.g., worker training and pre-task risk assessments) can be used to perform these functions; using technology is another means that has great promise. A wide range of technologies is available on the market, and many of them are safety-related. The technologies can be organized into seven general categories: communication and mobile computing, sensing, monitoring, visualization, automation, site control/site access, and artificial intelligence. Safety prevention and mitigation technology for last-minute changes does not have to be complicated; it can be as simple as a sensor.

Two technologies evaluated by RT-382 had high potential for minimizing SIFs: worker-equipment proximity alert technologies and work process monitoring and alert technologies. Of these, the team found that only cloud-based connected worker systems were able to prevent SIFs due to last-minute changes. Only a cloud-based connected worker system has the ability to monitor site conditions and work operations, detect last-minute changes, comprehend safety hazards due to last-minute changes, project the safety risk, and send an alert, all in real time. None of the technologies assessed was deemed to be able to identify options for mitigating the impacts of last-minute changes, decide which option to select, and implement the selected option in real time.

All technologies outfitted with AI capabilities are desired. AI provides the ability to perform all of the needed situational awareness steps when a last-minute change occurs. Adopting a technology that lacks AI capabilities would require human involvement to fulfill the situational awareness functions that the technology cannot perform.

According to the perspectives of RT-382, the most important selection criteria are technology effectiveness, cost, and ease of use. With respect to specific technologies, sensors for worker physiological status meet the selection criteria to the greatest extent, followed by sensors for monitoring surrounding site conditions and for tracking worker location on a jobsite.

Technology readiness, coupled with technology effectiveness, drive selection, diffusion, and ultimately success in technology adoption. Many current technologies have been developed to a level in which they are fully ready to deploy. Others, such as AI, require more development before they truly fulfill their potential effectively. As a result, at the present time, the crux of the issue regarding technology effectiveness is to understand last-minute changes and how to create a strategy using a portfolio of technologies and processes, rather than simply a single technology. The current state of development in technologies necessitates integrating multiple technologies. Creating an integrated system that effectively addresses and mitigates the impacts of last-minute changes in real time likely requires high-speed internet connection and data sharing across multiple platforms.

The technology adoption protocol developed by RT-382 provides organizations with a rigorous, objective means to select a technology that meets their needs and addresses the safety impacts of last-minute changes. The study results will help company leadership and safety professionals identify and comprehend last-minute changes, and equip them with the technologies necessary to mitigate the impact of last-minute changes and prevent SIFs.

6.2 Recommendations for Implementation in Practice and Future Research

As they reflected on the knowledge they gained from this study, the members of RT-382 believed that this research revealed important actions that the construction industry can and should take to improve safety. Moreover, RT-382 recommends further research to explore pertinent issues of concern that were exposed during the course of this study.

Given the high percentage of SIFs that occur due to last-minute changes, organizations should prioritize preventing last-minute changes from occurring. Eliminating the potential for a last-minute change coincides with the guidance suggested by the hierarchy of controls for safety management to first seek to design out the hazard from the system. Examples of ways to prevent last-minute changes include the following:

- Thorough and precise pre-task planning
- Detailed preliminary site assessments and site data collection
- Availability of, and easy access to, tools and supplies
- Anticipation of, and protection from, abnormal weather conditions
- Hard and positive separation of walking pathways and work areas from heavy equipment operations
- Continuous monitoring of site conditions and work processes

If last-minute changes cannot be prevented, the work and working conditions can be designed to lessen the risk associated with the last-minute changes. The work schedule, available personnel, and required productivity, for example, can be established such that they do not create stress for the worker during last-minute situations. The amount of design effort expended on a project can be set to optimize the amount and quality of design information needed for efficient and error-free construction. Planning and expecting a slower pace of work aids in lowering production pressures. Reducing, or if possible, eliminating the pressure that workers feel to accomplish their work lowers the chance of making a poor decision under pressure when a last-minute change occurs. Ensuring that workers have clear authority to stop work when an unexpected situation occurs, they actually exercise that authority, and are supported by coworkers and supervisors when they do so, can help to reduce the pressure as well.

Next, providing engineered controls – the focus of this research study – is another means to mitigate the impacts of last-minute changes on SIFs. While not eliminating or reducing the potential for a last-minute change, current technology can be used to protect workers when a last-minute change occurs. Examples of recommended engineering controls include: worker-equipment proximity alert systems, work area monitoring systems, and site control/site access systems. To make gains in safety performance, the construction industry should continue to invest in the research and development of new technologies, and actively participate in diffusing the technologies throughout the industry.

When a technology is adopted, construction organizations should make concerted efforts to disseminate the technologies throughout the organization and to ensure their consistent and effective use. All too often, technology use may be limited to a select project or division within an organization, or to a single sector of the industry. RT-382 recommends conducting research on how to best diffuse technologies throughout an organization, project, and the industry, and then create the data sources, networks, and education or training opportunities to enable and encourage their use. The desired research output would include a central repository, list, or document summarizing current technology availability along with the benefits that the technologies provide with respect to safety and last-minute changes. Additional research is recommended that maps the technologies to specific safety hazards (e.g., OSHA Focus Four), such that this safety information can be included with the available technology information.

Given that last-minute changes are often related to a change in the proximity of workers to equipment, and to a change in the planned work process, further development and implementation of technologies to mitigate these types of changes is recommended. Current worker-equipment proximity technologies are available and used in the industry. Continued development of proximity alert technologies should be pursued to increase their use, improve their applicability to both new and old equipment, and enhance their capabilities to enable the technologies to autonomously take appropriate action to prevent contact with workers in addition to simply providing an alert. Proximity alert technologies that have these features will help prevent countless struck-by incidents that result in worker fatalities.

The need for further development is even greater, and perhaps more challenging, for work process monitoring technologies. Future technologies should be pursued that are able to compare an ongoing work process to the planned work process, determine if the work is being conducted according to plan, and, if not, comprehend whether greater risk is present and whether to take immediate action to mitigate the risk – all in real time. Importantly, the immediate action should be more than just highlighting a trend or sending an alert to a human. These functions truly represent the promise of artificial intelligence, yet are presently in their infancy, and in some cases lacking, in current AI technologies. The research study exposed a need for continued development of AI capabilities. New AI technologies should be applicable to the dynamic and changing site conditions and environment of construction projects, and perform the functions in real time without human involvement if needed. As AI is developed and implemented in the future, consideration should be given to the balance between humans and technologies in the performance of work. In some cases, human involvement may be desired even though a new technology is available that can perform the function.

Realizing the benefits of AI amid the many different desired use cases and conditions on construction projects likely requires integration of many different technologies. No single technology can do everything. However, the ability of present integration systems to connect to, share data with/between, and control performance of multiple technologies is limited. Further research is needed to design systems that interface with and share data between different technologies. Fortifying technology integration will enable fully realizing the benefits of each connected technology without incurring unsustainable costs and project impacts.

Effective mitigation of the impacts of last-minute changes is dependent on the decisions made and actions taken when designing work site conditions and operations and in response to a last-minute change. Reliable and beneficial decisions and actions are needed whether performed by a technology or a human. RT-382 recommends training workers and giving them authority to stop work when a last-minute change occurs. To facilitate incorporation of technology as a means to make decisions in such situations, RT-382 recommends further research to create a model or rules for decision-making and actions related to work operations. The research should include investigations of the data requirements, and development of algorithms and a tool that integrate the data sources and provide access to the data for optimal decision-making.

Importantly, just as the construction industry's efforts and attention to improving safety are unwavering and never-ending, continued research is needed to identify and develop new technologies that can help prevent injuries and fatalities. As a start, researchers should explore the role of last-minute change during incident investigations to improve our understanding beyond the FACE program cases. Research should explore technologies that target and mitigate the causes of injury and fatality incidents, like last-minute changes. Research is needed to create technologies that can perform all of the functions and steps associated with situational awareness, safe behavior, and decision-making. Lastly, concerted efforts are needed by the industry to develop technologies that perform their intended operations effectively and meet the needs of the industry, and to make the technologies readily accessible, both physically and economically, to all construction organizations. Otherwise, the technologies will not be adopted, and exist as novelties or simply toys to play with.

References

Albert, A., Hallowell, M. R., and Kleiner, B. M. (2014). "Enhancing Construction Hazard Recognition and communication with Energy-Based Cognitive Mnemonics and Safety Meeting Maturity Model: Multiple Baseline Study." *Journal of Construction Engineering and Management*, ASCE, 140(2), https://doi.org/10.1061/(ASCE)CO.1943-7862.0000790.

Awolusi, I. G., Marks, E., and Hallowell, M. (2018). "Wearable Technology for personalized construction safety monitoring and trending: Review of Applicable Devices." *Automation in Construction*, Elsevier, 85, 96–106.

BLS (2021). *Injuries, Illnesses, and Fatalities: Census of Fatal Occupational Injuries (CFOI)* [webpage]. Washington, DC: U.S. Department of Labor, Bureau of Labor Statistics. https://www.bls.gov/iif/oshcfoi1.htm, Dec. 16, 2021.

Boston Dynamics (n.d.). *Spot®* [webpage]. Waltham, MA: Boston Dynamics. https://www.bostondynamics.com/spot.

Calculator.net (n.d.). *Sample Size Calculator* [webpage]. Calculator.net. The Woodlands, TX: Maple Tech International LLC. https://www.calculator.net/sample-size-calculator.html?type=1&cl=95&ci=5&pp=50&ps=215&x=86&y=8, accessed July 18, 2022.

Choe, S., Leite, F., Seedah, D., and Caldas, C. (2013). "Application of sensing technology in the prevention of backing accidents in construction work zones." *Proceedings of the ASCE International Workshop on Computing in Civil Engineering*, ASCE, 2013, 557-564.

CloudResearch (n.d.). *Determining Sample Size: How Many Survey Participants Do You Need?* [webpage]. CloudResearch.com. Flushing, NY: Prime Research Solutions, LLC. https://www.cloudresearch.com/resources/guides/statistical-significance/determine-sample-size/, accessed July 2022.

Endsley, M. R. (1995). "Toward a Theory of Situation Awareness in Dynamic systems." *Human Factors, Journal of the Human Factors and Ergonomics Society*, 37(1), 32-64, https://doi.org/10.1518/001872095779049543.

ESA (2008). "Technology Readiness Levels Handbook for Space Applications." TEC-SHS/5551/MG/ap, Issue 1, Rev. 6. Paris, France: European Space Agency, Sept. 2008.

FHWA (2017). *Technology Readiness Level Guidebook*. FHWA-HRT-17-047. Washington, DC: U.S. Department of Transportation, Federal Highway Administration. https://www.fhwa.dot.gov/publications/research/ear/17047/index.cfm, Sept. 2017.

Gambatese, J. A., Lee, H. W., and Nnaji, C. A. (2017). "Work Zone Intrusion Alert Technologies: Assessment and Practical Guidance," Final Report, SPR 790. Salem, OR: Oregon Department of Transportation (ODOT) and U.S. Department of Transportation, Federal Highway Administration (FHWA), June 2017, http://www.oregon.gov/ODOT/Programs/ResearchDocuments/SPR790_IntrusionAlertTech.pdf.

Gambatese, J. A., Pestana, C., and Lee, H. W. (2016). "Alignment between Lean Principles and Practices and Worker Safety Behavior." *Journal of Construction Engineering and Management*, ASCE, 143(1), DOI: 10.1061/(ASCE)CO.1943-7862.0001209.

GAO (2020). *Technology Readiness Assessment Guide: Best Practices for Evaluating the Readiness of Technology for Use in Acquisition Programs and Projects*. GAO-20-48G. Washington, DC: U.S. Government Accountability Office. https://www.gao.gov/products/gao-20-48g, Jan. 2020.

Haas, C. T., Nassir, H., Razavi, S., Young, D., Goodrum, P. M., Yeizer, J., Zhai, D., Homm, D., Caldas, C. H., Grau, D., and Gong, J. (2010). *Leveraging Technology to Improve Construction Productivity, Volume I: Historical Data Analysis*. Research Report 240-11. Austin, TX: Construction Industry Institute.

Haas, C. T., Nassir, H., Razavi, S., Young, D., Goodrum, P. M., Yeizer, J., Zhai, D., Homm, D., Caldas, C. H., Grau, D., and Gong, J. (2013). *Leveraging Technology to Improve Construction Productivity, Volume II: LEVER: The Predictive Model*. Research Report 240-12. Austin, TX: Construction Industry Institute.

Haas, C. T., Nassir, H., Razavi, S., Young, D., Goodrum, P. M., Yeizer, J., Zhai, D., Homm, D., Caldas, C. H., Grau, D., and Gong, J. (2010a). *Leveraging Technology to Improve Construction Productivity, Volume III: Technology Field Trials*. Research Report 240-13. Austin, TX: Construction Industry Institute.

