

Effectiveness Analysis of CCTV and Announcer on Accident Prevention In Construction OHS Culture

Alfadin Azzahrawaani El Nauval, Agung Wahyudi Biantoro

Universitas Mercu Buana, indonesia

Email: alfadinnauval@gmail.com, agung_wahyudi@mercubuana.ac.id

ABSTRACT

The construction industry faces major safety challenges, with workplace accidents remaining a persistent concern despite various interventions. Technology-based safety systems provide promising solutions for strengthening Occupational Health and Safety (OHS) management in high-risk environments. This study analyzes the influence of the Real-Time CCTV System, Announcer, Safety Leadership Program 4.0, and the work environment on OHS culture, as well as their impact on accident prevention in construction projects. A quantitative approach using Partial Least Squares Structural Equation Modeling (PLS-SEM) was applied, with data collected through questionnaires at construction sites and tested for validity, reliability, and structural relationships. Findings show that the Safety Leadership Program 4.0 and the work environment significantly influence the development of OHS culture. The Real-Time CCTV System demonstrated a near-significant effect, while the Announcer showed no significant impact on OHS culture. In terms of accident prevention, however, the Real-Time CCTV System and Announcer both had a direct and significant effect, whereas OHS culture, Safety Leadership Program 4.0, and the work environment did not show a direct influence. These results suggest that technology provides more immediate and measurable safety benefits by reducing hazards in real time, while cultural development and leadership initiatives are longer-term strategies requiring greater integration. In conclusion, the study emphasizes the importance of combining technological tools, safety leadership, and supportive environments to strengthen OHS culture and sustainably reduce risks in construction.

KEYWORDS

OHS culture, workplace safety, Real Time CCTV system, Safety Leadership Program 4.0, work environment, construction project



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INTRODUCTION

Construction workers are three times more likely to be killed on the job than workers in other industries, with approximately 60,000 fatal accidents occurring annually worldwide (Almaskati et al., 2024; Haupt & Pillay, 2016; Khodabandeh et al., 2016; Wijesekara et al., 2022). In Indonesia, data from the Ministry of Manpower (2022) reveals that the construction sector accounts for 32% of all workplace fatalities, with over 2,400 construction-related deaths reported in 2022 alone. The Bureau of Labor Statistics (2023) indicates that construction accidents cost companies an average of \$1.15 million per fatality and \$42,000 per non-fatal injury, excluding indirect costs such as productivity losses, legal fees, and reputational damage.

The construction industry is recognized as one of the most hazardous sectors, with a persistent prevalence of workplace accidents that pose significant risks to workers' health and safety (Buica et al., 2017; Darda'u Rafindadi et al., 2025; Jaafar et al., 2018; Mwangi, 2016; Nadhim et al., 2016). Despite the implementation of multiple safety measures and regulations, accident frequency remains a pressing concern, necessitating innovative approaches to enhance occupational safety and health (OSH). This thesis aims to investigate the effectiveness of integrating advanced technologies, specifically Real-Time Closed-Circuit Television (CCTV) systems and announcer systems, within the framework of a Safety Leadership Program 4.0, to prevent workplace accidents in construction projects.

The integration of technology into safety management is crucial for addressing the challenges faced by the construction industry (Larbi et al., 2024; Nnaji & Karakhan, 2020; Parsamehr et al., 2023; Sohu & Kassim, 2025; Yap et al., 2024). Real-Time CCTV systems provide continuous monitoring, enabling immediate responses to unsafe behaviors and conditions, while announcer systems facilitate effective communication of safety protocols and alerts. However, the successful implementation of these technologies requires a supportive organizational culture that prioritizes safety. The Safety Leadership Program 4.0 emphasizes the importance of leadership in fostering a proactive safety culture, encouraging worker engagement, and ensuring compliance with safety standards. The interaction between technology and safety culture creates a synergistic effect: technological interventions provide real-time hazard detection and immediate corrective actions, while a strong safety culture ensures sustained behavioral change and long-term compliance. This integration enhances accident prevention by creating multiple layers of protection—immediate technological responses to hazards and deeply embedded cultural practices that prevent risky behaviors from arising in the first place.

