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MONETARY BENEFIT QUANTIFICATION FOR SMART CONSTRUCTION SAFETY TECHNOLOGY

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Abstract

Construction sites are inherently hazardous environments where accidents can lead to severe human, financial, and legal consequences. Despite the growing adoption of safety regulations and monitoring systems, construction accidents remain a persistent issue, incurring substantial economic losses for companies and society. However, there is limited research on systematically quantifying the financial benefits of implementing smart safety technology, making it difficult for construction firms to make data-driven investment decisions. To address this gap, this study proposes a systematic approach to quantify the economic benefits of implementing smart safety technology at construction sites. The economic benefit is calculated in monetary values, based on accident case data from a real construction project in South Korea. Basic project information, including total construction costs, the number of workers, the number of equipment units, and the construction duration, is first collected. Then, the loss costs of safety accident, considering settlement costs, legal costs, interrupted construction costs, safety investigation costs, and penalties under the Serious Accident Punishment Act, are estimated. Subsequently, the potential number of fatalities by considering site characteristics and fatal accident rates in South Korea is predicted. Monte Carlo Simulation is conducted to reflect the uncertainties in a construction suspension period and a workforce size, enabling a more realistic economic analysis that is not confined to a specific case. The economic analysis confirms the range of investment costs for implementing smart safety technology that is economically beneficial. This provides construction firms with clearer criteria for making informed decisions about adopting smart safety equipment.

Keywords: Construction Safety, Smart Safety Equipment, Economic Feasibility, Monte Carlo Simulation

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1. Introduction

To protect workers from accidents, construction managers implement safety training, provide personal protective equipment, and manage high-risk areas. However, these conventional safety management methods have shown limitations in effectively preventing accidents [1]. While other industries have enhanced workplace safety levels through the adoption of smart safety technologies, the construction domain, which has a lower level of digital technology adoption, continues to experience frequent accidents [2].

The proactive introduction of smart technology has been proposed as an effective means to reduce on-site accidents in construction [3]. Smart safety technologies refer to a broad range of systems and devices that utilize digital technologies to prevent accidents and enhance worker protection on construction sites. Representative examples include wearable devices, computer vision systems, UAVs (Unmanned Aerial Vehicles), BIM (Building Information Modelling), IoT (Internet of Things), VR (Virtual Reality), and AR (Augmented Reality). Wearable devices monitor workers' conditions in real time and issue warnings in hazardous situations. Computer vision technology and UAVs verify the use of personal protective equipment and predict dangerous circumstances, while IoT is used to assess real-time risk factors. BIM is used to represent risks of jobsites for better management in 3D spatial perspectives. VR and AR provide more realistic safety training environments. Various studies have demonstrated the

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effectiveness of smart safety technology in improving situational awareness, automating risk detection, and enhancing overall project performance. However, despite these proven benefits, construction firms often perceive the adoption of such technologies primarily as an additional financial burden rather than a source of economic value [4].

Previous studies have consistently suggested that an appropriate level of investment in construction safety can enhance overall performance [5] and that the benefits gained from accident prevention can significantly surpass the associated costs [6]. These studies have emphasized the necessity and effectiveness of safety investments within the construction industry, theoretically supporting the idea that reducing accidents can lead to long-term financial gains. Nevertheless, in the context of implementing new technologies such as smart safety systems, there remains a lack of research that quantitatively estimates the specific economic benefits generated by these technologies. Most previous studies have primarily focused on demonstrating technical feasibility or qualitative improvements, without providing objective economic evidence sufficient to support investment decisions. As a result, skepticism persists in actual field settings regarding the financial advantages of smart safety technologies, and concerns over additional costs continue to serve as major barriers to adoption. Ultimately, this uncertainty leads to hesitation in decision-making, preventing the full realization of the potential value that smart safety technologies could bring to construction sites.