Hallowell, M. R. and Gambatese, J. A. (2009). "Qualitative Research: Application of the Delphi Method to CEM Research." Special Issue: Research Methodologies in Construction Engineering and Management, *Journal of Construction Engineering and Management*, ASCE, 136(1), 99–107.

Hallowell, M., Albert, A., and Kleiner, B. (2014). *Strategies for Improving Hazard Recognition*. Research Report 293-11. Austin, TX: Construction Industry Institute.

Hallowell, M., Alexander, D., and Gambatese, J. (2016a). *Precursor Analysis for the Construction Industry: A Systematic Method for Predicting and Preventing Fatal and Disabling Injuries*. Research Report 321-11. Austin, TX: Construction Industry Institute.

Hallowell, M. R., Hardison, D., and Desvignes, M. (2016b). "Information Technology and Safety: Integrating Empirical Safety Risk Data with Building Information Modeling, Sensing, and Visualization Technologies." *Construction Innovation*, Emerald Insight, 16(3), 323–347.

Hao, Q., Shen, W., Neelamkavil, J., and Thomas, J. R. (2008). "Change Management in Construction Projects." *Proceedings of the 2008 International Conference on Information Technology in Construction, Santiago, Chile*, 387–396.

Hasanzadeh, S., de la Garza, J., and Geller, E. S. (2020). "Latent Effect of Safety Interventions." *Journal of Construction Engineering and Management*, ASCE, 146(5), DOI: 10.1061/(ASCE)CO.1943-7862.0001812.

Hinze, J. (2002). *Making Zero Injuries a Reality*. Research Report 160-11, Austin, TX: Construction Industry Institute.

Hinze, J. and Gambatese, J. (1996). *Addressing Construction Worker Safety in Project Design*. Research Report 101-11. Austin, TX: Construction Industry Institute.

Hinze, J. and Hallowell, M. (2013). *Going Beyond Zero Using Safety Leading Indicators*. Research Report 284-11. Austin, TX: Construction Industry Institute.

Hinze, J. and Huang, X. (2003). *The Owner's Role in Construction Safety*. Research Report 190-11. Austin, TX: Construction Industry Institute.

Hoske, P., and Kunze, G. (2004). "Possible Applications of Panoramic Photogrammetry Concerning Construction Machines and Building Sites." *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 34 (Part 5), W16.

Irizarry, J., Gheisari, M., and Walker, B. N. (2012). Usability Assessment of Drone Technology as Safety Inspection Tools." *Electronic Journal of Information Technology in Construction*, ITcon.org, 17, 194–212.

Jebelli, H., Choi, B., and Lee, S. (2019). "Application of Wearable Biosensors to Construction Sites. I: Assessing Workers' Stress." *Journal of Construction Engineering and Management*, ASCE, 145(12), 04019079, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001729.

Karakhan, A., and Alsaffar, O. (2019). "Technology's Role in Safety Management." *Professional Safety*, American Society of Safety Professionals, 64(1), 43-45.

Khatib, J. M., Chileshe, N., and Sloan, S. (2007). "Antecedents and benefits of 3D and 4D modelling for construction planners." *Journal of Engineering, Design and Technology*, 5(2), 159–172, https://doi.org/10.1108/17260530710833202.

Kim, K., Kim, H., and Kim, H. (2017). "Image-based construction hazard avoidance system using augmented reality in wearable device." *Automation in Construction*, Elsevier, 83, 390-403.

Li, X., Yi, W., Chi, H. L., Wang, X., and Chan, A. P. (2018). "A Critical Review of Virtual and Augmented Reality (VR/AR) Applications in Construction Safety." *Automation in Construction*, Elsevier, 86, 150–162.

Lin, K. Y., Son, J. W., and Rojas, E. M. (2011). "A Pilot Study of a 3D Game Environment for Construction Safety Education." *Journal of Information Technology in Construction*, ITcon.org, 16(5), 69-84.

Liu, D. (2019). "Evaluating Industrialization Rate in Construction: A Quantification Model." PhD Dissertation, Oregon State University.

Luo, X., Li, H., Huang, T., and Rose, T. (2016). "A Field Experiment of Workers' Responses to Proximity Warnings of Static Safety Hazards on Construction Sites." *Safety Science*, Elsevier, 84, 216–224.

Maloney, W., Dadi, B. B., Jazayeri, El, and Liu, H. (2016). *Improving Site Safety Performance through Operational Excellence*. Research Report 317-11, Austin, TX: Construction Industry Institute.

Marks, E., Cho, Y., and Hinze, J. (2014). *Using Near Miss Reporting to Enhance Safety Performance*. Research Report 301-11, Austin, TX: Construction Industry Institute.

Mitropoulos, P., Abdelhamid, T. S., and Howell, G. A. (2005). "Systems Model of Construction Accident Causation." *Journal of Construction Engineering and Management*, ASCE, 131(7), 816–825, https://doi.org/10.1061/(ASCE)0733-9364(2005)131:7(816).

Navigant (2016). "Trends in Construction Technology – The Potential Impact on Project Management and Construction Claims." *Navigant Construction Forum*, London, UK: Navigant Consulting, Inc.

Nnaji, C., Gambatese, J., and Karakhan, A. (2018). "Predictors of Safety Technology Adoption in Construction." *Proceedings of the Joint CIB W099 and TG59 Conference*, Salvador, Brazil, Aug. 1–3, 2018.

Nnaji, C., Gambatese, J., Karakhan, A., and Eseonu, C. (2019). "Influential safety technology adoption predictors in construction." *Engineering, Construction and Architectural Management*, 26(11), 2655–2681, https://doi.org/10.1108/ECAM-09–2018-0381.

Park, M. W. and Brilakis, I. (2012). "Construction Worker Detection in Video Frames for Initializing Vision Trackers." *Automation in Construction*, Elsevier, 28(15): 15–25, https://doi.org/10.1016/j.autcon.2012.06.001.

Park, C. S. and Kim, H. J. (2013). "A Framework for Construction Safety Management and Visualization System." *Automation in Construction*, Elsevier, 33, 95–103.

Park, M. and Peña-Mora, F. (2003). "Dynamic change management for construction: Introducing the change cycle into model-based project management." *System Dynamics Review*, 19(3), 213–242, https://doi.org/10.1002/sdr.273.

PMI (2008). *A Guide to the Project Management Body of Knowledge*. ANSI/PMI 99-001–2008, Philadelphia, PA: Project Management Institute.

Poon, C. S. (2007). "Reducing Construction Waste." *Waste Management*, 27(12), 1715–1716, https://doi.org/10.1016/j.wasman.2007.08.013.

Randall, T. (2011). "Construction Engineering Requirements for Integrating Laser Scanning Technology and Building Information Modeling." *Journal of Construction Engineering and Management*, ASCE, 137(10), 797-805.

Rashidi, A., Dai, F., Brilakis, I., and Vela, P. (2013). "Optimized Selection of Key Frames for Monocular Videogrammetric Surveying of Civil Infrastructure." *Advance Engineering Informatics*, Elsevier, 27(2), 270–282. https://doi.org/10.1016/j.aei.2013.01.002.

Sepasgozar, S. M. E. and Bernold, L. E. (2013). "Factors Influencing Construction Technology Adoption." *Proceedings of the 19th CIB World Building Congress*, CIB, Brisbane, Australia, May 5-9, 2013.

Sheridan, T. B. and Verplanck, W. L. (1978). *Human and Computer Control of Undersea Teleoperators*. Technical Report, Cambridge, MA: MIT Man-Machine Laboratory.

Sigurdsson, S. O., Taylor, M. A., and Wirth, O. (2013). "Discounting the Value of Safety: Effects of Perceived Risk and Effort." *Journal of Safety Research*, Elsevier, 46, 127–134.

SmartMarket Insight (2019). “Using Technology to Improve Risk Management in Construction.” Bedford, MA: Dodge Data and Analytics.

Smith, K. and Hancock, P. A. (1995). “Situation Awareness Is Adaptive, Externally Directed Consciousness.” *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1), 137–148, https://doi.org/10.1518/001872095779049444.

Sun, M., Fleming, A., Senaratne, S., Motawa, I., and Yeoh, M. L. (2006). “A Change Management Toolkit for Construction Projects.” *Architectural Engineering and Design Management*, 2(4), 261–271, https://doi.org/10.1080/17452007.2006.9684621.

Tang, S., Shelden, D. R., Eastman, C. M., Pishdad-Bozorgi, P., and Gao, X. (2019). “A Review of Building Information Modeling (BIM) and the Internet of Things (IoT) Devices Integration: Present Status and Future Trends.” *Automation in Construction*, Elsevier, 101, 127–139.

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

Wang, P., Wu, P., Wang, J., Chi, H. L., and Wang, X. (2018). “A Critical Review of the Use of Virtual Reality in Construction Engineering Education and Training.” *International Journal of Environmental Research and Public Health*, 15(6), 1204, DOI: 10.3390/ijerph15061204.

Weinstein, M., Gambatese, J., and Hecker, S. (2005). “Can Design Improve Construction Safety?: Assessing the Impact of a Collaborative Safety-in-Design Process.” *Journal of Construction Engineering and Management*, ASCE, 131(10), 1125–1134, https://doi.org/10.1061/(ASCE)0733-9364(2005)131:10(1125).

Zhang, S., Sulankivi, K., Kiviniemi, M., Romo, I., Eastman, C. M., and Teizer, J. (2015). “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.

Zhang, Y., Luo, H., Skitmore, M., Li, Q., and Zhong, B. (2019). “Optimal Camera Placement for Monitoring Safety in Metro Station Construction Work.” *Journal of Construction Engineering and Management*, ASCE, 145(1), 1–13, https://doi.org/10.1061/(ASCE)CO.1943-7862.0001584.

Zhu, Z., Ren, X., and Chen, Z. (2017). “Integrated Detection and Tracking of Workforce and Equipment from Construction Jobsite Videos.” *Automation in Construction*, Elsevier, 81(9), 161–171, https://doi.org/10.1016/j.autcon.2017.05.005.

Appendix A: Research Goal, Objectives, Methodology, and Supporting Documents

The research aimed to investigate and document technologies that can be used to identify and manage last-minute work changes to prevent potential serious injuries and fatalities. The study placed special emphasis on technologies that directly support the identification of and response to last-minute changes and/or unplanned work. The targeted output from the study was guidance for adopting and implementing the technologies to positively impact safety performance. The team established the following objectives and tasks to meet these goals:

1. Identify and characterize current practices, competencies, and skills needed to detect and respond to change, with specific focus on last-minute changes and safety.
2. Determine instances and opportunities in the safety decision-making process in which technologies could be practically deployed and provide beneficial results.
3. Identify currently available technologies that could benefit safety, especially in change situations, plus the technology features, cost, availability, and other relevant characteristics.
4. Identify technology adoption factors and processes to use when selecting safety technologies.
5. Determine which currently available technologies have potential for improving safety, when they are particularly useful, and what their expected cost and impact on safety is.
6. Further investigate one or two of the identified technologies in practice to evaluate their utility, impacts, and value, and recommend further development.
7. Create, evaluate, and validate a safety technology adoption protocol.
8. Document the research findings and outputs for dissemination by CII.

The methodology the team developed to conduct the research study was a mixed-methods approach involving reviews of archival literature, quantitative analyses of injury/fatality data, online surveys of targeted industry personnel, and focus group surveys of research team members. The overall planned research design is depicted in Figure 19.

	Change and Safety Decision-making Characterization *(Tasks 1 and 2)*	**Technology Identification and Mapping** *(Tasks 3, 4, and 5)*	**Technology Application and Assessment** *(Tasks 6 and 7)*	**Documentation for Dissemination** *(Tasks 7 and 8)*
Research Activities	• Literature review • Focus group interviews with Research Team 382 (RT-382) and the Safety CBA (SCBA)	• Internet search, including CII Horizon 360 • Literature review • Focus group interviews with RT and SCBA	• Field application and assessment of one or two technologies • Identification and assessment of adoption strategies and protocols	• Finalize technology adoption protocol • Write and submit research documentation
Outputs	• Competencies and skills needed in the presence of change • Opportunities for technology application to affect safety	• Available technologies that could positively impact safety • Factors that affect technology adoption	• Case studies of technology application for safety • Validation of the safety technologies and adoption protocol	• Recommended technologies for enhancing safety • Technology assessment protocol and guidance for safety applications

Figure 19. Research Study Design

RT-382 members provided much of the data used for this study, drawing on their collective personal experience and expertise. RT-382 consisted of approximately 20 industry professionals from owner/client, engineering, construction, and other (e.g., insurance, technology provider, and operational consulting) firms. The industry members of RT-382 were supported by three university academics. As described below, the team's industry members served as an expert panel for Delphi studies on various topics throughout the study. The Delphi method is a multi-round, systematic, and supervised technique that relies on input from a panel of experts to establish a collective understanding of a topic of interest. For the Delphi studies performed by RT-382, industry team members comprised the expert panel and the academics administered the surveys. The Delphi method has been used successfully in construction-related research to develop findings based on the practical experience and insights of industry practitioners.