Previous research has demonstrated varying levels of success with technology-based safety interventions in construction (Hossain et al., 2025; Newaz et al., 2024). Park et al. (2020) found that computer vision systems could reduce safety violations by 35% through real-time monitoring, while Luo et al. (2021) reported that integrated surveillance systems decreased accident rates by 28% in transport megaprojects. However, studies by Zhang and Li (2022) indicated that technology alone was insufficient without proper organizational support, achieving only a 15% improvement in safety outcomes. Leadership-focused interventions have shown promise, with research by Gao et al. (2023) demonstrating that safety leadership programs improved safety climate scores by 42% and reduced incident rates by 31%. Despite these individual successes, a significant research gap remains: no comprehensive studies have examined the simultaneous integration of Real-Time CCTV systems, announcer systems, and the Safety Leadership Program 4.0 within a unified framework. Most existing research focuses on single interventions rather than the synergistic effects of combined technological and leadership approaches.

The urgent practical need for this research is underscored by the substantial economic and human costs of construction accidents. Beyond the immediate human tragedy, workplace accidents result in average direct costs of \$39,000 per incident, with indirect costs reaching 4–10 times higher, including productivity losses, equipment damage, project delays, and increased insurance premiums (Construction Industry Institute, 2023). Legal risks are also substantial, with construction companies facing litigation costs averaging \$2.3 million per major accident case. The integration of CCTV, announcer systems, and the Safety Leadership Program 4.0

represents a potential paradigm shift toward proactive, technology-enhanced safety management—a model that has received limited empirical investigation despite its promising theoretical foundations.

This research addresses a significant gap in the existing literature by comprehensively evaluating the interplay between technology, work environment, and OSH culture in the context of construction safety. Specifically, it uniquely examines the combined effect of Real-Time CCTV systems, announcer systems, and the Safety Leadership Program 4.0 on accident prevention using PLS-SEM methodology, providing the first holistic analysis of these integrated interventions in construction safety management. By employing a quantitative approach and utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM), this study seeks to analyze the relationships between Real-Time CCTV, announcer systems, safety leadership, and the work environment, and their collective impact on accident prevention.

This research aims to: (1) analyze the direct and indirect effects of Real-Time CCTV systems, announcer systems, the Safety Leadership Program 4.0, and the work environment on OHS culture and accident prevention; (2) evaluate the mediating role of OHS culture in the relationship between safety interventions and accident prevention; and (3) develop evidence-based recommendations for integrated technology–leadership approaches to construction safety. The benefits of this research include providing construction managers with validated frameworks for technology integration, offering policymakers empirical evidence for safety regulation development, and contributing to the academic understanding of multi-modal safety intervention effectiveness. The findings are expected to provide valuable insights into the effectiveness of technological interventions in enhancing safety culture and reducing workplace accidents. Ultimately, this study aims to contribute to the development of a more robust and sustainable safety management system in the construction industry, ensuring a safer working environment for all stakeholders involved.

RESEARCH METHOD

This research employed a quantitative approach with a descriptive-exploratory method to examine the relationships between the Real-Time CCTV system, announcer, Safety Leadership Program 4.0, and the work environment in relation to OHS culture and accident prevention. The study was conducted through a case study at an oil tank project in Balongan, as well as several other construction projects, including buildings and infrastructure, to obtain a broader overview.

Data sources consisted of both primary and secondary data. Primary data were collected through questionnaires distributed to 82 respondents, selected using purposive sampling. Direct observations at project sites were also carried out to record workers' safety behavior in response to the CCTV and announcer systems. Secondary data were obtained from occupational safety documents, accident records, OHS training reports, and monitoring technology data already implemented at the sites.

The research instrument was a questionnaire using a five-point Likert scale to measure respondents' level of agreement with indicators of the study variables. Validity and reliability tests were conducted to ensure that the indicators consistently represented their constructs.

Data analysis was performed using the Partial Least Squares Structural Equation Modeling (PLS-SEM) method, which allowed for testing structural relationships between latent

variables and observed indicators. This approach enabled the development of predictive models relevant to the implementation of technology-based occupational safety systems in construction projects.