Therefore, a structured economic analysis is necessary to quantitatively assess the financial viability of implementing smart safety technologies. The objective of this study is to evaluate the Economic Feasibility (EF) of deploying smart safety technologies by comparing accident prevention benefits with the associated implementation costs. The analysis proceeds through the following steps. First, fundamental project information is collected from an actual construction site, including total construction costs, number of workers, number of equipment, project duration, and labor costs. Second, additional expenditures associated with accidents are identified, such as settlement costs, legal costs, construction interruption costs, safety investigation costs, and the period of construction suspension due to fatal accidents. Third, based on the project's scale, duration, and number of workers, the average fatality rate derived from historical data is applied to estimate the potential number of fatalities that could occur at the site. This step allows for a realistic reflection of accident risk. Fourth, Monte Carlo Simulation (MCS) is conducted to probabilistically incorporate variability in key factors such as the number of workers and construction suspension periods, thereby deriving a generalized distribution of potential accident-related loss costs across multiple scenarios. Finally, the estimated number of potential fatalities, accident-related loss costs obtained from the MCS, improvements in accident prevention rates achieved through smart technologies, and the cost of implementing these technologies are integrated to assess at what level of accident reduction efficiency and investment cost economic benefits begin to emerge for smart safety technology adoption in construction sites.

2. Related Work

2.1. Cost Calculation in the Occurrence of Accidents

Various studies have analyzed the economic losses from accidents and the significance of safety cost investments in the construction sector. One study in Australia estimated the actual costs of construction accidents, classifying them into direct and indirect costs [7]. The study found that indirect costs significantly exceeded direct costs, and the range of accident costs was calculated and presented. Another study developed a cost-loss estimation framework reflecting the characteristics of the Korean construction industry, estimating losses per individual [4]. According to a study based on data from the U.S. Bureau of Labor Statistics [8], the economic impact of construction-related injuries was estimated by quantifying direct, indirect, and quality-of-life costs. Direct costs encompassed medical expenses, inpatient care, and rehabilitation services, whereas indirect costs included wage losses of injured workers, productivity declines due to work stoppages, and expenses related to workplace reorganization. The study also found that the total cost of construction accidents accounted for a substantial portion of the private industry’s overall costs, with the average cost per injury exceeding that of other sectors. While previous research primarily focused on calculating costs arising from accidents, a study in Istanbul, Turkey examined how much safety costs constitute of the total construction costs [9]. Using activity-based risk assessment, initial safety costs including personal protective equipment, collective protective measures, and training were estimated at about 1.92% of the total construction costs. Another study using Spanish construction industry data, industrial safety costs, consisting of insurance, preventive measures, accident-related costs, and recovery costs, represented about 5% of the total expenses [10]. These prior studies provide valuable data on the cost structure of accidents at construction sites and offer insights into how much should be invested in accident prevention.

2.2. Estimating the Economic Benefits of Accident Prevention

Numerous studies have evaluated the economic impact of accident prevention achieved through the implementation of safety technologies. One study quantitatively assessed the safety investment costs required to prevent major accidents during chemical processes, along with the expected economic benefits, using the Net Present Value method [11]. In this study, major loss categories included work stoppages, equipment and facility damage, and economic losses associated with fatalities. In the automotive sector, research on the EF of intelligent speed adaptation systems incorporated costs such as digital map and sensor installation, maintenance, equipment updates, and map updates, while reflecting accident reduction and fuel savings as benefits, based on an Net Present Value analysis [12]. In the maritime industry, the EF of implementing Wi-Fi-based radio frequency identification tags for passenger tracking was assessed by applying the cost of averting a fatality method, comparing system installation costs to the number of fatalities potentially averted [13]. Furthermore, the economic value of incomplete flood warning and response systems was estimated using the relative economic value method, comprehensively considering the annual average flood damage costs, additional costs due to forecast uncertainty, and warning system implementation costs [14]. In the case of earthquake early warning systems, a Benefit-Cost analysis was conducted by incorporating the economic benefits of damage prevented by warnings, the annual probability of earthquake occurrence, and forecast accuracy [15]. Similarly, the EF of sprinkler installations in buildings was evaluated through a Benefit-Cost analysis, taking into account direct loss costs such as property damage and human casualties, as well as fire frequency [16]. As such, prior studies have quantitatively assessed the accident prevention effects across various industries and evaluated the economic benefits of adopting technologies and systems.

2.3. Knowledge Gap of Previous Studies

Prior research has either focused on identifying the cost structures of construction site accidents or quantitatively analyzing the effects of safety technology adoption in other industries. These studies have contributed significantly to supporting the necessity of accident prevention investments and the economic benefits of technology implementation. However, in the construction industry, there remains a notable lack of studies that quantitatively assess the economic benefits of introducing smart safety technologies. Without clear empirical evidence or precise projections regarding the EF of smart safety technology adoption, construction firms are likely to perceive such investments as uncertain or risky. Therefore, this study aims to address this gap by quantitatively estimating the accident prevention benefits derived from the deployment of smart safety technologies at construction sites and evaluating their EF.