At the start of the study, the team academics asked the industry team members to complete an online survey about their educational background, work experience, involvement in professional organizations, and record of authorship. The intent of the survey was to qualify each team member as an expert in the field. Based on the survey responses, and an accepted standard for qualifying a person as an expert for Delphi studies (Hallowell and Gambatese, 2009), all team members met the minimum requirements and, therefore, were accepted as member of the expert panel.

The research protocol and target population were submitted to the Institutional Review Board (IRB) at Oregon State University for review and approval for research involving human subjects. IRB approval was obtained, after which data collection commenced.

It should be noted that the initial research methods implemented were established given the limitations in place due to the COVID-19 pandemic. Social distancing and travel restrictions limited team meetings and data collection to online formats. As a result, the researchers chose online surveys and monthly focus group discussions as the primary research methods. Later, as COVID-19 restrictions eased, research tasks were conducted in-person and on construction sites, or in a lab setting where possible.

The researchers conducted this project as the following series of tasks, which are described in further detail in the following sections:

- Change and Safety Decision-making Characterization (Tasks 1 and 2)
- Technology Identification and Mapping (Tasks 3, 4, and 5)
- Technology Application and Assessment (Tasks 6 and 7)
- Documentation for Dissemination (Tasks 7 and 8)

Change and Safety Decision-making Characterization (Tasks 1 and 2)

The initial phase of the study was designed to: (1) identify and characterize current practices, competencies, and skills needed to detect and respond to change, with specific focus on last-minute changes and safety; and (2) determine instances and opportunities in the safety decision-making process in which technologies could be practically deployed and provide beneficial results. These researchers accomplished tasks through a comprehensive literature review in parallel with multiple informal focus group discussions with the industry members of RT-382 during monthly team meetings, and a formal presentation and focus group discussion with SCBA members during a monthly SCBA meeting.

RT-382 members supported initial discussions with personal reflections on change and safety in their own organizations through the development of “change diaries.” Each team member maintained a change diary in which they recorded the changes that occurred in their workplace and/or on their projects over a period of several months, the causes of the changes, how the changes influenced safety, and what could have been implemented to prevent or address the change. The change diaries were then discussed during subsequent team meetings to add practical context to the discussions. The results of the change diaries, literature review, and focus group discussions were used to confirm the research scope and plan, and develop the definitions of change and last-minute change as described above. These efforts also helped to expose current technologies to investigate in Tasks 3, 4, and 5.

Technology Identification and Mapping (Tasks 3, 4, and 5)

The second phase of the study focused on technology identification and mapping to the characteristics of last-minute changes and decision-making that affect worker safety. Task 3 entailed identifying currently available technologies that could benefit safety, especially in last-minute change situations, plus the technology features, cost, availability, and other relevant characteristics. The researchers identified technologies through a comprehensive literature review and online search, focused discussions with RT-382 and SCBA members, a review of the CII Horizon 360 website, continuous monitoring of industry news feeds throughout the course of the study, and their personal experience. All technologies identified that could potentially address the impact of last-minute changes on SIFs were recorded for further evaluation.

The range of technologies considered included information technologies that are implemented during project planning, management, and training that could enable teams to better predict last-minute changes before they occur in the field (e.g., machine learning and other artificial intelligence). Such technologies could be implemented to anticipate and prevent changes that have undesirable safety impacts. Additionally, the research team explored how hardware and visualization technologies may assist with work monitoring and identification of last-minute changes when they actually occur. The range of technologies for this situation could include sensors to monitor when relevant changes in position have occurred like wearables that track the location and proximity of workers, materials, tools, and hazards, and visualization technologies like augmented reality that help workers to better identify, interpret, and respond to changes as they navigate the work environment. There may also be an opportunity to link information technology used in upstream planning to downstream visualization hardware.

Accompanying the identification of technologies was the identification of technology adoption factors and processes to use when selecting technologies for a project or for use throughout an organization (Task 4). This task was designed to recognize the organizational, project, and technological criteria of concern for implementation of the technologies in practice. As described in Section 4.1, this process began with an initial set of technology selection criteria identified in previous research (Nnaji et al., 2019). The academics then conducted a rigorous process using multiple steps to qualify and weight the criteria for relevance to last-minute changes and safety, and confirm them as adoption factors. The researchers used the following steps during and between the monthly team meetings:

1. An initial focus group session with RT-382 that asked RT-382 members to rate the importance of each selection criteria.
2. An online survey completed by RT-382 to rank a shortlist of the adoption factors (created from Step 1) according to their importance for technology selection and implementation.
3. Multiple breakout group discussions among RT-382 to identify the “must have” and “good to have” selection criteria.

Finally, using the results from Tasks 1 through 4, Task 5 aimed to determine which currently available technologies have potential for improving safety, when they are particularly useful, and what their expected cost and impact on safety is. The research process began by first determining the types of last-minute changes that commonly lead to SIF events, followed by mapping available technologies to the highly impactful types of last-minute changes.

To expose the predominant types of last-minute changes that lead to SIF events, the researchers conducted an analysis of archived injury and fatality cases contained in two data repositories. The primary source was the database of fatality incident descriptions developed as part of the Fatality Assessment and Control Evaluation (FACE) Program within the National Institute for Occupational Safety and Health (NIOSH) (https://www.cdc.gov/niosh/face/default.html). The FACE Program maintains a database of detailed descriptions of fatality incidents (“cases”) in various industries across the United States. The database consists of case reports developed by NIOSH and case reports developed and contributed by various states. The case descriptions are intended to provide a resource for learning about particularly hazardous conditions and how to prevent additional fatalities under similar conditions in the future. Not all work-related fatalities in the U.S. are captured in the case reports. The FACE Program targets cases involving confined spaces, electrocutions, machine-related, falls from elevation, working youth, logging, deaths of foreign-born workers, and energy production. To ensure that the cases reviewed for the study are representative of the current types of construction projects undertaken, construction work processes employed, and technologies utilized, the researchers limited the FACE Program cases to those incidents that occurred after the year 2000.

A total of 39 NIOSH FACE Program cases after 2000 are available online. The researchers included all 39 cases in their review. A total of 215 state FACE Program cases after 2000 are also available online. For the state FACE cases it selected for review, the research team initially utilized the following equation to determine the sample size (Calculator.net, n.d.; CloudResearch, n.d.):

$$\text{Sample Size} = \frac{\dfrac{z^2 \times p(1-p)}{e^2}}{1 + \left(\dfrac{z^2 \times p(1-p)}{e^2 \times N}\right)}$$

where:

- z-statistic = 1.96 based on a confidence level of 95%
- margin of error, e = 5% = 0.05
- population proportion, p = 50%
- population size, N = 215

Using these parameters, the team calculated the sample size for the state FACE Program to be 138 cases, which it rounded up to 140 cases to be more convenient. The researchers then randomly selected 140 cases from the state FACE Program database to review to ensure a representative sample of cases. Based on these criteria, RT-382 reviewed a total of 179 cases (39 NIOSH FACE Program cases and 140 state FACE Program cases).

The RT-382 researchers, in consultation with the team's industry members, then developed a rubric to guide the FACE case review, to ensure a rigorous and consistent evaluation of each case. (The rubric is provided in Appendix C.) Once the rubric was complete, the researchers then reviewed each case. The team confirmed the assessment process and its results in two ways:

1. One academic performed an initial review of approximately 30 cases. Each of the other three academics was then given 10 cases from the initial list of 30 to review. The results of the reviews were then compared to verify consistency.
2. Each industry team member was asked to review a subset of the first academic's 30 cases during a team meeting. Team members were randomly divided into three subgroups, and each was given two FACE Program cases to discuss and review collectively. The academics facilitated the focus group discussions.

The results of both validation efforts revealed close correlation with the results of the initial review by a single academic, with minor exceptions. The process revealed that the evaluation mindset and decisions of the initial reviewer were accurate and consistent with those of the rest of RT-382. The team made minor modifications to the rubric for clarity and continued to review cases until all 179 had been reviewed.

Beyond their review of FACE Program cases, team members also provided detailed incident reports from their own companies or organizations to include for review. In this way, the team collected six detailed incident reports, with the academics utilized during focus group discussions with the industry members to explore the presence of last-minute changes and the connections between change, safety, and technologies.

The industry members of the team also provided extensive lists of injury and fatality incidents and near misses. These lists provided summary descriptions of SIF incidents and near misses. As part of their analysis of these cases, the researchers mapped available technologies to each case that involved a change. Based on the context of the work operations being performed when the incident occurred, along with what type of last-minute change that led to each fatality, the researchers could identify one or more technologies from the catalog of technologies that, if implemented, could have prevented or mitigated the impacts of each last-minute change.

Technology Application and Assessment (Tasks 6 and 7)

Following the initial mapping of technologies to types of last-minute changes, the next phase was intended to identify and evaluate promising technologies for recommendation in practice. Task 6 included further investigation and evaluation of two categories of the identified technologies – worker-equipment proximity alert technologies and work process change monitoring technologies – to evaluate their readiness, utility, impacts, and value, and recommend further development. The team selected specific technologies to implement based on input and discussions among its membership, the results of Task 5, and the project and technology resources available to its member companies and the researchers. The research process used for this task are described in detail in Section 3.2.

The survey questionnaires used to evaluate each technology category are provided in Appendix C. The Worker-Equipment Proximity Alert Technology Survey solicited operator perspectives about each technology, its current extent of use, effectiveness, barriers to use, and applicability to adoption factors. The questionnaire was distributed to equipment operators and industry practitioners with experience with heavy equipment. RT-382 members distributed the link to the questionnaire to others in their organizations who operated heavy equipment or had experience working with or on heavy equipment. A total of nine survey responses were received.

For the work process change monitoring technologies, RT-382 began by identifying potential technologies that fit within this category. The researchers then contacted the manufacturers of the technologies and invited them to give presentations to RT-382 during the team's monthly meetings. Five technology manufacturers scheduled presentations, one per monthly team meeting.

Following the technology manufacturers' presentations, RT-382 members completed a work process change monitoring technology survey (the Smart Construction Technology Survey, provided below). The purpose of this survey was to have team members evaluate each of the technologies presented. Questions specifically focused on technology, organizational, user, and external-related factors. Following each manufacturer presentation, the academics sent a link to the questionnaire to RT-382 members. The number of responses for each technology survey varied depending on how many team members had attended the meeting. The number of responses to the surveys ranged from four to 11, with an average of 7.8 responses per technology.

RT-382 created a technology adoption protocol (Task 7) following the focused evaluations of the two technology categories. The protocol is intended to give organizations a rigorous process for evaluating potential technologies to ensure success in their application, acceptance, and diffusion throughout the organization. The research process began with a review of literature to collect examples of existing technology adoption protocols, followed by multiple interactions with team members to refine and confirm both the technology adoption protocol and adoption factors utilized within the protocol. The researchers developed checklists to accompany each assessment level in the protocol. Initial versions of these checklists were developed based on the team analyses used to identify adoption factors, their importance, and priority ranking (shown in Tables 11 and 12). The researchers then presented the initial versions of the checklists at team meetings to obtain industry members' feedback and refine the checklists. During meetings, the academics conducted a Delphi survey (Preliminary Feasibility Evaluation and Technology Assessment checklists only) and solicited comments from team members to gain consensus on the adoption factors and format of the checklist questions. The Pilot Test, Field Application, and Demonstration Assessment checklist was initially reviewed during a team meeting, then pilot tested during a team meeting and following laboratory demonstrations of various technologies at an industry technology lab. The researchers incorporated the feedback they received from industry members during these efforts into each checklist.

Documentation for Dissemination (Tasks 7 and 8)

The study concluded with the development of research outputs and deliverables. The technology adoption protocol was evaluated by industry members and finalized for distribution (Task 7) as described in Section 4.2. Lastly, Task 8 involved drafting study documents for dissemination by CII (this report and the documentation that created the team's page in the CII Knowledge Base), and presenting study results to the CII community, chiefly via the 2022 CII Annual Conference.

Worker-Equipment Proximity Alert Technology Survey

Thank you for agreeing to participate in this brief survey.

We are interested in your perspectives about available technologies designed to alert workers and equipment operators of the close proximity of workers to equipment. Specifically, we are interested in your opinions about their effectiveness and drawbacks/barriers, and issues to consider when deciding whether to adopt the technologies to detect last-minute changes in the proximity of workers to equipment.