RESULT AND DISCUSSION

This study involved 82 respondents from various construction projects, including buildings, infrastructure, and oil tank facilities. The majority of respondents were male workers with more than five years of experience, originating from the Project and HSSE (Health, Safety, Security, and Environment) divisions, who are directly involved in the implementation and supervision of occupational safety. Most of them participated in oil tank projects, which are considered high-risk environments, and held various positions that provided a broad perspective on the implementation of Real-Time CCTV, announcers, and the OHS culture within construction work environments.

Descriptive analysis results indicated that all variables—Real-Time CCTV, announcer, Safety Leadership Program 4.0, work environment, OHS culture, and accident prevention—were positively perceived by the respondents. Monitoring technologies such as CCTV and announcers were considered effective in providing early warnings and supporting safety actions on-site. Meanwhile, training through safety programs also contributed to enhancing workers' awareness. A collaborative work environment, support from supervisors, and active involvement of management in enforcing safety policies were seen as important reinforcements in shaping a safety culture. In addition, workers demonstrated a good understanding of potential hazards and the application of preventive measures, reflecting readiness to establish a safe and disciplined work environment on a sustainable basis.

The SEM-PLS analysis in this study was conducted using SmartPLS to test the relationships between the independent variables (Real-Time CCTV, Announcer, Safety Leadership Program 4.0, and Work Environment), the mediating variable (OHS Culture), and the dependent variable (Accident Prevention). The initial stage, the outer model, aimed to assess the validity and reliability of the research instrument through tests of convergent validity, discriminant validity, and reliability, to ensure that each indicator consistently represented the construct being measured.

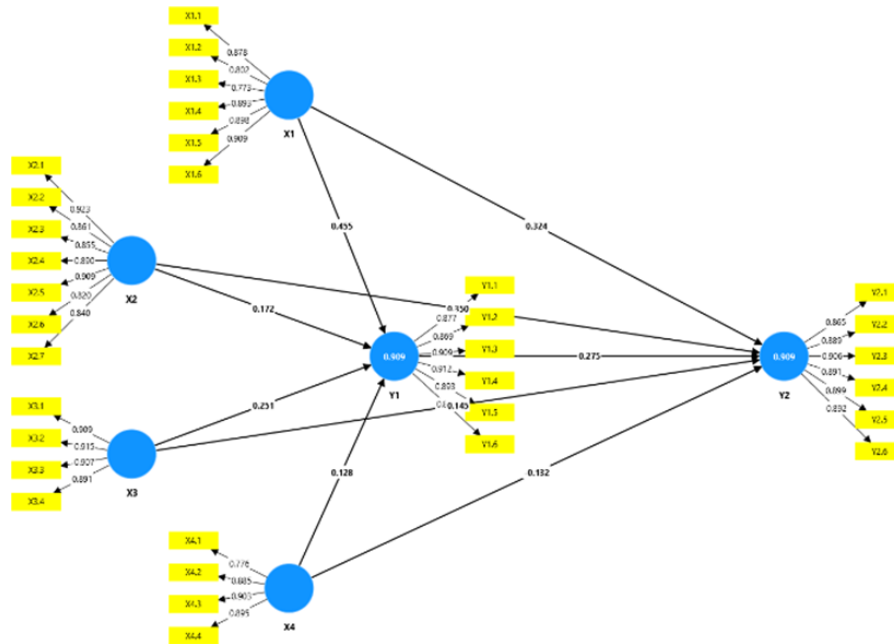


Figure 1 Model PLS-SEM Algorithm

Source: Authors' analysis using SmartPLS software

The Structural Equation Modeling–Partial Least Square (SEM-PLS) analysis was employed in this study to examine the relationships between the independent variables (Real-Time CCTV System, Announcer, Safety Leadership Program 4.0, and Work Environment), the mediating variable (OHS Culture), and the dependent variable (Accident Prevention). The assessment was carried out through the outer model stage to evaluate the construct's validity and reliability.

