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DIGITAL INNOVATIONS IN CONSTRUCTION HEALTH AND SAFETY: A SYSTEMATIC LITERATURE REVIEW

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Abstract

The construction industry is one of the most hazardous industries, with persistently high rates of injuries and fatalities. Traditional approaches to safety management are largely reactive, relying on inspections, checklists and investigations after incidents occur. These approaches are valuable but often insufficient to prevent recurring accidents or establish proactive safety cultures. In recent years, digital technologies such as Building Information Modelling (BIM), wearable devices, Internet of Things (IoT) sensors, Artificial Intelligence (AI) and immersive virtual environments have entered the construction sector. These technologies enable earlier hazard detection, real-time monitoring and improved training opportunities for workers and managers. This study systematically reviews digital technologies applied in construction health and safety between 2015 and 2025. The review follows the PRISMA framework and analyses peer-reviewed literature retrieved from Scopus and Discover databases. After screening and applying inclusion criteria, 68 studies were selected for analysis. The findings classify digital technologies across five analytical dimensions including stage of application, mode of application, response type, machine-human interaction and nature of deployment. Results show that digital technologies contribute to hazard detection, immersive training, real-time monitoring and data-driven safety planning. Despite clear benefits, adoption remains uneven due to cost, interoperability challenges, limited digital literacy and concerns about privacy. The review concludes that digital technologies are transforming safety management from reactive compliance to proactive risk prevention, offering significant potential to improve worker protection and safety performance across the construction industry.

Keywords: construction safety; digital technologies; BIM; wearables; proactive risk management.

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1. Introduction

Construction is one of the most essential industries for economic and social development, yet it remains among the most hazardous due to the nature of its work environments. It plays a vital role in shaping infrastructure and supporting national growth but continues to record some of the highest rates of injuries and fatalities worldwide. Tasks such as working at heights, handling heavy equipment and operating in dynamic site conditions make construction inherently risky [1].

Traditional health and safety management practices remain largely reactive, focusing on inspections, checklists and investigations after incidents occur. While these measures support compliance, they are often insufficient to prevent recurring hazards or establish a strong proactive safety culture [1]. Digital transformation in construction has accelerated rapidly in recent years, supported by tools such as BIM, wearable devices, IoT sensors, drones and artificial intelligence. Together, these technologies enable safety managers to move from reactive to proactive risk control by integrating real-time data and predictive analysis into everyday operations [2]. Despite the potential of these technologies, their practical integration remains inconsistent across the industry. Financial constraints, interoperability

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challenges, cultural resistance and regulatory ambiguity continue to limit adoption. Many organizations still rely on traditional paper-based safety management systems that identify hazards only after incidents occur [3].

The aim of this research is to investigate how digital technologies can improve construction health and safety through hazard detection, safety warnings and practical application across construction projects. The study specifically identifies digital technologies used in construction safety, examines their functions and explores their strengths and limitations.

2. Literature review

2.1. Digital innovations for health and safety

The construction industry has increasingly embraced digital technologies as part of efforts to improve health and safety management. Conventional safety approaches respond after hazards emerge and depend on periodic inspections, which limits their effectiveness. Digital solutions provide opportunities for proactive monitoring, predictive analytics and immersive training environments. Technologies such as BIM, AR/VR, wearable devices, sensor-based tools and robotics enhance hazard detection, simulate safe work practices and generate real-time data for informed decision-making [4, 5].

2.2. Classification of digital technologies

Digital technologies for construction health and safety can be classified according to their stage of application, mode of application, response type, machine-human interaction and nature of deployment.

At the design stage, modelling tools such as BIM identify hazards early and improve safety planning. Immersive environments created using AR and VR allow workers to practice tasks and recognise risks before entering construction sites [6]. During construction activities, wearable devices monitor workers' physiological conditions while drones and sensor networks provide real-time alerts about site hazards [7]. BIM primarily functions as a digital repository for design and construction information, whereas digital twins incorporate real-time, bi-directional data exchange through sensors and IoT systems. Unlike static BIM environments, digital twins continuously update site conditions and support predictive safety monitoring and adaptive decision-making [8].