3. Quantitative Economic Feasibility Analysis of Smart Safety Technology Adoption

3.1. Economic Feasibility Analysis

In general, companies invest in technology with the goal of generating direct profits, whereas implementing safety equipment aims to achieve economic benefits by reducing costs associated with accidents [11]. In other words, the cost effectiveness of smart safety technologies should be evaluated based on the economic gains realized through accident prevention, which must be calculated using potential accident cost savings.

However, it is difficult to predict how many accidents may occur at a construction site and how much accident reduction could be achieved through the adoption of smart safety technologies. Accident occurrence and reduction are influenced by multiple factors, including site scale, number of workers, and project duration. Therefore, in order to quantitatively estimate the accident reduction effect of smart safety technology adoption, it is first necessary to calculate the potential number of accidents. To this end, this study estimates the potential number of fatalities by comprehensively considering historical fatal accident rates by site, the number of workers, and the project duration, as expressed in Eq. (1):

$$Pnf = Frw \times Now \times Pd \tag{1}$$

where "Pnf" represents the potential number of fatalities, "Frw" refers to the fatality rate per 10,000 workers, "Now" indicates the number of workers at the site, and "Pd" denotes the project duration in years.

Based on the estimated potential number of fatalities, this study calculates the accident reduction effect by applying the accident prevention probability of smart safety technologies. Considering the reduction in various accident-related costs—including settlement costs, legal costs, safety investigation costs, construction interruption costs, and penalties for serious accidents—the overall EF of investing in smart safety technologies is calculated using Eq. (2):

$$Ef = Ap \times Pnf \times (Sc + Lc + Sic + Icc + Ps) – Is \tag{2}$$

Here, "Ap" is the accident prevention probability of smart safety technology, "Pna" is the potential number of fatalities, "Sc" is settlement costs, "Lc" is legal costs, "Sic" is safety investigation costs, "Icc" is interrupted construction costs, "Ps" is penalties for serious accidents, and "Ise" is the investment in smart safety technology. Through this structured estimation process, the study aims to quantitatively assess the EF of smart safety technology adoption at construction sites and provide practical decision-making criteria for investment evaluation.

3.2. Monte Carlo Simulation

When accident-related costs at construction sites are analyzed deterministically based on a single case, the results are confined to that scenario and fail to adequately capture the diverse conditions of actual sites. Economic losses from accidents vary significantly across projects, and if the variability of influencing factors is not considered, accident-related losses may be underestimated or overestimated, thereby undermining the reliability of the EF analysis. To overcome these limitations, this study applies MCS. The models key variables as random variables and derives the probability distribution of outcomes through repeated simulations [17]. By adopting this approach, accident-related costs can be represented not as fixed values but as random variables with probabilistic characteristics [18], enabling a more realistic economic evaluation that accounts for diverse site conditions and uncertainties. In this study, the variability of key input factors was considered based on actual data, including the number of workers according to site scale, the period of construction suspension caused by accidents, and settlement amounts. Through this MCS process, accident cost variations under diverse scenarios are reflected, allowing for a more precise evaluation of the EF of adopting smart safety technologies.

4. Case Study

4.1. Background

The Korean construction industry recorded an annual average of approximately 600 fatalities between 2001 and 2022 [19]. The fatality rate per 10,000 persons stands at 2.16, which is approximately 2.1 times higher than the overall industry average and significantly exceeds the OECD average [20]. These statistics highlight the persistent exposure of the Korean construction sector to serious safety risks and the urgent need to develop more effective accident prevention strategies. Traditional safety training and management efforts alone are insufficient to significantly reduce accidents at construction sites. It is essential to proactively prevent accidents through the adoption of advanced technologies such as smart safety equipment. Against this backdrop, this study aims to quantitatively analyze the economic benefits of introducing smart safety technologies in the Korean construction industry. This study focuses on the potential cost savings from accident-related expenses that construction firms would otherwise incur, thereby reinforcing the practical justification for adopting smart safety technologies. Previous studies have analyzed the total costs associated with fatal accidents [4], but they focused primarily on the overall societal costs incurred after accidents. They did not specifically analyze the detailed cost items that construction firms must directly bear when adopting safety equipment. Moreover, new institutional factors such as the Serious Accident Punishment Act, enacted in 2022, were not considered in prior research. This law imposes criminal liability on management personnel, such as CEOs, if one or more fatalities occur, if two or more workers are injured and require treatment for more than six months, or if three or more occupational illnesses occur within a year due to the same cause. In cases of violations of safety and health obligations, managers can face a minimum of one year of imprisonment and fines of up to KRW 1 billion. Therefore, this study comprehensively evaluates not only the direct and indirect costs incurred by construction firms in the event of accidents, but also the additional legal risks and fines introduced by the Serious Accident Punishment Act, providing a more realistic and precise assessment of the EF of adopting smart safety technologies.