Table 1. Loading Factor

	X1	X2	X3	X4	Y1	Y2
X1.1	0.878	-	-	-	-	-
X1.2	0.802	-	-	-	-	-
X1.3	0.773	-	-	-	-	-
X1.4	0.893	-	-	-	-	-
X1.5	0.898	-	-	-	-	-
X1.6	0.909	-	-	-	-	-
X2.1	-	0.923	-	-	-	-
X2.2	-	0.861	-	-	-	-
X2.3	-	0.855	-	-	-	-
X2.4	-	0.890	-	-	-	-
X2.5	-	0.909	-	-	-	-
X2.6	-	0.820	-	-	-	-
X2.7	-	0.840	-	-	-	-
X3.1	-	-	0.909	-	-	-
X3.2	-	-	0.915	-	-	-
X3.3	-	-	0.907	-	-	-
X3.4	-	-	0.891	-	-	-
X4.1	-	-	-	0.776	-	-
X4.2	-	-	-	0.885	-	-
X4.3	-	-	-	0.903	-	-
X4.4	-	-	-	0.895	-	-
Y1.1	-	-	-	-	0.877	-
Y1.2	-	-	-	-	0.869	-
Y1.3	-	-	-	-	0.909	-

	X1	X2	X3	X4	Y1	Y2
Y1.4	-	-	-	-	0.912	-
Y1.5	-	-	-	-	0.893	-
Y1.6	-	-	-	-	0.863	-
Y2.1	-	-	-	-	-	0.865
Y2.2	-	-	-	-	-	0.889
Y2.3	-	-	-	-	-	0.906
Y2.4	-	-	-	-	-	0.891
Y2.5	-	-	-	-	-	0.899
Y2.6	-	-	-	-	-	0.892

Source: Authors' analysis using SmartPLS

The results show that all indicators have loading factor values above 0.70, indicating that each indicator is able to represent its corresponding construct well.

Table 2. *Average Variance Extracted (AVE)*

Variable	AVE
Real-Time CCTV System (X1)	0,740
Announcer (X2)	0,760
Safety Leadership Program 4.0 (X3)	0,820
Work Environment (X4)	0,750
OHS Culture (Y1)	0,787
Accident Prevention (Y2)	0,793

Source: Authors' analysis using SmartPLS

The Average Variance Extracted (AVE) values for all constructs also exceed the threshold of 0.50, indicating that the variables in the model possess strong convergent validity.

Discriminant validity was tested using the cross loading method and the Fornell-Larcker Criterion.

Table 3. *Cross Loading*

	X1	X2	X3	X4	Y1	Y2
X1.1	0.878	0.921	0.788	0.693	0.823	0.874
X1.2	0.802	0.825	0.618	0.542	0.683	0.773
X1.3	0.773	0.685	0.699	0.625	0.731	0.694
X1.4	0.893	0.776	0.748	0.782	0.841	0.769
X1.5	0.898	0.822	0.747	0.767	0.859	0.822
X1.6	0.909	0.827	0.760	0.761	0.863	0.838
X2.1	0.894	0.923	0.815	0.778	0.868	0.860
X2.2	0.845	0.861	0.795	0.692	0.822	0.807
X2.3	0.787	0.855	0.801	0.631	0.833	0.805
X2.4	0.853	0.890	0.818	0.722	0.863	0.867
X2.5	0.858	0.909	0.799	0.673	0.804	0.869
X2.6	0.762	0.820	0.648	0.500	0.669	0.738
X2.7	0.737	0.840	0.672	0.563	0.715	0.749
X3.1	0.809	0.826	0.909	0.800	0.815	0.790
X3.2	0.732	0.753	0.915	0.684	0.776	0.748
X3.3	0.725	0.779	0.907	0.629	0.787	0.778
X3.4	0.796	0.826	0.891	0.690	0.828	0.827
X4.1	0.550	0.536	0.590	0.776	0.593	0.502
X4.2	0.724	0.723	0.661	0.885	0.720	0.683
X4.3	0.728	0.627	0.680	0.903	0.736	0.643
X4.4	0.785	0.703	0.744	0.895	0.779	0.689
Y1.1	0.826	0.795	0.758	0.743	0.877	0.775
Y1.2	0.738	0.708	0.786	0.807	0.869	0.763
Y1.3	0.860	0.855	0.816	0.771	0.909	0.863

	X1	X2	X3	X4	Y1	Y2
Y1.4	0.857	0.836	0.810	0.737	0.912	0.843
Y1.5	0.824	0.834	0.784	0.654	0.893	0.791
Y1.6	0.854	0.847	0.763	0.663	0.863	0.846
Y2.1	0.820	0.819	0.732	0.707	0.751	0.865
Y2.2	0.808	0.828	0.746	0.646	0.792	0.889
Y2.3	0.854	0.888	0.761	0.674	0.854	0.906
Y2.4	0.802	0.814	0.790	0.602	0.806	0.891
Y2.5	0.814	0.829	0.811	0.628	0.853	0.899
Y2.6	0.849	0.821	0.800	0.658	0.846	0.892

Source: Authors' analysis using SmartPLS

The results of the cross-loading analysis show that most indicators have the highest correlation with their respective original constructs compared to other constructs, confirming the conceptual distinction between constructs in the model.