Technologies are applied at different stages of construction and help to increase safety. In the design stage, BIM-based tools help identify hazards before physical work begins and support prevention-through-design practices [9]. For training and workspace preparation, AR/VR simulations recreate construction environments and high-risk scenarios, strengthening hazard recognition and building safe work behaviours [4, 10]. During site operations and inspections, wearables and sensor networks track worker health and environmental conditions in real time, while drones and cameras provide aerial perspectives and evidence for safety audits and hazard assessments [11–13]. These applications support compliance, prevent accidents and enable adaptive safety strategies throughout the project lifecycle.

2.3. Functions of digital technologies

The reviewed literature highlights several key functions of digital technologies in construction safety. Sensor networks and wearable devices support hazard detection and prediction by identifying unsafe postures, fatigue or environmental risks before accidents occur [2, 14, 15]. Training and simulation are enhanced through immersive AR and VR applications that allow workers to rehearse hazardous tasks and emergency procedures in safe environments [4, 10]. Real-time monitoring is achieved through wearable devices and IoT systems that continuously track worker health and site conditions. Immersive virtual reality environments support safety planning by enabling workers and managers to simulate hazardous scenarios, including the safe operation of unmanned aerial vehicles in construction contexts [16]. Decision support and safety planning are further enhanced through BIM and digital twin models that integrate safety information into project planning and management processes [8, 17]. Digital safety technologies present a range of strengths that make them valuable across the construction lifecycle. They improve hazard visibility through BIM-based modelling and site-wide sensors, offer predictive insights using AI and machine learning and create immersive training environments through AR/VR that allow workers to rehearse high-risk activities without exposure to danger [4, 10]. Wearables and IoT devices also contribute by generating continuous streams of safety data that can be transformed into actionable insights, enabling rapid intervention and supporting more informed decision-making [14].

2.4. Strengths, limitations and opportunities

Digital safety technologies offer several advantages including real-time data collection, predictive risk modelling and immersive training environments. Table 1 summarises the major strengths, limitations and future opportunities associated with key digital technologies used in construction safety with the evidence supporting from reviewed literature.

Table 1. Strengths, Limitations and Opportunities of Digital Safety Technologies with supporting evidence

Technology	Strengths	Limitations	Opportunities	Supporting Evidence
BIM	Early hazard detection	Data complexity	Digital twins	[9, 12, 17]
AR/VR	Immersive training	Equipment cost	Remote training	[4, 10, 12, 16]
Wearables	Real-time monitoring	Privacy concerns	AI safety analytics	[2, 14, 15]
IoT Sensors	Environmental monitoring	Integration issues	Smart sites	[8, 14]

However, several barriers continue to restrict widespread adoption including high initial costs, interoperability challenges, limited digital literacy and worker resistance to monitoring technologies [2, 3, 17]. Despite these challenges, advances in artificial intelligence and digital twins present opportunities for more accurate risk prediction and proactive safety management [6].

Challenges remain particularly for small and medium-sized enterprises that often lack financial resources, digital expertise and technological infrastructure. Evidence indicates that larger firms have begun experimenting with digital approaches such as BIM integration for prevention through design [9, 18], drones for inspections [13] and wearables for fatigue monitoring [2, 14]. However, interoperability issues, high implementation costs and the absence of clear regulatory guidance continue to restrict wider adoption of digital safety technologies across the industry [3, 19].

3. Practical applications of digital technologies

Digital technologies provide practical solutions for improving safety management across construction projects. Wearable technologies such as smart helmets and wristbands track workers' physiological conditions including fatigue, temperature and movement. These tools provide early warnings before workers reach unsafe thresholds, reducing the likelihood of accidents [2, 15].