4.2. Data Acquisition

In this study, we selected Project A, a railway project in which an actual accident occurred, as a case example. The total construction cost was USD 291,438,980, and the project duration was 60 months. During this time, an average of 299 workers and 40 pieces of construction equipment were employed on a daily basis. Additional costs arising from the accident were obtained from actual data provided by the construction site’s stakeholders. Table 1 presents various cost items for Project A and their respective amounts. The safety investigation cost was USD 36,430, and in the event of a fatal accident, the settlement costs to compensate the bereaved family were USD 728,597. The penalty under the Serious Accident Punishment Act was USD 72,860, and the legal costs amounted to USD 291,439. The interrupted construction costs were USD 1,630,763, calculated by including the wages that needed to be paid to workers who could not work during the suspension and the costs of halting the equipment operation.

Table 1. Detailed Information of Project A

Factors	Project A
Total Construction Cost (USD)	291,438,980
Period (Months)	60
Number of Workers (Persons)	299
Number of Equipment (Units)	40
Period of Construction Suspension (Days)	40
Settlement Cost (USD)	728,597
Legal Cost (USD)	291,439
Interrupted Construction Cost (USD)	1,640,763
Safety Investigation (USD)	36,430
Serious Accident Punishment Act (USD)	72,860

4.3. Cost and Benefit

The economic benefits of implementing smart safety technology are calculated based on the costs that can be avoided through accident prevention. By summing the settlement costs, legal costs, interrupted construction costs, and fines under the Serious Accident Punishment Act presented in Table 1, a total construction cost of USD 291,438,980 is derived, which corresponds to the actual accident-related costs incurred in the case of Project A. To calculate the accident prevention benefits using Eq. (2), it is necessary to additionally consider the potential number of accidents and the accident prevention probability resulting from the introduction of smart safety technology.

Fig. 1 illustrates the number of fatal accidents per 10,000 workers based on the size of construction sites in Korea. For sites employing between 100 and 299 workers, which corresponds to Project A's workforce size of 299 workers, a fatal accident rate of 0.000156 is applied [19]. Given that the project duration is five years, the cumulative number of workers amounts to 1,495. Applying the fatal accident rate to this cumulative workforce and calculating through Eq. (1) results in an estimated 0.223418 potential fatalities. Using the estimated potential number of fatalities, the accident prevention benefits can be quantitatively calculated. Specifically, by multiplying the potential fatalities by the total accident-related costs in Project A, an expected loss of approximately USD 646,597 is derived. This figure represents the amount of loss that could occur if no accident prevention measures are taken. Conversely, it also represents the economic benefit that could be secured if all fatal accidents are prevented through the implementation of smart safety technology.

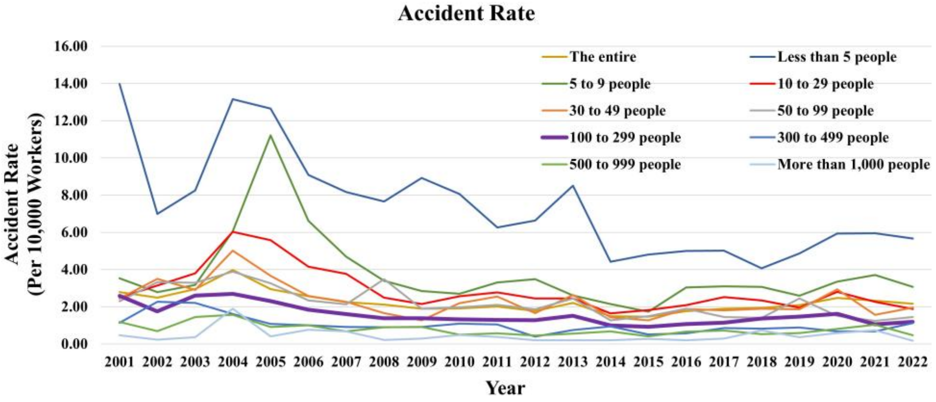

Fig. 1. Fatal Accident Rate in Korea (2001–2022)

The cost of implementing smart safety technology was estimated by assuming that a certain percentage of the total construction costs would be invested. For Project A, the total construction costs are USD 291,438,980, and 1% of this amount corresponds to approximately USD 2,914,390. However, this implementation cost exceeds the total potential accident-related costs of Project A. When summing the cost of implementing smart safety technology and the potential savings from accident prevention, the result becomes negative, indicating that at a 1% investment rate, the EF cannot be secured.