Table 4. *Fornell-Larcker Criterion*

	X1	X2	X3	X4	Y1	Y2
X1	0.860	-	-	-	-	-
X2	0.942	0.872	-	-	-	-
X3	0.847	0.880	0.906	-	-	-
X4	0.812	0.752	0.775	0.866	-	-
Y1	0.933	0.917	0.886	0.821	0.887	-
Y2	0.926	0.936	0.869	0.732	0.918	0.890

Source: Authors' analysis using SmartPLS

The evaluation results using the Fornell-Larcker criterion show that the square root of the AVE value for each construct is higher than the correlations with other constructs, indicating that discriminant validity has been met. This means that each construct in the model is clearly distinguishable from the others.

Reliability testing was conducted using two approaches, namely Cronbach's Alpha and Composite Reliability (CR).

Table 5. *Cronbach's Alpha*

Variable	Cronbach's alpha
Real-Time CCTV System (X1)	0,929
Announcer (X2)	0,947
Safety Leadership Program 4.0 (X3)	0,927
Work Environment (X4)	0,888
OHS Culture (Y1)	0,946
Accident Prevention (Y2)	0,948

Source: Authors' analysis using SmartPLS

Table 6. *Composite Reliability*

Variable	Composite reliability (rho_a)	Composite reliability (rho_c)
Real-Time CCTV System (X1)	0,933	0,945
Announcer (X2)	0,950	0,957
Safety Leadership Program 4.0 (X3)	0,927	0,948
Work Environment (X4)	0,900	0,923
OHS Culture (Y1)	0,947	0,957
Accident Prevention (Y2)	0,948	0,958

Source: Authors' analysis using SmartPLS

All constructs have Cronbach's Alpha values above 0.70, indicating a high level of internal consistency. In addition, both rho_A and rho_C values of Composite Reliability (CR) also show excellent results, exceeding the recommended threshold. This indicates that the

instrument used in this study is not only stable but also capable of accurately and consistently measuring the constructs under various measurement conditions.

Thus, the results of the outer model testing demonstrate that the research instrument is valid and reliable for use in the subsequent inner model analysis. These findings reinforce the confidence that the conceptual model developed has met the technical requirements of the SEM-PLS methodology. With a solid foundation of validity and reliability, the study can proceed to examine the direct and indirect effects between variables, as well as assess the extent to which OHS Culture mediates the relationship between safety technology and accident prevention in construction projects.

Therefore, all indicators in the model possess excellent measurement quality and are suitable for the next stage of analysis. With an instrument that has been proven valid and reliable, the subsequent analysis can provide an accurate picture of the influence of the Real-Time CCTV System, Announcer, Safety Leadership Program 4.0, and Work Environment on Accident Prevention both directly and through the mediation of OHS Culture.

In the Inner Model analysis stage, evaluation is carried out to assess the structural relationships between the latent constructs in the PLS-SEM model used. This testing aims to examine the strength and significance of both direct and indirect effects among the variables in the research model.