The technologies that we would like you to consider are the following:

- Real-time Proactive Radio Frequency Warning and Alert Technology
- Blind Spot Assist
- Equipment Anti-Collision System (e.g., ZoneSafe)
- Parking package with 360° camera
- Active Brake Assist
- Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)
- Computer Vision-based System (e.g., Blaxtair System)

Detailed information about each of these technologies is available at this link. Please review the information about the technologies, and then answer the survey questions.

Q1. Have you used or do you currently use any of the following equipment proximity alert technologies for heavy equipment operations on construction projects?

	Yes (1)	No (2)
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○
Blind Spot Assist	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○
Parking package with 360° camera	○	○
Active Brake Assist	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○

Q2. Do you plan to use any of the following equipment proximity technologies in the future?

	Yes (1)	No (2)
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○
Blind Spot Assist	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○
Parking package with 360° camera	○	○
Active Brake Assist	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○

Q3. Why do you not plan to use the technology in the future? Please explain your answer.

	Why?
Display This Choice if Answer in Q2 Was "No" Real-time Proactive Radio Frequency Warning and Alert Technology	
Display This Choice if Answer in Q2 Was "No" Blind Spot Assist	
Display This Choice if Answer in Q2 Was "No" Equipment Anti-Collision System (e.g., ZoneSafe)	
Display This Choice if Answer in Q2 Was "No" Parking package with 360° camera	
Display This Choice if Answer in Q2 Was "No" Active Brake Assist	
Display This Choice if Answer in Q2 Was "No" Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	
Display This Choice if Answer in Q2 Was "No" Computer Vision-based System (e.g., Blaxtair System)	

Q4. How effective do you think the following equipment proximity technologies are for detecting last-minute changes in the proximity of workers to equipment?

	Not effective (0)	Minimally effective (1)	Slightly effective (2)	Moderately effective (3)	Very effective (4)	Extremely effective (5)	I don't know
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○	○	○	○	○	○
Blind Spot Assist	○	○	○	○	○	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○	○	○	○	○	○
Parking package with 360° camera	○	○	○	○	○	○	○
Active Brake Assist	○	○	○	○	○	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○	○	○	○	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○	○	○	○	○	○

Q5. Why do you think the technologies listed below are not effective at detecting last-minute changes in the proximity of workers to equipment? Please explain your answer.

	Why?
Display This Choice if Answer in Q4 Was "No" Real-time Proactive Radio Frequency Warning and Alert Technology	
Display This Choice if Answer in Q4 Was "No" Blind Spot Assist	
Display This Choice if Answer in Q4 Was "No" Equipment Anti-Collision System (e.g., ZoneSafe)	
Display This Choice if Answer in Q4 Was "No" Parking package with 360° camera	
Display This Choice if Answer in Q4 Was "No" Active Brake Assist	
Display This Choice if Answer in Q4 Was "No" Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	
Display This Choice if Answer in Q4 Was "No" Computer Vision-based System (e.g., Blaxtair System)	

Q6. What do you think are the drawbacks/barriers, if any, to using each of the following technologies for detecting the proximity of workers to heavy equipment? Please select all that apply.

	Purchase cost	Maintenance cost	Difficult to use	Unable to install on older equipment	Reduces productivity	Other	No drawbacks or barriers	I don't know
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○	○	○	○	○	○	○
Blind Spot Assist	○	○	○	○	○	○	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○	○	○	○	○	○	○
Parking package with 360° camera	○	○	○	○	○	○	○	○
Active Brake Assist	○	○	○	○	○	○	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○	○	○	○	○	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○	○	○	○	○	○	○

Q7. Please describe the other drawbacks/barriers for each of the following technologies.

	Other drawbacks or barriers
Display This Choice if Answer in Q6 Was "Other" Real-time Proactive Radio Frequency Warning and Alert Technology	
Display This Choice if Answer in Q6 Was "Other" Blind Spot Assist	
Display This Choice if Answer in Q6 Was "Other" Equipment Anti-Collision System (e.g., ZoneSafe)	
Display This Choice if Answer in Q6 Was "Other" Parking package with 360° camera	
Display This Choice if Answer in Q6 Was "Other" Active Brake Assist	
Display This Choice if Answer in Q6 Was "Other" Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	
Display This Choice if Answer in Q6 Was "Other" Computer Vision-based System (e.g., Blaxtair System)	

Q8. What technology-related factors do you think are important to consider when deciding whether to adopt each of the following technologies? Please select all that apply.

	Proven technology effectiveness	Technology brand	Technology durability	Technology reliability	Triability	Technical attributes and features included	Complexity of technology	Impact on safety or ability to track safety performance	Integration with existing systems/work processes	All of the factors
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○	○	○	○	○	○	○	○	○
Blind Spot Assist	○	○	○	○	○	○	○	○	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○	○	○	○	○	○	○	○	○
Parking package with 360° camera	○	○	○	○	○	○	○	○	○	○
Active Brake Assist	○	○	○	○	○	○	○	○	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○	○	○	○	○	○	○	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○	○	○	○	○	○	○	○	○

Q9. What user-related factors do you think are important to consider when deciding whether to adopt each of the following technologies? Please select all that apply.

	Ease of use	Training required for optimum performance	Individual innovativeness	Technical capabilities of users	All of the factors
Real-time Proactive Radio Frequency Warning and Alert Technology	○	○	○	○	○
Blind Spot Assist	○	○	○	○	○
Equipment Anti-Collision System (e.g., ZoneSafe)	○	○	○	○	○
Parking package with 360° camera	○	○	○	○	○
Active Brake Assist	○	○	○	○	○
Reflective Material Sensor (e.g., SEEN Safety's IRIS 860)	○	○	○	○	○
Computer Vision-based System (e.g., Blaxtair System)	○	○	○	○	○

Q10. Please provide any additional comments about the equipment proximity technologies listed above and their potential application to detect last-minute changes in the proximity of workers to equipment.

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Q11. Please suggest any additional technologies that may be useful for detecting last-minute changes in the proximity of workers to equipment.

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Smart Construction Technology Evaluation Survey

Please answer the following questions about the smart construction technology developed by ___________. Documents describing the technology that were provided by ___________ are available on the RT-382 Trello website for reference, if needed.

When answering the questions, please consider the technology for use in detecting and mitigating potential safety impacts due to last-minute changes* in a construction work process.

After completing the evaluation, we will discuss the team's collective input on the technology at a future RT-382 team meeting.

* A last-minute change is a change that occurs or manifests at the work face when there is limited time available to plan for and address the change.

Q1. Please indicate the extent to which you think each of the following technology-related factors would be a concern with the technology.

	Not a concern (0)	Minimal concern (1)	Low level concern (2)	Moderate concern (3)	High level concern (4)	Significant concern (5)	I don't know
Technology effectiveness	○	○	○	○	○	○	○
Technology brand	○	○	○	○	○	○	○
Technology reliability	○	○	○	○	○	○	○
Triability	○	○	○	○	○	○	○
Technical attributes and features included	○	○	○	○	○	○	○
Complexity of technology	○	○	○	○	○	○	○
Ability to impact safety or track safety performance	○	○	○	○	○	○	○
Integration with existing systems/ work processes	○	○	○	○	○	○	○

Q2. Please indicate the extent to which you think each of the following organizational-related factors would be a concern with the technology.

	Not a concern (0)	Minimal concern (1)	Low level concern (2)	Moderate concern (3)	High level concern (4)	Significant concern (5)	I don't know
Capital cost of technology	○	○	○	○	○	○	○
Observability	○	○	○	○	○	○	○
Organization culture	○	○	○	○	○	○	○
Potential cost savings from using technology	○	○	○	○	○	○	○
Technology budget within organization	○	○	○	○	○	○	○
Top management degree of involvement	○	○	○	○	○	○	○
Having an adoption plan in place	○	○	○	○	○	○	○
Having a Site Champion for each project site	○	○	○	○	○	○	○
Buy-in from the Project Manager	○	○	○	○	○	○	○
Projects will not pick up the budget unless they can pass the cost on to the owner	○	○	○	○	○	○	○
Corporate office will not pick up the budget unless they can pass the cost on to a project	○	○	○	○	○	○	○
Paying for ongoing maintenance cost	○	○	○	○	○	○	○

Q3 Please indicate the extent to which you think each of the following external-related factors would be a concern with the technology.

	Not a concern (0)	Minimal concern (1)	Low level concern (2)	Moderate concern (3)	High level concern (4)	Significant concern (5)	I don't know
Client demand	○	○	○	○	○	○	○
Direct competitors adopting similar technology	○	○	○	○	○	○	○
Industry-level change required for technology adoption	○	○	○	○	○	○	○
Partners adopt similar technology	○	○	○	○	○	○	○
Technical support from manufacturer	○	○	○	○	○	○	○
Technical support required for optimum performance	○	○	○	○	○	○	○
Mobile device restrictions on brownfield sites or within a plant	○	○	○	○	○	○	○
Use in hazardous areas	○	○	○	○	○	○	○
Use in remote locations	○	○	○	○	○	○	○

Q4. Please indicate the extent to which you think each of the following user-related factors would be a concern with the technology.

	Not a concern (0)	Minimal concern (1)	Low level concern (2)	Moderate concern (3)	High level concern (4)	Significant concern (5)	I don't know
Ease of use	○	○	○	○	○	○	○
Training required for optimum performance	○	○	○	○	○	○	○
Individual innovativeness	○	○	○	○	○	○	○
Technical capabilities of users	○	○	○	○	○	○	○

Q5. What do you think is the present technology readiness level (TRL) of this technology? Detailed descriptions of the technology readiness levels can be found at this link.

- ○ TRL 1: Initial technology basic principles are qualitatively postulated and observed by initial scientific research.
- ○ TRL 2: Potential practical applications and applicability are identified. The potential required procedure or material to reach the goal of using this technology is confirmed.
- ○ TRL 3: Initial development of the concepts, which include analytical and experimental proof, has started.
- ○ TRL 4: Alpha prototype procedure or system has been tested in the lab within a controlled environment. Results can provide evidence to prove that the targets of the concepts are achievable.
- ○ TRL 5: Prototype procedure or system has been tested in a simulated environment. Results show that the target can be achieved in a relevant environment.
- ○ TRL 6: Prototype procedure or system has been piloted on multiple projects with confirmed positive effects (beta prototype system level).
- ○ TRL 7: Concept of the prototype procedure or system has been accepted by enterprise-wide deployment (integrated pilot system level).
- ○ TRL 8: Actual procedure or system is qualified and completed through multiple deployments, proving the validation and positive impact of the technology (pre-commercial demonstration).
- ○ TRL 9: Actual procedure or system proves the effectiveness of the technology through successful operations in the operating environment. Technology is ready for full commercial deployment and has become a new proven, impactful, and sustainable enterprise standard.
- ○ I don’t know/Not sure

Q6. Please provide any additional comments about the technology and its potential application to detect last-minute changes in a construction work process.

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Fatality Assessment and Control Evaluation (FACE) Program
Case Review Rubric

Database: The database from which the report was collected.

Report Number: The report number from either the NIOSH FACE report database or the state FACE report database.

Title: The title from the FACE report.

Type of work: The type of work being conducted when the accident happened.

Hazard: The hazard present that led to the accident.

Result: The immediate action that caused the fatality.

Energy type: The primary type of energy associated with the result that led to the injury/fatality. Possible answers: chemical, electrical, gravity, mechanical, motion, pressure, sound, radiation, temperature, or biological. (See table below for definitions.)

Change Characteristics:

- *Hazards caused by a change?* Was the hazard that led to the incident caused by a change? Possible answers: Yes, No, or Maybe (Not enough information)
    - If the answer is No, all other Change Characteristics entries will be Not Applicable.
    - If the answer is Maybe, all other Change Characteristics, except type of change, will be Not Applicable.
    - If Yes, *what was the change?* What was the change that created the hazard that resulted in the incident?
- *Anticipated?* Could the change have been anticipated under normal conditions before the work began and anticipated with sufficient time to react/respond? Possible answers: Yes or No.
    - For example, a change like a car accident caused by vehicles not related to the construction work is assumed to be a change that could not be anticipated.
- *Recognizable?* Could the affected person have recognized the change would lead to a safety hazard with sufficient knowledge and time to react/respond? Possible answers: Yes or No.
- *Avoidable?* Could the affected person have avoided the change with sufficient time before it happened? Possible answers: Yes or No.
- *Type:* The type of change that caused the hazard in the incident. Example possible answers include, but are not limited to: process, environment, timing/schedule, design, work/equipment path, separation, location, access, work area intrusion, etc.

- *Last-minute?* Was the change a last-minute change?
  Possible answers: Yes or No.
  - A last-minute change is a change that occurs or manifests at the work face when there is limited time available to plan for and address the change.
- *Change connectivity:* Degree of connectivity of the affected person to the change (i.e., how "close" is the affected person to the origin of the change), or level of responsibility of the affected person for the change. Possible answers: Low, Medium, or High.