Therefore, this study assumes that Project A invests between 0.01% and 0.1% of the total construction costs in smart safety technology, corresponding to an investment range of approximately USD 29,144 to USD 291,439. By estimating the implementation costs as a proportion of the total construction costs, the appropriate scale of investment required to prevent accidents and achieve EF can be determined.

4.4. Application of Monte Carlo Simulation

To evaluate the EF of implementing smart safety technology more realistically, this study conducted MCS by incorporating the variability of construction suspension periods, the number of workers, and settlement costs, based on the Project A case. First, the variability of the construction suspension period was modelled using data from construction site accidents in South Korea over the past four years (2020–2023) [21]. In 2020, the average suspension period was 49.6 days across 581 cases; in 2021, it was 51.4 days across 584 cases; in 2022, 63.7 days across 561 cases; and in 2023, 54.3 days across 579 cases. The minimum and maximum average values across these years were identified as 49.6 and 63.7 days, respectively. A lognormal distribution was fitted to represent this variability, and the Kolmogorov–Smirnov test confirmed its suitability with the highest p-value of approximately 0.87. Thus, the construction suspension period was assumed to follow a lognormal distribution. Second, for settlement costs, 30 accident cases from 2021 to 2024 were collected from law firm websites in South Korea, with amounts ranging from USD 80,145 to USD 728,59 [22]. The lognormal distribution again provided the best fit, supported by the highest Kolmogorov–Smirnov p-value of approximately 0.816 Third, the number of workers was assumed to follow a triangular distribution, based on the fact that the workforce size in the Project A case falls within the 100 to 299 range, which corresponds to the accident rate classification. This assumption reflects the typical worker distribution for construction sites of similar scale.

Based on these variable settings, the MCS results are summarized in Fig. 2. The figure presents the individual simulation outcomes for construction suspension period, settlement costs, and number of workers, as well as the total loss distribution combining all factors. The mean total loss derived from the simulation was approximately USD 2,307,398. This value is lower than the fixed accident cost previously calculated for Project A, indicating that Project A experienced relatively higher accident costs compared to typical construction sites. In subsequent scenario analysis and EF evaluation, this study utilized the mean total loss value obtained from the MCS as the reference accident cost for further analysis.

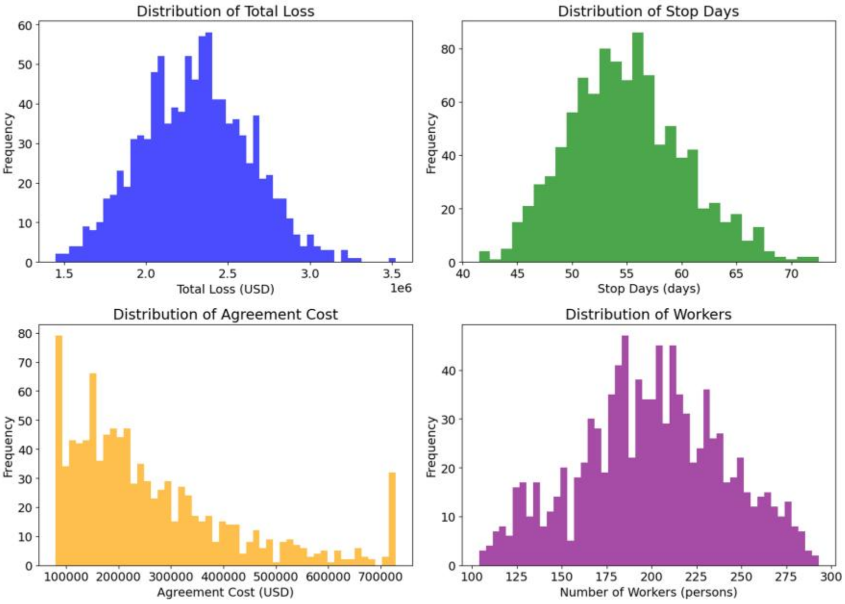

Fig. 2. Total Loss Derived from MCS

5. Result and Discussion

MCS results for Project A indicated that the mean potential fatal accident loss cost was USD 2,307,398. By multiplying this value by the estimated potential number of fatalities, the potential loss amount was calculated to be approximately USD 515,514. If smart safety technology could prevent 100% of fatal accidents, the entire amount could be considered as the preventive benefit. Since the actual fatality reduction rate achievable by smart safety technology is not yet clearly known, this study explores how economic benefits would vary if 0% to 70% of fatal accidents could be prevented.