Environmental sensors and IoT platforms extend monitoring to the wider worksite by detecting hazards such as noise, dust, heat exposure and toxic gases. Drones equipped with cameras enable remote inspection of hazardous locations, reducing the need for workers to enter dangerous areas [13]. BIM also plays an important role during the design stage by embedding safety considerations into digital models. By visualising hazards before construction begins, BIM enables prevention-through-design practices that reduce risks during project execution [9, 19]. Together, these technologies provide earlier hazard detection, improved worker awareness and more effective communication of safety information across construction projects. Recent studies further demonstrate that practical applications are most effective when multiple digital technologies are integrated rather than implemented in isolation. Review evidence shows that wearables, AR/VR, AI and navigation-related systems can support proactive safety through monitoring, immersive training, automation and collision prevention [20]. BIM-based immersive virtual reality improves workspace planning by identifying hazard zones, equipment spaces and layout congestion before site work begins [21]. Safety ontology models further support BIM interoperability by linking safety concepts with digital models, allowing hazards to be identified and managed earlier in the project lifecycle [22]. Immersive VR training improves excavation safety by strengthening hazard identification, safety knowledge and long-term retention compared with traditional manual-based training [23]. Artificial intelligence supports safety by predicting accidents, detecting hazards and managing risks through integration with BIM, wearables, computer vision, robotics and IoT systems [24]. Wearable technologies such as smart helmets, vests and vibration sensors provide real-time monitoring of worker health, fatigue and exposure to unsafe conditions [25]. Integrated digital delivery frameworks combine BIM, VR/AR, smart PPE, sensors, IoT, AI and UAVs to support proactive and collaborative safety management across the project lifecycle [26]. AR, BIM and sensor-based inspection tools can also improve inspection accuracy, reduce human error and lower physical workload during construction activities [27].

4. Reflection on risks

While digital technologies offer clear safety benefits, their implementation also introduces new risks that must be considered. Wearable monitoring systems may raise concerns about privacy and surveillance if workers feel that their personal data are being misused. High costs associated with digital systems and technical complexity may create barriers for small and medium enterprises that lack financial resources or technical expertise. Interoperability issues between different technologies can also create challenges when integrating BIM, sensors and wearable devices into existing workflows. In addition, some workers may resist new technologies due to discomfort, lack of familiarity or concerns about increased monitoring. Without appropriate training and clear policies regarding data usage, these technologies may generate distrust among workers rather than improving safety outcomes. Recognising these risks is essential to ensure that digital technologies are implemented responsibly and effectively within construction environments [2, 3, 17].

Despite the benefits of digital integration, several operational and organisational risks remain. Successful implementation depends on effective interoperability between software platforms, consistent data standards and clearly defined digital workflows [28, 29]. In the absence of these conditions, organisations may experience fragmented information, duplication of effort and reduced confidence in the outputs generated by digital tools [30, 31]. There is also a risk that advanced technologies are introduced without sufficient workforce training or organisational readiness, limiting their practical value and creating resistance among users [32, 33]. To maximise the benefits of digital safety technologies, organisations should adopt phased implementation strategies supported by governance frameworks, targeted training and continuous evaluation of system performance [34, 35].

5. Methodology

A systematic literature review was adopted to examine the use of digital technologies in construction health and safety. The review followed the PRISMA 2020 framework to ensure transparency in identifying, screening and analysing relevant studies. Peer-reviewed literature was retrieved from Scopus and Discover databases. The search strategy used Boolean combinations of keywords including "construction safety", "digital technologies", "BIM", "wearables", "IoT", "digital twin", "AR/VR" and "hazard detection". Only peer-reviewed English-language studies published between 2015 and 2025 and directly related to construction health and safety were included. After removing duplicates and applying inclusion and exclusion criteria, 68 studies were selected for analysis. Studies were screened based on relevance to construction health and safety, methodological clarity and direct application of digital technologies. Non-peer-reviewed articles, conference papers and studies unrelated to construction safety were excluded. Quality assessment was conducted through manual evaluation of methodological transparency, relevance and consistency with the research objectives. Data extracted from each study included the digital technologies used, research methods, safety applications and key findings. Thematic synthesis was then applied to identify patterns across technologies, project stages and safety functions. The PRISMA flow diagram showing the literature screening process is shown in Fig. 1. In addition to thematic synthesis, a bibliometric analysis was conducted using VOSviewer software to explore relationships between key research themes within the selected literature. Keyword co-occurrence analysis was applied to visualise clusters of digital technologies used in construction health and safety research and is illustrated in Fig. 2. This approach helps identify dominant themes and emerging trends in areas such as BIM, wearable technologies, artificial intelligence, sensors and immersive technologies. The bibliometric network highlights the central role of BIM in current safety research.