Technology to mitigate the change: The technology which could have been implemented to potentially mitigate the change. Possible answers: Any technology in the technology list, or question mark if no applicable technology is identified.

Applicability of technology to the change: The extent to which the technology identified is able to perform the steps necessary to identify and mitigate a change:

1. Identify the change.
2. Comprehend the change.
3. Project the impending risk.
4. Decide whether to take action.
5. Take any action deemed to be necessary.

Possible ratings:
0 = Not applicable, 1 = Very low, 2 = Low, 3 = Moderate, 4 = High, 5 = Very high, and ? = Not sure

If no technology was identified to mitigate the change, the rating in these five categories will be a question mark as well.

1. *Identification:* The ability of the technology to identify the change.
2. *Comprehension:* The ability of the technology to recognize, interpret, and evaluate the change event.
3. *Projection:* The ability of the technology to predict the future impact of the change (i.e., the safety risk).
4. *Decision:* The ability of the technology to make a decision to address or mitigate the change:
   a. The ability of the technology to make a decision whether to alert the potentially affected worker of the change.
   b. The ability of the technology to make a decision about whether and how to revise the work operation to mitigate the potential impact of the change. (If the technology cannot make this decision, the potentially affected worker then must do Step 4b and possibly Step 5 if deemed necessary.)
5. *Implementation:* The ability of the technology to implement the revised operation, if deemed necessary based on Step 4b.

Targeting Investigations of FACE Report: Possible answers: confined spaces, electrocutions, machine-related, falls from elevation, working youth, logging, deaths of foreign-born workers, and energy production (https://www.cdc.gov/niosh/face/desc.html).

Reference Section from the Report: An excerpt from the FACE report that provides useful information used to develop the answers for the case.

Energy Types and Definitions

Energy Category	Definition	Examples
Gravity	Force caused by the attraction of mass to the earth	Uneven work surface, work at height, unsecured materials, overhead support structures
Motion	Change in the physical position or location of objects or substances	Traffic, mobile equipment, projectiles, dust particles, soil movement
Mechanical	Working parts of a machine or assembly, including rotation, vibration, tension, or compression	Auger, cable, chain fall, angle grinder, gears, pulleys
Electrical	Presence of electrical charge or current	Wires, power lines, power tools, extension cords, transformer, relay
Sound	Audible vibration caused by the contact or two or more objects	Heavy machinery, pile driving, power tools, nail gun
Pressure	Liquid or gas compressed or under vacuum	Pneumatic tire, piping system, tank, hydraulic lines
Temperature	Intensity of heat in an object or substance	Friction, engines, sudden pressure change, steam
Chemical	Toxic objects or substances that pose health risks	Solvents, engine exhaust, silica, wood dust, liquid concrete
Radiation	Objects or substances that emit electromagnetic waves or subatomic particles	Welding, sun exposure, x-ray testing, radioactive waste
Biological	Living organisms or viruses	Bees, snakes, alligators, bears, restrooms

Appendix B: Technology Catalog

The following tables provide detailed information about each of the technologies identified as having potential for preventing SIFs due to last-minute work changes. The technologies are organized into seven categories:

- Category 1: Sensing
- Category 2: Monitoring
- Category 3: Visualization
- Category 4: Site Control/Site Access
- Category 5: Automation
- Category 6: Artificial Intelligence (AI)
- Category 7: Communication/Mobile Computing

Note: The data provided for the technologies included in Category 7 (quick response codes and dynamic safety signage) are for information purposes only. These technologies cannot detect any changes by themselves and, therefore, have limited benefit to the study scope. The technologies were not included in the technology analyses conducted.

Category 1: Sensing

Technology 1.1: Location Sensor – Sonar

Technology Characteristic	Description
Features (what does it have)	Uses sound pulse and echoes to measure the location of an object.
Capabilities (what can it do)	Emits sound pulses and receive echoes to determine the location of an object.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the location of each object in the work area
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	Low
Availability	Readily available to projects
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.2: Location Sensor – Global Positioning System (GPS)

Technology Characteristic	Description
Features (what does it have)	Uses satellite imagery to determine the location of an object.
Capabilities (what can it do)	Determines the location of an object on the construction site.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the location of each object on the site.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE, Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.3: Weather Sensor

Technology Characteristic	Description
Features (what does it have)	Uses electric currents and pressure and temperature measurements to determine weather conditions on the site.
Capabilities (what can it do)	Measures the weather conditions (temperature, humidity, pressure, wind speed, etc.) on the construction site.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect changes in the weather on the construction site.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	Medium
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018 (This article mentions many other individual sensors, such as temperature, humidity, pressure, etc. sensors, but no sensor that measures all weather conditions.) Example: https://www.acurite.com/shop-all/weather-instruments/weather-stations/pro-color-weather-station-with-forecast-temperature-humidity-wind-00622m.html

Technology 1.4: Light Sensor – Low Level of Light

Technology Characteristic	Description
Features (what does it have)	Uses light energy to measure the light level on the site.
Capabilities (what can it do)	Turns on lights if the amount of light is not sufficient for safe work operations.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the light level on the construction site.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.5: Light Sensor – High Level of Light

Technology Characteristic	Description
Features (what does it have)	Uses light energy to measure the light level on the site.
Capabilities (what can it do)	Turns off lights if the amount of light is too much for safe work operations.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the light level on the construction site.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.6: Noise Sensor

Technology Characteristic	Description
Features (what does it have)	Uses an internal diaphragm which can convert the vibration of the diaphragm to an electrical signal indicating the level of noise present.
Capabilities (what can it do)	Measures the magnitude of sound (decibels) to which workers are exposed on the construction site.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the magnitude of sound on the construction site.
Type of injury incident prevented	Acoustic trauma
Level of impact on injury frequency	Medium
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.7: Pressure Sensor

Technology Characteristic	Description
Features (what does it have)	Internal components that can sense the air pressure.
Capabilities (what can it do)	Measures the air pressure on the construction site.
Cost	Not applicable
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the air pressure on the construction site.
Type of injury incident prevented	Barotrauma
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.8: Temperature Sensor

Technology Characteristic	Description
Features (what does it have)	Internal components that can sense the air temperature.
Capabilities (what can it do)	Measures the temperature on the construction site.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the temperature on the construction site.
Type of injury incident prevented	Heat exhaustion, heatstroke
Level of impact on injury frequency	High
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Awolusi et al., 2018

Technology 1.9: Vibration Sensor

Technology Characteristic	Description
Features (what does it have)	A wristband-type biosensor, such as a smart watch, worn by a person to measure the amount of vibration present.
Capabilities (what can it do)	Measures the rate of vibrations on tools or equipment, such as a jackhammer.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the amount of vibration that a worker is exposed to.
Type of injury incident prevented	Repetitive motion injuries to joints/muscles
Level of impact on injury frequency	Medium
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE
Level of automation	2
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it still in the development process
Applicability to last-minute changes	High
References and additional resources	

Technology 1.10: Magnetic Field Sensor – Magnetometer

Technology Characteristic	Description
Features (what does it have)	Monitors and measures a change in the magnetic field at a specified location.
Capabilities (what can it do)	Measures the change in the magnetic field at a specific location.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Detect a change in the magnetic field that may affect worker safety.
Type of injury incident prevented	Vision and heart performance
Level of impact on injury frequency	Low
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Unknown
Extent of current use	Low
Availability	Unknown
Applicability to last-minute changes	Unknown
References and additional resources	Awolusi et al., 2018

Technology 1.11: Smart Sensor

Technology Characteristic	Description
Features (what does it have)	Internal components that can sense changes in environmental conditions.
Capabilities (what can it do)	Detects hazardous conditions like fire, humidity, leaks from a pipe, asbestos, or other toxins.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when it is installed on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Alerts people when hazards like fire, high humidity, leaks from a pipe, asbestos, or other toxins exist on the construction site.
Type of injury incident prevented	Vision and heart performance
Level of impact on injury frequency	Low
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Unknown
Extent of current use	Low
Availability	Unknown
Applicability to last-minute changes	Unknown
References and additional resources	

Category 2: Monitoring

Technology 2.1: Real-time Proactive Radio Frequency Warning and Alert Technology

Technology Characteristic	Description
Features (what does it have)	Wearable equipment for workers and equipment installed on a vehicle to warn the driver if there is an object nearby.
Capabilities (what can it do)	Detects the radio frequency identification (RFID) tag on both the personal protection unit (PPU) and the equipment protection unit (EPU). If the two tags are within a certain distance apart, it will alert both the person who wears the PPU and the driver of the equipment with EPU.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when workers are working on the construction site with moving equipment.
Additional resources needed to operate	None
Technology user(s)	Workers
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Protect workers from being struck by moving equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE, Administrative
Level of automation	2
Current extent of development	Fully developed, but still can improve
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Teizer et al., 2010

Technology 2.2: Blind Spot Assist

Technology Characteristic	Description
Features (what does it have)	A device installed on heavy equipment to warn the operator if there is an object in the blind spot of the equipment.
Capabilities (what can it do)	Notifies equipment operator that there is an object in the blind spot of the equipment.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the equipment is operating.
Additional resources needed to operate	None
Technology user(s)	Equipment operators
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent the equipment from hitting workers or objects in the blind spot of the equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	3
Current extent of development	Fully developed, but still can improve
Extent of current use	Medium
Availability	Limited availability because it still in the development process
Applicability to last-minute changes	High
References and additional resources	Teizer et al., 2010

Technology 2.3: Proximity Warning System (PWS)

Technology Characteristic	Description
Features (what does it have)	A device installed on heavy equipment to warn the operator if there is an object that is too close to the equipment.
Capabilities (what can it do)	Notifies the equipment operator that there is an object close to the moving equipment or the moving equipment is approaching objects
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when workers are working on the construction site with moving equipment.
Additional resources needed to operate	None
Technology user(s)	Workers
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Protect workers from being struck by moving equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE, Administrative
Level of automation	2
Current extent of development	Fully developed, but still can improve
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Choe et al., 2013; Kim et al., 2017; Luo et al., 2016; Nnaji et al., 2018. Example: https://zonesafe.net/

Technology 2.4: Vehicle Sensors for Operator Fatigue

Technology Characteristic	Description
Features (what does it have)	A device installed on heavy equipment to detect/ monitor the condition of the condition of the operator.
Capabilities (what can it do)	Notifies the driver that he or she is fatigued and must take a break.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when workers are driving the vehicle on or off the construction site.
Additional resources needed to operate	None
Technology user(s)	Workers
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Keep the driver awake and alert while driving vehicles and operating equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	6
Current extent of development	Fully developed, but still can improve
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Examples: https://www.cat.com/en_US/by-industry/mining/articles/fatigue-management.html https://www.youtube.com/watch?v=A66zgJ4Oj8o

Technology 2.5: Telematics for Vehicle Condition

Technology Characteristic	Description
Features (what does it have)	A device installed on a vehicle or equipment to detect/monitor the condition of the vehicle/equipment.
Capabilities (what can it do)	Notifies the driver that the vehicle is not in the appropriate condition to operate.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when workers are driving the vehicle on the construction site.
Additional resources needed to operate	None
Technology user(s)	Workers
Ease of use, training required	Easy to use; training may be required
Identified use for safety	Keep the vehicle in the appropriate conditions while being operated
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	3
Current extent of development	Fully developed, but still can improve
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Example: https://www.foxwelltech.com/product/item-20.html

Technology 2.6: Automated Cutting Protection

Technology Characteristic	Description
Features (what does it have)	A brake that is installed on a table saw to stop the saw blade to prevent a cut injury.
Capabilities (what can it do)	Stops the saw blade immediately if the blade is about to severely cut a worker.
Cost	$79.00 to $99.00
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used whenever people need to use the table saw on the construction site.
Additional resources needed to operate	None
Technology user(s)	Worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Protect worker’s fingers
Type of injury incident prevented	Cut injury
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE
Level of automation	10
Current extent of development	Fully developed
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Example: https://www.sawstop.com/

Technology 2.7: Camera Network Systems (CNS), Human-Controlled

Technology Characteristic	Description
Features (what does it have)	A network of cameras to provide real-time video monitoring of the site.
Capabilities (what can it do)	Uses cameras to monitor the construction site and send alerts to workers before the accident happens.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on the construction sites. All of the time when a worker is working on the construction site.
Additional resources needed to operate	Portable computer (e.g., table/laptop)
Technology user(s)	Safety Manager
Ease of use, training required	Easy to use; training required for the safety manager
Identified use for safety	Monitor the construction operation and talk to a worker directly via itself if that worker is close to hazards.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	Fully developed and reliable
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Hallowell et al., 2016b; Park and Brilakis, 2012; Rashidi et al., 2013; Tang et al., 2019; Zhang et al., 2019; Zhu et al., 2017. Example: https://www.truelook.com/