Table 2 presents the economic benefits and losses for different investment ratios, ranging from 0.01% to 0.1% of the total construction costs, and for reductions in fatal accident occurrence from 10% to 70% through the implementation of smart safety technology. In the table, negative values indicate scenarios resulting in economic losses, while positive values indicate scenarios achieving economic profits.

Table 2. Reduction of Fatal Safety Incidents and Percentage of Total Construction Cost Used for Smart safety technology

Reduction of Fatal Safety Incidents (%) Percentage of Total Construction Cost Used (%)	10	20	30	40	50	60	70
0.1	-291,439	-239,888	-188,336	-136,785	-33,682	69,421	172,524
0.09	-262,295	-210,744	-159,192	-107,641	-4,538	98,565	201,668
0.08	-233,151	-181,600	-130,048	-78,497	24,606	127,709	230,811
0.07	-204,007	-152,456	-100,904	-49,353	53,750	156,853	259,955
0.06	-174,863	-123,312	-71,761	-20,209	82,894	185,996	289,099
0.05	-145,719	-94,168	-42,617	8,935	112,038	215,140	318,243
0.04	-116,576	-65,024	-13,473	38,079	141,181	244,284	347,387
0.03	-87,432	-35,880	15,671	67,223	170,325	273,428	376,531

0.02	-58,288	-6,736	44,815	96,366	199,469	302,572	405,675
0.01	-29,144	22,408	73,959	125,510	228,613	331,716	434,819

For instance, investing 0.1% of the total construction costs and achieving a 60% reduction in fatalities would result in an economic benefit of approximately USD 69,421. Conversely, achieving only a 50% reduction at the same investment level would result in an economic loss of approximately USD 33,682. Based on these results, it can be concluded that when smart safety technology reduces potential fatalities by 60% or more, any investment ratio between 0.01% and 0.1% of the total construction costs yields additional economic benefits. Furthermore, the analysis suggests that higher investment ratios require correspondingly higher levels of accident prevention efficiency; for example, investing 0.01% of the total construction costs requires only a 20% reduction in fatalities to realize economic benefits.

These findings emphasize that strategic decision-making, which simultaneously considers the investment scale and the expected accident prevention effectiveness, is critical when introducing smart safety technology. Strategies that minimize initial investment while maximizing accident prevention effects are expected not only to enhance economic profitability but also to contribute substantially to improving overall site safety.

6. Conclusion

This study quantitatively demonstrated that the adoption of smart safety technology at construction sites should not be regarded merely as an additional cost, but rather as a means to achieve economic benefits when appropriate investment ratios and accident prevention efficiencies are secured.

Based on Project A, a MCS was conducted to estimate the mean accident loss cost, incorporating variations in construction suspension periods, number of workers, and settlement costs. The EF of implementing smart safety technology was then assessed. The analysis revealed that when potential fatalities are reduced by 60% or more, any investment ratio between 0.01% and 0.1% of the total construction costs can yield positive economic benefits. Notably, lower investment ratios require lower thresholds for accident prevention efficiency to achieve profitability. These findings suggest that strategic decision-making that jointly considers the scale of investment and the expected accident prevention effectiveness is essential when introducing smart safety technologies. Approaches that minimize the initial investment burden while maximizing accident prevention effects are expected to not only improve economic outcomes but also contribute significantly to enhancing the overall safety culture at construction sites.

However, this study focused exclusively on fatal accidents, excluding minor injuries. This exclusion was intentional to emphasize the economic feasibility of preventing fatal incidents. If minor injuries are also considered in future studies, the expected economic benefits are likely to increase further. Moreover, this study is limited by its focus on a single country—South Korea—potentially affecting the generalizability of the results. To address this limitation, future research should incorporate international comparisons to evaluate the broader applicability of the findings. In addition, expanding the analysis to include various accident types and assessing the cost-effectiveness of specific smart safety technologies can provide a more comprehensive understanding of their value.

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