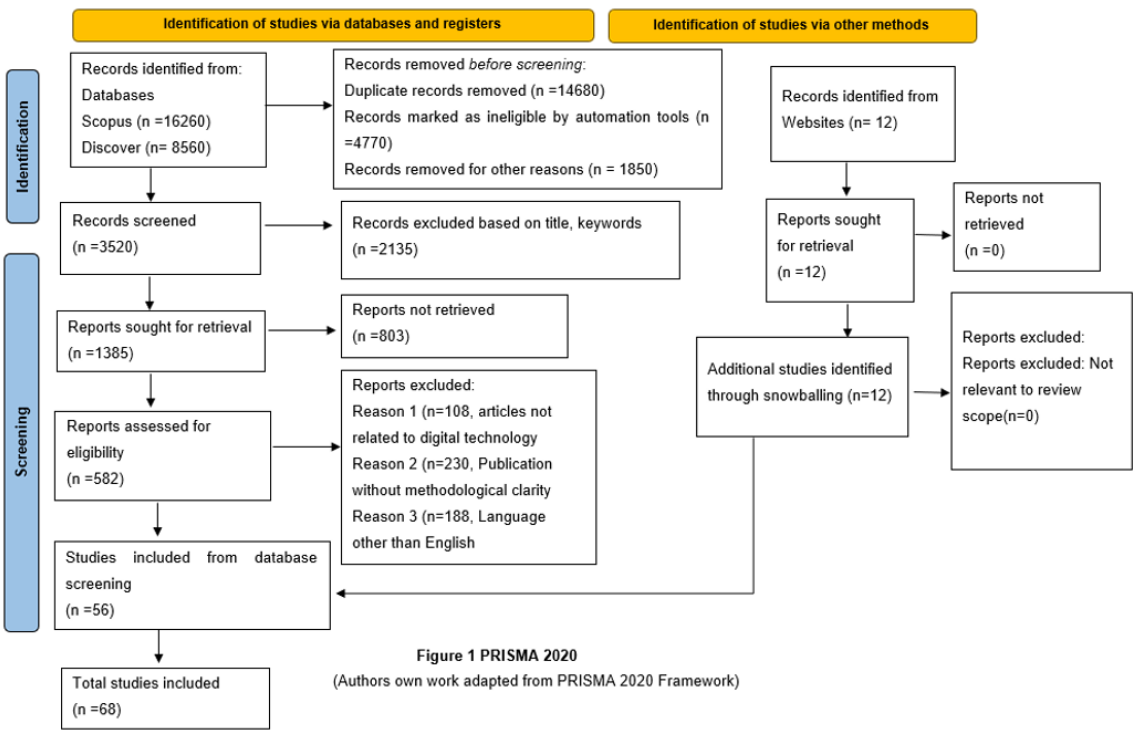

Figure 1. PRISMA flow diagram showing the literature screening process

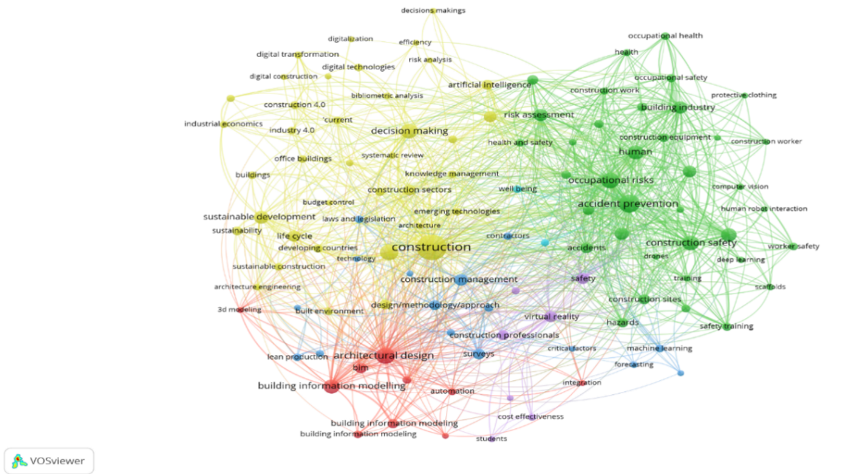

Figure 2. Keyword co-occurrence network of digital technologies in construction health and safety generated using VOSviewer

6. Results

The review findings show that digital technologies contribute to construction safety through four key outcomes: improved hazard visibility, enhanced training, proactive risk management and data-driven safety planning. These relationships between digital technologies, safety functions, construction stages and safety outcomes are illustrated in Fig. 3.