Technology 2.8: Drone/Unmanned Aerial Vehicle (UAV)

Technology Characteristic	Description
Features (what does it have)	An unmanned aerial vehicle with cameras that is used to monitor the conditions on a site.
Capabilities (what can it do)	Uses cameras to monitor the construction site from the viewpoint above the work site and communicate with workers directly.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on the surface of the construction sites. All of the time when a worker is working on the construction site and is visible from above the site.
Additional resources needed to operate	Portable computer (e.g., table/laptop)
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; training required for the safety manager
Identified use for safety	Monitor the construction work and communicate with a worker directly if that worker is close to hazards.
Type of injury incident prevented	All
Level of impact on injury frequency	Medium
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process
Applicability to last-minute changes	Medium
References and additional resources	Irizarry et al., 2012

Technology 2.9: Wearable – Worker Monitoring

Technology Characteristic	Description
Features (what does it have)	A biosensor that can recognize worker physical conditions (e.g., stress, heart rate, temperature, body position, etc.) and alert the worker if needed.
Capabilities (what can it do)	Analyzes the worker's stress level and alert the worker if the worker exhibits a high stress condition.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when a worker is working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Accurately determines the stress level of workers and identifies when the stress level is high.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative, PPE
Level of automation	4
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process
Applicability to last-minute changes	High
References and additional resources	Jebelli et al., 2019

Technology 2.10: Parking Package with 360° Camera

Technology Characteristic	Description
Features (what does it have)	An assist system that includes multiple cameras on the equipment to allow the operator to see the physical environment surrounding the equipment.
Capabilities (what can it do)	Provides a visual screen showing the physical environment surrounding the equipment to the equipment operator.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the equipment is operating especially when backing up.
Additional resources needed to operate	None
Technology user(s)	Equipment operator
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent the equipment from hitting other workers or objects around the equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	3
Current extent of development	Fully developed in other industries, but not in the construction industry.
Extent of current use	Low
Availability	Limited availability because it is still in the development process
Applicability to last-minute changes	High
References and additional resources	Example: https://www.youtube.com/watch?v=30o_nue0-oE

Technology 2.11: Active Brake Assist

Technology Characteristic	Description
Features (what does it have)	An assist system that is installed on heavy equipment to stop the equipment when it is about to hit an object such as a worker or object.
Capabilities (what can it do)	Stops the equipment when the equipment may strike a worker or objects.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the equipment is operating.
Additional resources needed to operate	None
Technology user(s)	Equipment operator
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent the equipment from hitting workers or objects in front of the equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	7 or 8
Current extent of development	Fully developed in other industries, but not in the construction industry.
Extent of current use	Low
Availability	Limited availability because it is still in the development process
Applicability to last-minute changes	High
References and additional resources	Example: https://www.youtube.com/watch?v=d1h_dHLWfL4

Technology 2.12: Equipment Proximity System – Retroreflective Sensor

Technology Characteristic	Description
Features (what does it have)	An assist system that can be installed on equipment to let the operator know that there is a worker(s) or objects close to or in the path of the equipment.
Capabilities (what can it do)	Detects standard day/night high-visibility vests, cones, and markers. Provides an alert to the operator when the equipment may crush/strike a worker or object.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the equipment is operating.
Additional resources needed to operate	None
Technology user(s)	Equipment operator
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent the equipment from hitting workers or objects close to the equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	3
Current extent of development	Fully developed
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	High
References and additional resources	Example: https://www.seensafety.com/

Technology 2.13: Equipment Proximity System – Machine Vision

Technology Characteristic	Description
Features (what does it have)	An assist system that includes multiple cameras on heavy equipment to allow the operator to see the physical environment surrounding the equipment.
Capabilities (what can it do)	Uses machine vision and artificial intelligence capabilities. Provides a visual screen that shows the environment surrounding the equipment to the equipment operator.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the equipment is operating especially when backing up.
Additional resources needed to operate	None
Technology user(s)	Equipment operator
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent the equipment from hitting workers or objects around the equipment.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	3
Current extent of development	Fully developed
Extent of current use	Low
Availability	Readily available to the project
Applicability to last-minute changes	High
References and additional resources	Example: http://blaxtair.com/

Category 3: Visualization

Technology 3.1: Laser Scanning and Lidar

Technology Characteristic	Description
Features (what does it have)	A device that emits light or a laser to create a digital representation of the surrounding environment.
Capabilities (what can it do)	Uses a laser beam to rapidly scan an object or the surrounding conditions on the construction site to build a 3D model of the scan.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used during the design and construction phase, and to monitor the site for changes to the design.
Additional resources needed to operate	A computer program such as BIM.
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the designer and project manager
Identified use for safety	Detect hazards before an accident happens by comparing actual conditions to planned conditions.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Engineering, Substitution, Elimination
Level of automation	2
Current extent of development	Developed, but still needs improvements for practical and economically feasible application
Extent of current use	Medium
Availability	Readily available to all workers
Applicability to last-minute changes	Low
References and additional resources	Karakhan and Alsaffar, 2019; Randall, 2011; SmartMarket Insight, 2019 Example: https://knowledge.autodesk.com/support/recap/learn-explore/caas/simplecontent/content/3d-laser-scanning-bim.html

Technology 3.2: Photogrammetry

Technology Characteristic	Description
Features (what does it have)	A visual method to analyze photographic images and videos.
Capabilities (what can it do)	Measure photographic images and videos to recreate motion paths and identify hazards on the construction site.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used during the design and construction phase, and to monitor the site for changes to the design.
Additional resources needed to operate	None
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the designer and project manager
Identified use for safety	Detect hazards before an accident happens by comparing actual conditions to planned conditions.
Type of injury incident prevented	All
Level of impact on injury frequency	Low
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Engineering, Substitution, Elimination
Level of automation	1
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process
Applicability to last-minute changes	Low
References and additional resources	Hoske and Kunze; 2004; Karakhan and Alsaffar, 2019; Navigant, 2016; SmartMarket, 2019; Tang et al., 2019.

Technology 3.3: Virtual Reality (VR) – Off-site

Technology Characteristic	Description
Features (what does it have)	A computer program that works with VR glasses to allow people to view a physical environment virtually and identify potential hazards and safety controls.
Capabilities (what can it do)	Allows people to view a construction site virtually and identify potential hazards and safety controls.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used during the design and construction phase, and to monitor the site for changes to the design.
Additional resources needed to operate	None
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the designer and project manager
Identified use for safety	Detect hazards before an accident happens by comparing actual conditions to planned conditions.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative, Engineering
Level of automation	2
Current extent of development	Developed, but still needs improvements
Extent of current use	Medium
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	Low
References and additional resources	Hallowell et al., 2016b; Li et al., 2018; Lin et al., 2011; Navigant, 2016; Park and Kim, 2013; SmartMarket, 2019; Wang et al., 2018. Example: https://aquicore.com/blog/virtual-reality-changing-construction-industry/

Technology 3.4: Augmented Reality (AR) – On-site

Technology Characteristic	Description
Features (what does it have)	A computer program that works with a portable computer (e.g., tablet) to allow people to walk through a physical environment and identify potential hazards and safety controls.
Capabilities (what can it do)	Allows people to walk through a construction site virtually and identify potential hazards and safety controls.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used during the design and construction phase, and to monitor the site for changes to the design.
Additional resources needed to operate	Physical construction site and portable computer (e.g., tablet/laptop)
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the designer and project manager
Identified use for safety	Detect hazards before an accident happens by comparing actual conditions to planned conditions.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	Medium
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative, Engineering
Level of automation	2
Current extent of development	Developed, but still needs improvements
Extent of current use	Medium
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	Medium
References and additional resources	Hallowell et al., 2016b; Li et al., 2018; Lin et al., 2011; Navigant, 2016; Park and Kim, 2013; SmartMarket, 2017; Wang et al., 2018. Example: https://www.bigrentz.com/blog/augmented-reality-construction

Category 4: Site Control/Site Access

Technology 4.1: BIM-based Fall Hazard System

Technology Characteristic	Description
Features (what does it have)	Computer software that automatically identifies a potential opening or edge on a slab or roof which would create a fall hazard. Then, the system adds a fall protection installation task and protection removal task to the project schedule.
Capabilities (what can it do)	Automatically identify a potential opening or edge on a slab or roof and then add fall protection tasks and protection removal tasks to the project schedule.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	During the design and construction phase, and to monitor the design after any changes to the design.
Additional resources needed to operate	Computer
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the designer and project manager
Identified use for safety	Prevent fall hazards on the construction site
Type of injury incident prevented	Fall injury
Level of impact on injury frequency	Low
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Engineering
Level of automation	4
Current extent of development	Still in research and testing
Extent of current use	Medium
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	Medium
References and additional resources	Zhang et al., 2015

Technology 4.2: Automated Flagger Assistance Device (AFAD)

Technology Characteristic	Description
Features (what does it have)	A system which includes a traffic signal, traffic sign, and an automatic control system to control/limit vehicles entering a work area.
Capabilities (what can it do)	Identify when vehicles, people, and equipment intrude into a work zone and replaces a human flagger.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Roadway or traffic projects
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Prevent objects, such as vehicles or pedestrians, from intruding into the work zone.
Type of injury incident prevented	Bruise, run over/struck by equipment
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Fully developed, but still can improve
Extent of current use	High
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Brown et al., 2018; Gambatese et al., 2017; Karakhan and Alsaffar, 2019; Nnaji et al., 2018. Example: https://www.northamericatraffic.com/products/flagging-devices/rcf2-4-automated-flagger-assistance-device#tab-features

Technology 4.3: Work Zone Intrusion Alert System

Technology Characteristic	Description
Features (what does it have)	A device installed on the boundary of a work zone to alert workers of a vehicle intrusion into the work zone.
Capabilities (what can it do)	Detects an intrusion of an object, such as a vehicle and people, into a work area.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all work taking place on all construction sites. All of the time when workers are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; no training is required
Identified use for safety	Alert workers of objects, such as vehicles or pedestrians, intruding into the work zone.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	2
Current extent of development	Fully developed, but still can improve
Extent of current use	High.
Availability	Readily available to all workers
Applicability to last-minute changes	High
References and additional resources	Navigant, 2016; Tang et al., 2019; Nnaji et al., 2018; SmartMarket Insight, 2019 Examples: • Traffic Guard Worker Alert System: https://www.aoindustrialsupply.com/product/worker-alert-system/ • Intellicone: https://www.highwayresource.co.uk/intellizone/ • Sonoblaster: https://www.tapconet.com/product/sonoblaster-work-zone-intrusion-alarm-and-accessories • AWARE: https://theasphaltpro.com/articles/oldcastle-aware-system/

Category 5: Automation

Technology 5.1: Autonomous Vehicle/Unmanned Ground Vehicle (UGV)

Technology Characteristic	Description
Features (what does it have)	A vehicle equipped with computer technology and cameras to allow the vehicle to drive by itself without the need for an operator.
Capabilities (what can it do)	Operate on its own without the need for an onboard operator.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when the project needs the vehicle on the construction site.
Additional resources needed to operate	None
Technology user(s)	All
Ease of use, training required	Easy to use; training required for the manager
Identified use for safety	Eliminate exposure to driving hazards for the driver
Type of injury incident prevented	Bruise, vehicle crash
Level of impact on injury frequency	Medium
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Elimination
Level of automation	6
Current extent of development	Developed, but still needs improvements
Extent of current use	High
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Example: https://www.cat.com/en_US/news/machine-press-releases/caterpillar-achieves-two-billion-tonnes-hauled-with-autonomous-trucks-system.html

Technology 5.2: Single-task Robots/Unmanned Ground System (UGS)

Technology Characteristic	Description
Features (what does it have)	Robotic equipment designed to perform a specific work task (e.g., bricklaying) with limited or no control by a user.
Capabilities (what can it do)	Performs construction work
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	For all projects on which the specific work operation is to be performed.
Additional resources needed to operate	None
Technology user(s)	Workers
Ease of use, training required	Easy to use; training required for the worker
Identified use for safety	Remove workers from the work location to eliminate/ reduce exposure to the hazards
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Elimination
Level of automation	8
Current extent of development	Varies, depending on type of work performed
Extent of current use	Low
Availability	Varies, depending on robot
Applicability to last-minute changes	Medium
References and additional resources	