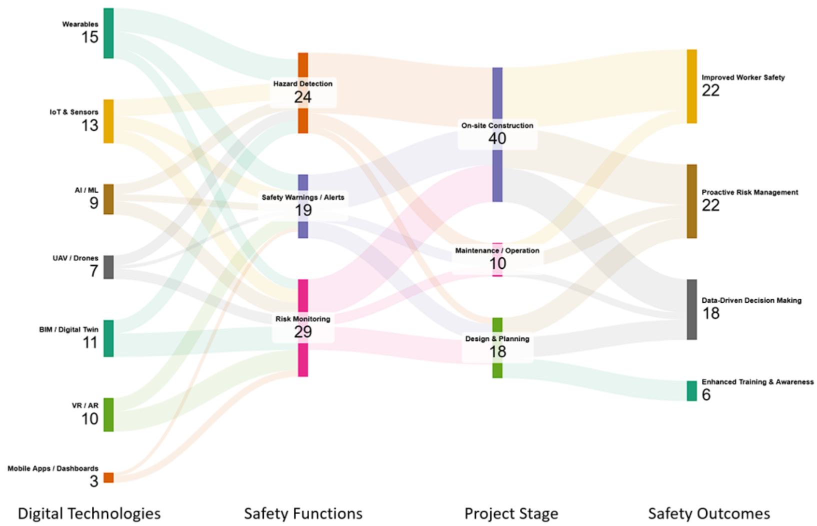

Figure 3. Sankey diagram illustrating relationships between digital technologies, safety functions, construction stages and safety outcomes. The numerical values represent the frequency of occurrence of themes identified within the reviewed studies.

Wearable devices and environmental sensors provide real-time monitoring of worker health and site conditions. Drones and computer vision technologies extend monitoring capabilities to hazardous areas where human access may be dangerous. Immersive technologies such as AR and VR strengthen worker training by simulating hazardous situations and improving hazard recognition. BIM and digital twin systems integrate safety data into project planning, allowing managers to identify risks and implement preventive measures earlier in the project lifecycle.

6.1. Contributions of digital technologies in health and safety

The review findings show that digital technologies contribute to construction health and safety through several interconnected pathways. As illustrated in the Sankey diagram, tools such as wearables, AR/VR, IoT sensors, AI/ML, drones, BIM and mobile platforms support functions including hazard detection, safety warnings, risk monitoring and design integration. These technologies operate across project stages, particularly during on-site construction but also during design and maintenance. The literature identifies four key outcomes: improved hazard visibility and monitoring, stronger training and worker awareness, proactive risk management, and data-driven safety planning.

a. Enhancing hazard visibility and monitoring

Digital technologies improve hazard visibility and monitoring on construction sites. Traditional safety practices rely heavily on manual inspections, supervision and incident reporting, which are often reactive and limited by human observation. Digital tools enhance risk awareness and enable earlier hazard detection.

Wearable technologies such as smart helmets and biometric devices monitor workers' physiological conditions including pulse, temperature and movement. These tools can detect fatigue, heat stress and unsafe postures before incidents occur, providing early warnings for workers and supervisors. Environmental sensors and IoT systems extend monitoring to the wider site by detecting hazards such as dust, toxic gases and noise. Drones and computer vision technologies enable inspection of hazardous areas and automatic detection of unsafe behaviours or missing PPE. At the design stage, BIM contributes to hazard prevention by identifying risks such as fall hazards or spatial conflicts before construction begins. When combined with IoT data, BIM can evolve into digital twin systems that integrate real-time information with predictive analysis. Immersive technologies such as AR and VR also improve hazard recognition by simulating hazardous environments and enabling workers to practise tasks safely.

b. Strengthening training and worker awareness

Digital technologies enhance training effectiveness and worker awareness. Traditional training methods such as manuals or toolbox talks often fail to reflect real site conditions. Digital tools provide interactive and immersive environments that improve engagement and learning outcomes.

Virtual reality allows workers to experience hazardous situations in simulated environments, improving hazard recognition and decision-making. Augmented reality further supports training by overlaying safety information onto real environments and highlighting hazard zones during site activities. BIM-based training also improves safety awareness by visualising construction sequences and potential hazards using 4D models. When combined with VR or AR, these models allow workers to explore site conditions before work begins. Wearable devices can also provide behavioural data related to fatigue or posture, helping trainers identify unsafe practices and target training interventions.

c. Proactive risk management through real-time monitoring

Digital technologies enable proactive risk management through real-time monitoring. Construction sites are dynamic environments where hazards can develop quickly, and traditional safety systems often respond only after incidents occur.

Wearable devices monitor physiological indicators such as heart rate, fatigue and posture, allowing early detection of unsafe conditions. IoT sensor networks capture environmental data including temperature, dust, noise and vibration, generating alerts when thresholds are exceeded. Artificial intelligence can analyse these datasets to identify patterns and predict potential risks. Drones and computer vision technologies further expand monitoring by detecting structural hazards and unsafe behaviours across large construction sites. When integrated with BIM and digital twins, these data streams create dynamic site representations that help managers assess risks and adjust plans in real time.

d. Data-driven decision making and safety planning

Digital technologies also support data-driven decision making and safety planning. Traditional safety management often relies on manual observations and post-incident investigations, which are reactive and subjective. Digital systems generate continuous datasets that support more informed planning.

BIM enables hazards to be visualised within 3D and 4D project models alongside schedules and resources. Automated rule-checking tools can identify potential risks during the planning stage. Digital twins extend this capability by combining BIM models with real-time data from sensors and wearable devices, allowing managers to test scenarios and evaluate safety interventions.

IoT platforms and wearable devices provide detailed data on worker health and environmental conditions, enabling managers to make timely decisions such as adjusting schedules or implementing protective measures. VR and AR technologies further support planning by allowing managers and workers to rehearse construction activities and identify risks before work begins.

7. Discussions

The findings indicate that digital technologies are shifting construction safety management from reactive inspection toward proactive risk prevention. Real-time monitoring systems allow managers to detect hazards earlier and respond more quickly to changing site conditions.

However, adoption remains uneven across the construction sector. Large organisations are more likely to adopt BIM, IoT and advanced analytics, while smaller contractors often face barriers related to cost, technical expertise and infrastructure. Greater collaboration between industry, government and research institutions is required to promote digital literacy, provide financial incentives and develop regulatory guidance supporting digital safety practices.

Advances in digital technologies present important opportunities for improving construction health and safety. Artificial intelligence and machine learning can support predictive analytics by analysing data from wearables, IoT sensors and site monitoring systems, enabling hazards to be identified earlier than traditional supervision methods.

Digital twins also offer significant potential. By integrating BIM models with real-time data from sensors and wearable devices, digital twins create dynamic site representations that allow managers to test scenarios and implement preventive measures. As technology costs decrease, these systems may become more accessible to smaller construction firms.

Global developments in interoperability and regulatory frameworks also create opportunities. Aligning international approaches such as OSHA proactive training systems, UK HSE prevention-through-design principles and EU IoT standards with New Zealand regulations could support stronger adoption. Integrating these practices within HSWA 2015 and WorkSafe NZ initiatives may further encourage the use of digital safety technologies across the sector.

These global developments are also relevant to the New Zealand construction sector, where injury and fatality rates remain relatively high. The Health and Safety at Work Act (HSWA) 2015 strengthened the regulatory framework and emphasised proactive risk management and shared responsibility among duty holders. In response, some organisations have begun adopting digital approaches such as BIM for prevention-through-design, drones for site inspections and wearable technologies for fatigue monitoring. Environmental sensors are also increasingly used to monitor site conditions such as noise, dust and air quality. These technologies demonstrate growing potential for improving hazard detection and supporting more proactive safety planning.

Despite these developments, the adoption of digital safety technologies in New Zealand remains uneven. The construction industry is dominated by small and medium enterprises that often face barriers related to high implementation costs, limited digital expertise and uncertainty regarding the benefits of new technologies. As a result, many firms continue to rely on traditional inspection and reporting methods. Targeted policy support, industry training programmes and clearer regulatory guidance may help accelerate the adoption of digital safety technologies across the sector. The study contributes by integrating fragmented digital safety technologies into a unified analytical framework linking technology functions, project stages and safety outcomes.

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