Technology 5.3: Automated Site Monitoring Robot

Technology Characteristic	Description
Features (what does it have)	A robot that moves by itself around a site and collects physical site data through a camera. The collected data is then sent to a database, such as a BIM.
Capabilities (what can it do)	Automatically inspects the construction site by itself and sends the collected data to a database, such as BIM.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	Used during the construction phase, and all of the time when people are working on the construction site.
Additional resources needed to operate	Computer, tablet/laptop
Technology user(s)	Designer, Project Manager
Ease of use, training required	Easy to use; training required for the manager
Identified use for safety	Detect hazards before an accident happens by comparing actual conditions to planned conditions.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Substitution
Level of automation	6
Current extent of development	Developed, but still needs improvements
Extent of current use	Medium
Availability	Readily available to the project
Applicability to last-minute changes	Medium
References and additional resources	Example: https://www.bostondynamics.com/spot

Technology 5.4: Wearable – Work Assistance (e.g., Exoskeleton)

Technology Characteristic	Description
Features (what does it have)	Wearable auxiliary equipment that provides mechanical force to help the user perform intensive tasks such as moving heavy objects or conducting repetitive work.
Capabilities (what can it do)	Helps the user during intensive tasks such as moving heavy objects or performing repetitive work with mechanical force.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time if the worker has a heavy or repetitive work on the construction site.
Additional resources needed to operate	None
Technology user(s)	Worker
Ease of use, training required	Easy to use; training required for the manager
Identified use for safety	Decrease the need for using human force and muscle fatigue.
Type of injury incident prevented	Body Injury
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	PPE
Level of automation	4
Current extent of development	Developed, but still needs improvements
Extent of current use	Medium
Availability	Readily available to the project
Applicability to last-minute changes	High
References and additional resources	Examples: https://www.suitx.com/ https://www.bioservo.com/professional/ironhand https://eksobionics.com/

Category 6: Artificial Intelligence (AI)

Technology 6.1: Machine Vision

Technology Characteristic	Description
Features (what does it have)	A system that usually includes lighting, a camera to obtain images, software to analyze images, and output devices, and is used to analyze a physical environment.
Capabilities (what can it do)	Analyzes received images and determines the content depicted in the images.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when people are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; training may require to the manager
Identified use for safety	Detect hazards before an accident happens.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	8
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	High
References and additional resources	Examples: https://www.intenseye.com/ https://en.wikipedia.org/wiki/Machine_vision

Technology 6.2: Machine Learning/Deep Learning

Technology Characteristic	Description
Features (what does it have)	Computer software that utilizes previous experience and data to make predictions about future events/ conditions.
Capabilities (what can it do)	Improves the algorithms in the software by itself through previous experience and data. Then, it will use improved algorithms to make predictions.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when people are working on the construction site.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; training may require to the manager
Identified use for safety	Predict hazards before an accident happens.
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	8
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	High
References and additional resources	Example: https://en.wikipedia.org/wiki/Machine_learning

Technology 6.3: Natural Language Processing

Technology Characteristic	Description
Features (what does it have)	Computer software that can understand the meaning of the written content in a document or dataset, and then organizes and categorizes the information for review and analysis.
Capabilities (what can it do)	This technology can understand the meaning of the contents of data or a document. Then, the software organizes and categorizes the information from the data or document by itself.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when AI related programs are operating.
Additional resources needed to operate	None
Technology user(s)	Safety Manager, worker
Ease of use, training required	Easy to use; training may require to the manager
Identified use for safety	Automatically interpret content in documents that may impact safety on the site
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	8
Current extent of development	Still in research and testing
Extent of current use	Low
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	Low
References and additional resources	Example: https://en.wikipedia.org/wiki/Natural_language_processing

Category 7: Communication/Mobile Computing

Technology 7.1: Quick Response (QR) Code

Technology Characteristic	Description
Features (what does it have)	A two-dimensional barcode that acts as a machine-readable optical label which contains information about the item to which it is attached.
Capabilities (what can it do)	Provide quick access to information associated with the item to which it is attached.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	On all objects present on a construction site.
Additional resources needed to operate	Camera to read/scan the code
Technology user(s)	All
Ease of use, training required	Easy to use; limited training required
Identified use for safety	Interpretation of safety documentation
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	1
Current extent of development	High
Extent of current use	Low
Availability	Readily available to the project
Applicability to last-minute changes	Low
References and additional resources	Example: https://www.investopedia.com/terms/q/quick-response-qr-code.asp

Technology 7.2: Digital Safety Signage

Technology Characteristic	Description
Features (what does it have)	An electronic signage system that displays safety messages.
Capabilities (what can it do)	Automatically displays messages to workers regarding safety hazards present and actions to take to mitigate the hazards.
Cost	Not available
Applications (when, where, how, on what types of projects, trades, site conditions, operations, etc.)	All of the time when people are working on the construction site.
Additional resources needed to operate	Networked computer, access to wireless network
Technology user(s)	Project Manager, worker
Ease of use, training required	Training required to use
Identified use for safety	Inform workers of a hazard present on a work site and how to protect themselves from the hazard
Type of injury incident prevented	All
Level of impact on injury frequency	High
Level of impact on injury severity	High
Type of control (PPE, Administrative, Engineering, Substitution, or Elimination)	Administrative
Level of automation	8
Current extent of development	Developed, but still can be improved
Extent of current use	Low
Availability	Limited availability because it is still in the development process.
Applicability to last-minute changes	High
References and additional resources	

Appendix C: Technology Adoption Protocol Assessment Checklists

The technology adoption protocol contains three levels of assessment:

1. Preliminary Feasibility Evaluation
2. Technology Assessment
3. Pilot Test/Field Application/Demonstration and Assessment

Use a checklist at each assessment level to evaluate the technology. These checklists are provided over the following pages.

1. Preliminary Feasibility Evaluation

What is the name of the technology being evaluated?

____

____

What is the target application or use case of the technology?

____

____

1. Does this technology have potential capabilities to prevent or mitigate last-minute changes?

Yes	No
☐	☐

2. Is the capital cost of the technology affordable for the organization?

Yes	No
☐	☐

3. Are there any potential cost savings from using the technology?

Yes	No
☐	☐

4. Is the cost of operating and maintaining the technology affordable for the organization?

Yes	No
☐	☐

5. Is the technology easy to use?

Yes	No
☐	☐

6. Is the technology proven to be reliable in applications it is being considered/ evaluated for?

Yes	No
☐	☐

7. Is the technology scalable across the organization at the enterprise level?

Yes	No
☐	☐

8. Can the technology be used on multiple projects and on local sites?

Yes	No
☐	☐

Assessment Results: If the answer to any of the questions is “No,” the following assessments can be skipped and the technology omitted from consideration for adoption.

2. Technology Assessment

What is the name of the technology being evaluated?

____

____

What is the target application or use case of the technology?

____

____

Part 1. Organization Factors

1.1 What is the capital cost of the technology?

Extremely Expensive (–3)	Very Expensive (–2)	Somewhat Expensive (–1)	Average Cost (0)	Somewhat Inexpensive (1)	Very Inexpensive (2)	Extremely Inexpensive (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.2 To what extent does the technology create a competitive advantage or disadvantage compared with the competition?

Extreme Disadvantage (–3)	Significant Disadvantage (–2)	Minor Disadvantage (–1)	No Advantage or Disadvantage (0)	Minor Advantage (1)	Significant Advantage (2)	Extreme Advantage (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.3 How compatible is the technology with current processes and technologies?

Extremely Incompatible (–3)	Very Incompatible (–2)	Somewhat Incompatible (–1)	Average Compatibility (0)	Above Average Compatibility (1)	Very Compatible (2)	Extremely Compatible (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.4 Can the technology be observed before adoption?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

1.5 How will the technology change the organization’s culture?

Extreme Negative Change (–3)	Significant Negative Change (–2)	Somewhat Negative Change (–1)	No Change (0)	Somewhat Positive Change (1)	Significant Positive Change (2)	Extreme Positive Change (3)	I don’t know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

If a change will occur, describe how the technology will change the organization’s culture.

____

____

1.6 What is the organization’s general overall attitude toward innovation associated with technology?

Extremely Opposed (–3)	Very Opposed (–2)	Somewhat Opposed (–1)	Neither Receptive nor Opposed (0)	Somewhat Receptive (1)	Very Receptive (2)	Extremely Receptive (3)	I don’t know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.7 What is the level of potential cost impact from using the technology?

Significant Additional Cost (–3)	Moderate Additional Cost (–2)	Minimal Additional Cost (–1)	No Impact (0)	Minimal Cost Savings (1)	Moderate Cost Savings (2)	Significant Cost Savings (3)	I don’t know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.8 Does the organization have sufficient safety budget to support implementation of the technology?

No (–3)	Yes (3)	I don’t know/ Need more information
☐	☐	☐

1.9 What is the degree of interest, support, and involvement from top management in the adoption of the technology? (e.g., executive support, and consistent messaging from the executive sponsor)

Extremely Opposed (–3)	Very Opposed (–2)	Somewhat Opposed (–1)	No Support (0)	Minimal Support (1)	Moderate Support (2)	Significant Support (3)	I don’t know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.10 Does the organization have an adoption and implementation plan in place for the technology?

No (–3)	Yes (3)	I don’t know/ Need more information
☐	☐	☐

1.11 Does the organization have an adoption and implementation partner, or is the organization seeking one?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

1.12 Is there a champion for the technology on each project site?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

1.13 To what extent do Project Managers buy-in and support adoption of the technology?

Extremely Objection (–3)	Significant Objection (–2)	Some Objection (–1)	No Buy-in or Support (0)	Some Buy-in and Support (1)	Significant Buy-in and Support (2)	Extreme Buy-in and Support (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.14 What is the level of additional financial resource impact associated with operating and maintaining the technology?

Significant Additional Financial Resources (–3)	Moderate Additional Financial Resources (–2)	Minimal Additional Financial Resources (–1)	No Additional Financial Resources (0)	Minimal Cost Savings (1)	Moderate Cost Savings (2)	Significant Cost Savings (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.15 To what degree can the cost of the technology be passed on to others (e.g., clients)?

Significant Opposition (–3)	Moderate Opposition (–2)	Minimal Opposition (–1)	No Impact (0)	Minimal Transfer (1)	Moderate Transfer (2)	Significant Transfer (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.16 To what degree can the cost of the technology be charged to each project?

Significant Limitations (–3)	Moderate Limitations (–2)	Minimal Limitations (–1)	No Impact (0)	Minimal Transfer (1)	Moderate Transfer (2)	Significant Transfer (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

1.17 To what extent were the technology end-users involved in technology selection and evaluation, and did they support selection of the technology?

Significant Opposition (–3)	Moderate Opposition (–2)	Minimal Opposition (–1)	No Involvement and Support (0)	Minimal Involvement and Support (1)	Moderate Involvement and Support (2)	Significant Involvement and Support (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

Part 2. Individual User Factors

2.1 How easy is it to use the technology?

Extremely Difficult to Use (–3)	Highly Difficult to Use (–2)	Somewhat Difficult to Use (–1)	Average Ease of Use (0)	Above Average Ease of Use (1)	Very Easy to Use (2)	Extremely Easy to Use (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

2.2 To what extent is training required for optimum technology operation and performance?

Extremely Extensive Training Required (–3)	Highly Extensive Training Required (–2)	Somewhat Extensive Training Required (–1)	Average Training Required (0)	Somewhat Intuitive to Use (1)	Very Intuitive to Use (2)	Extremely Intuitive to Use (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

2.3 What is the level of individual innovativeness/creativity in the organization?

Extremely Uncreative (–3)	Highly Uncreative (–2)	Somewhat Uncreative (–1)	Average Creativity (0)	Above Average Creativity (1)	Highly Creative (2)	Extremely Creative (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

2.4 What is the general level of technical capability of the users in the organization?

Extremely Low Capabilities (–3)	Very Low Capabilities (–2)	Some Capabilities (–1)	Average Capability (0)	Above Average Capability (1)	High Capability (2)	Extremely High Capability (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

Part 3. Technology Factors

3.1 How durable is the technology?

Extremely Delicate (–3)	Highly Delicate (–2)	Somewhat Delicate (–1)	Average Durability (0)	Above Average Durability (1)	Highly Durable (2)	Extremely Durable (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.2 What is the reliability of the technology in applications it is being considered/ evaluated for?

Extremely Unreliable (–3)	Highly Unreliable (–2)	Somewhat Unreliable (–1)	Average Reliability (0)	Above Average Reliability (1)	Highly Reliable (2)	Extremely Reliable (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.3 Can the end-user test the technology before adopting it?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

3.4 How versatile is the technology?

Extremely Specialized (–3)	Highly Specialized (–2)	Somewhat Specialized (–1)	Average Versatility (0)	Above Average Versatility (1)	Highly Versatile (2)	Extremely Versatile (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.5 To what extent does the technology have features needed to perform the specified task?

Very Many Required Features Missing (–3)	Many Required Features Missing (–2)	Some Required Features Missing (–1)	Required Features Present (0)	Some Additional Features Present (1)	Many Additional Features Present (2)	Very Many Additional Features Present (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.6 How complex is the technology?

Extremely Uncomplicated (–3)	Very Uncomplicated (–2)	Somewhat Uncomplicated (–1)	Average Complexity (0)	Above Average Complexity (1)	Very Complex (2)	Extremely Complex (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.7 How well does the technology integrate with currently existing systems/work processes?

Extremely Incompatible (–3)	Highly Incompatible (–2)	Somewhat Incompatible (–1)	Average Compatibility (0)	Above Average Compatibility (1)	Highly Compatible (2)	Extremely Compatible (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.8 To what degree can the technology be used in hazardous areas/conditions?

Extreme Limitations in Hazardous Conditions (–3)	Significant Limitations in Hazardous Conditions (–2)	Some Limitations in Hazardous Conditions (–1)	No Limitations (0)	Can Be Used in Some Hazardous Conditions (1)	Can Be Used in Many Hazardous Conditions (2)	Can Be Used in Extreme Hazardous Conditions (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

3.9 Can the technology be used remotely?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

Part 4. External Factors

4.1 Is the technology required by one or more clients?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

4.2 Are there government policies and/or regulations related to, or requiring use of, the technology or a similar technology?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

4.3 Is there an industry standard for using the technology?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

4.4 Does the organization need to implement the technology in response to changes in the industry?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

4.5 Have the organization's partners and/or close associates adopted the technology or a similar technology?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

4.6 To what degree does the technology manufacturer provide technical support?

Extremely Limited Support (–3)	Very Limited Support (–2)	Somewhat Limited Support (–1)	Average Support (0)	Above Average Support (1)	Significant Support (2)	Extensive Support (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

4.7 To what extent is technical support required for optimum performance?

Extremely Critical (–3)	Very Critical (–2)	Somewhat Critical (–1)	Average Requirement (0)	Above Average Independence (1)	Significantly Independent (2)	Extremely Independent (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

Part 5. Vendor Factors

5.1 To what degree does the vendor provide after-sales service for the technology?

Extremely Limited Service (–3)	Very Limited Service (–2)	Somewhat Limited Service (–1)	Average Service (0)	Above Average Service (1)	Significant Service (2)	Extensive Service (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

5.2 Does the vendor provide a performance guarantee with the technology?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

5.3 Does the vendor provide a warranty with the technology?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

5.4 To what extent does the vendor provide training for the technology?

Extremely Limited Training (–3)	Very Limited Training (–2)	Somewhat Limited Training (–1)	Average Training (0)	Above Average Training (1)	Significant Training (2)	Extensive Training (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

5.5 To what extent does the vendor provide maintenance services for the technology?

Extremely Limited Services (–3)	Very Limited Services (–2)	Somewhat Limited Services (–1)	Average Services (0)	Above Average Services (1)	Significant Services (2)	Extensive Services (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

5.6 Does the vendor have a relationship/motivation program?

No (–3)	Yes (3)	I don't know/ Need more information
☐	☐	☐

5.7 What is the vendor organization's capacity to support the technology in any way?

Extremely Limited Capacity (–3)	Very Limited Capacity (–2)	Somewhat Limited Capacity (–1)	Average Capacity (0)	Above Average Capacity (1)	Significant Capacity (2)	Extensive Capacity (3)	I don't know/ Need more information
☐	☐	☐	☐	☐	☐	☐	☐

Technology Assessment Analysis and Results

Complete the summary analysis table below based on the answers to each of the question above.

Assessment Section	Total # of Factors	Number of Factors in Each Category				Subtotal of Positive and Negative Scores	
		Negative Factors (A)	Neutral Factors (B)	Positive Factors (C)	"I don't know" (IDK) Factors (D)	Subtotal Negative Score (E)	Subtotal Positive Score (F)
Part 1: Organization Factors	17						
Part 2: Individual User Factors	4						
Part 3: Technology Factors	9						
Part 4: External Factors	7						
Part 5: Vendor Factors	7						
Total	**44**						
Total Assessment Score (Column E + Column F) =							
Maximum Possible	–	44	44	44	44	–132	+132

Total Assessment Score

range: –132 to +132

Modified Total Assessment Score

range: –3 × (44 – IDK factors) to 3 × (44 – IDK factors)

Interpretation of Results:

1. If the total number of "I don't know" (IDK) factors is high, the evaluation is not valid. More information is needed.
2. If the Total Assessment Score is high, perform the Pilot Test/Field Application/ Demonstration assessment for further consideration and possible adoption.
3. If the Total Assessment Score is low or negative, the technology should not be adopted.

3. Pilot Test, Field Application, and Demonstration Assessment

What is the name of the technology being evaluated?

____

____

What is the target application or use case of the technology?

____

____

Part 1. Technology Development

1. What is the extent of development of the technology (Technology Readiness Level)?

TRL 1	TRL 2	TRL 3	TRL 4	TRL 5	TRL 6	TRL 7	TRL 8	TRL 9
☐	☐	☐	☐	☐	☐	☐	☐	☐

(See the table provided below for a description of each TRL level.)

2. Is this technology ready to use?

Yes	No
☐	☐

3. What is the level of automation (LOA) of the technology?

1	2	3	4	5	6	7	8	9	10
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

(See the table provided below for a description of each automation level.)

4. Is the level of automation of this technology enough for the usage purpose?

Yes	No
☐	☐

5. Is this technology easy to use?

Yes	No
☐	☐

6. Does this technology integrate with existing technologies?

Yes	No
☐	☐

7. What type of control is the technology?

PPE	Administrative	Engineering	Substitution	Elimination
☐	☐	☐	☐	☐

Part 2. Technology Applicability to Last-minute Changes

8. Does the technology have the ability to monitor site conditions and work operations?

Yes	No
☐	☐

9. Does the technology have the ability to detect last-minute changes?

Yes	No
☐	☐

9a. If Yes to Question 9, what kind(s) of last-minute change can the technology detect?

____

____

9b. If Yes to Question 9, does the technology detect and act upon last-minute changes within an appropriate time?

Yes	No
☐	☐

10. Does the technology prevent SIFs due to last-minute changes?

Yes	No
☐	☐

11. Does the ability of the technology to detect and respond to last-minute changes provide a positive impact?

Yes	No
☐	☐

12. Does weather impact the technology's ability to detect and respond to last-minute changes?

Yes	No
☐	☐

13. Does the technology have the ability to comprehend safety hazards resulting from last-minute changes? Note: In this context, comprehend means to determine that a hazard exists and to identify the type and nature of the hazard.

Yes	No
☐	☐

14. Does the technology have the ability to project the safety risk from last-minute changes? Note: In this context, projecting the safety risk means to estimate and foresee the consequences of worker exposure to the hazard based on injury frequency and severity.

Yes	No
☐	☐

Part 3. Technology Alerts

15. Does the technology have the ability to send alerts to affected workers and/or those who oversee the work?

Yes	No
☐	☐

15a. If Yes to Question 15, what kind(s) of alerts does the technology send (e.g., visual, audio)?

____

____

15b. If Yes to Question 15, does the technology send alerts to affected workers and/or responsible parties within an appropriate time?

Yes	No
☐	☐

15c. If Yes to Question 15, does the alert work well enough to warn workers?

Yes	No
☐	☐

Part 4. Technology Decisions and Actions

16. Does the technology have the ability to identify options/alternatives for mitigating the impacts of last-minute changes?

Yes	No
☐	☐

16a. If Yes to Question 16, does the technology identify options/alternatives for mitigating the impacts of last-minute changes within an appropriate time?

Yes	No
☐	☐

17. Does the technology have the ability to decide which option(s) to select to mitigate last-minute changes?

Yes	No
☐	☐

17a. If Yes to Question 17, does the technology make the decision within an appropriate time?

Yes	No
☐	☐

17b. If Yes to Question 17, what kind(s) of decisions can the technology make?

____

____

17c. If Yes to Question 17, are the decisions effective for preventing serious injuries and fatalities (SIFs)?

Yes	No
☐	☐

18. Does the technology have the ability to implement the selected action(s) after making the decision?

Yes	No
☐	☐

18a. If Yes to Question 18, does the technology take action within an appropriate time?

Yes	No
☐	☐

18b. If Yes to Question 18, what kind(s) of actions can the technology make?

____

____

18c. If Yes to Question 18, are the actions effective for preventing serious injuries and fatalities (SIFs)?

Yes	No
☐	☐

Technology Readiness Levels (TRLs)

Phase	Technology Readiness Level (TRL)	Description and Requirements
Basic Research	1	• Initial technology basic principles are qualitatively postulated and observed by initial scientific research. • Do basic scientific principles support the concept? • Has the technology development methodology or approach been developed?
	2	• Potential practical applications and applicability are identified. The potential required procedure or material to reach the goal of using this technology is confirmed. • Are potential system applications identified? • Are system components and the user interface at least partly described? • Do preliminary analyses or experiments confirm that the application might meet the user's need?
	3	• Initial development of the concepts, which include analytical and experimental proof, has started. • Are system performance metrics established? • Is system feasibility fully established? • Do experiments or modeling and simulation validate performance predictions of system capability? • Does the technology address a need or introduce an innovation in the field of construction?
Applied Research	4	• Alpha prototype procedure or system has been tested in the lab within a controlled environment. Results can provide evidence to prove that the targets of the concepts are achievable. • Are end-user requirements documented? • Does a plausible draft integration plan exist, and is component compatibility demonstrated? • Were individual components successfully tested in a laboratory environment (a fully-controlled test environment where a limited number of critical functions are tested)?
	5	• Prototype procedure or system has been tested in a simulated environment. Results show that the target can be achieved in a relevant environment. • Are external and internal system interfaces documented? • Are target and minimum operational requirements developed? • Is component integration demonstrated in a laboratory environment (i.e., fully controlled setting)?

Development	6	• Prototype procedure or system has been piloted on multiple projects with confirmed positive effects (beta prototype system level). • Is the operational environment (i.e., user community, physical environment, and input data characteristics, as appropriate) fully known? • Was the prototype tested in a realistic and relevant environment outside the laboratory? • Does the prototype satisfy all operational requirements when confronted with realistic problems?
	7	• Concept of the prototype procedure or system has been accepted by enterprise-wide deployment (integrated pilot system level). • Are available components representative of production components? • Is the fully integrated prototype demonstrated in an operational environment (i.e., real-world conditions, including the user community)? • Are all interfaces tested individually under stressed and anomalous conditions?
	8	• Actual procedure or system is qualified and completed through multiple deployments, proving the validation and positive impact of the technology (pre-commercial demonstration). • Are all system components form-, fit-, and function-compatible with each other and with the operational environment? • Is the technology proven in an operational environment (i.e., meets target performance measures)? • Was a rigorous test and evaluation process completed successfully? • Does the technology meet its stated purpose and functionality as designed?
Implementation	9	• Actual procedure or system proves the effectiveness of the technology through successful operations in the operating environment. Technology is ready for full commercial deployment and has become a new proven, impactful, and sustainable enterprise standard. • Is the technology deployed in its intended operational environment? • Is information about the technology disseminated to the user community? • Is the technology adopted by the user community?

Levels of Automation (LOA) Analysis and Conversion to Construction *(Liu, 2019)*

LOA	Description *(Sheridan and Verplanck 1978)*	Data Collection	Decision			Perform	Notify	Constr. LOA	Description
			Alt.	*Sel.*	*App.*				
1	Human does the whole job up to the point of turning it over to the computer to implement	H*	H	H	H	H	N/A	1	Construction workers do the whole job with assistance of human-controlled machine
2	Computer helps by determining the options	C**	C/H	H	H	H	N/A	2	Sensors embedded to collect data for human to analyze
3	Computer helps to determine options and suggests an option, which human need not follow	C	C	H	H	H	N/A	3	Intelligent automated system; system assists human workers on data analysis and decision-making
4	Computer selects action and human may or may not do it	C	C	C/H	H	H	N/A		
5	Computer selects action and implements it if human approves	C	C	C	H	H	N/A		
6	Computer selects action, and informs human in plenty of time to stop it	C	C	C	C	C/H	N/A	4	Highly intelligent automated system; system makes decisions and performs the work. Provides performance report and system warning to human workers when necessary.
7	Computer does whole job and necessarily tells human what it did	C	C	C	C	C	If necessary		
8	Computer does whole job and tells human what it did only if human explicitly asks	C	C	C	C	C	Need to ask		
9	Computer does whole job and decides what the human should be told	C	C	C	C	C	C decide to tell		
10	Computer does the whole job if it decides it should be done, and if so, tells human, if it decides that the human should be told	C	C	C	C	C	C decide not to tell	5	Highly intelligent automated system; system makes decisions and performs the work without notifying human workers.

Notes

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