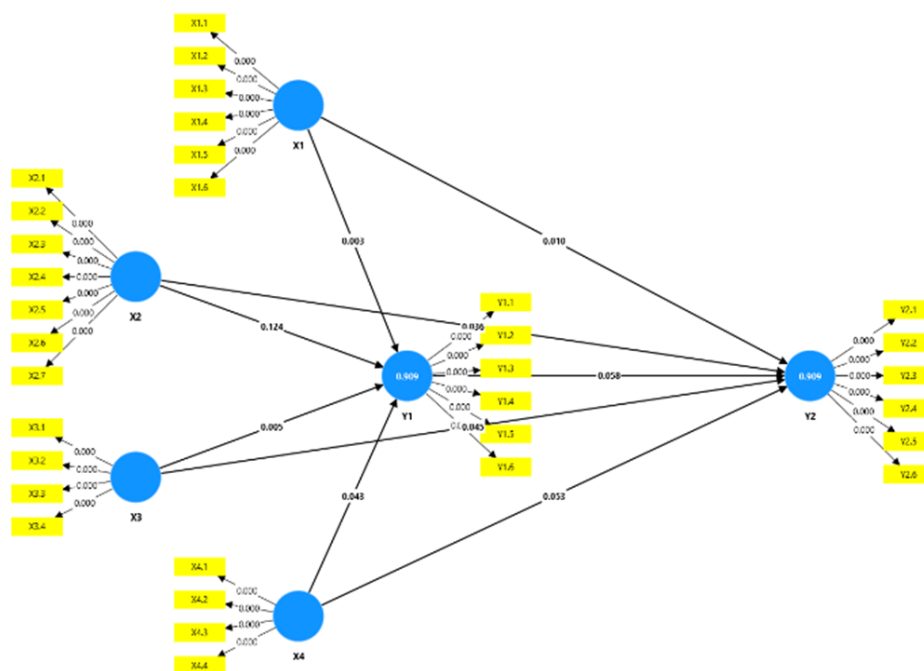


Figure 2 Bootstrapping Model

Source: Authors' analysis using SmartPLS software

Figure 2 presents the results of the inner model analysis using the bootstrapping method, which illustrates the direction and strength of the relationships between latent constructs through path coefficients. The multicollinearity test based on Variance Inflation Factor (VIF) values indicates that the majority of indicators fall below the acceptable threshold, meaning that there is no significant multicollinearity issue within the model.

Table 7. Coefficient of Determination

Variable	R-square	R-square adjusted
OHS Culture (Y1)	0,909	0,905
Accident Prevention (Y2)	0,909	0,903

Source: Authors' analysis using SmartPLS

The R-square value for both the OHS Culture and Accident Prevention variables is 0.909, indicating that more than 90% of the variance in these two variables can be explained by the independent constructs in the model. This demonstrates that the model has a very strong predictive ability and is reliable for explaining the relationships among variables.

Table 8. *Effect Size*

	X1	X2	X3	X4	Y1	Y2
X1	-	-	-	-	0.199	0.084
X2	-	-	-	-	0.027	0.110
X3	-	-	-	-	0.135	0.040
X4	-	-	-	-	0.054	0.055
Y1	-	-	-	-	-	0.075
Y2	-	-	-	-	-	-

Source: Authors' analysis using SmartPLS

In the effect size (f^2) analysis, the Real-Time CCTV System and the Safety Leadership Program 4.0 variables have a moderate effect on OHS Culture, while the Announcer and Work Environment contribute smaller effects. For the Accident Prevention variable, the greatest contribution comes from the Announcer, followed by the Real-Time CCTV System and OHS Culture, although all fall within the small to moderate effect category. These findings indicate that all variables in the model play a role in shaping the safety culture and encouraging accident prevention, either through direct or indirect effects, with OHS Culture serving as a mediator that enhances the effectiveness of safety systems in construction projects.

Path coefficients are used to evaluate the strength and significance of the relationships between latent variables in the structural model. This test is important to confirm that the direction and strength of the hypothesized relationships can be statistically supported. Significant path coefficient values are determined based on p-values less than 0.05.

Table 9. Path Coefficient

	Original sample	T statistics	P values
X1 -> Y1	0.455	2.781	0.003
X1 -> Y2	0.324	2.373	0.010
X2 -> Y1	0.172	1.162	0.124
X2 -> Y2	0.350	1.823	0.036
X3 -> Y1	0.251	2.663	0.005
X3 -> Y2	0.145	1.707	0.045
X4 -> Y1	0.128	1.730	0.043
X4 -> Y2	-0.132	1.635	0.053
Y1 -> Y2	0.275	1.587	0.058

Source: Authors' analysis using SmartPLS

Based on the path coefficient results, most of the relationships between constructs in the research model are statistically significant, although not all hypotheses are accepted. The Real-Time CCTV System, Safety Leadership Program 4.0, and Work Environment have a positive and significant influence on OHS Culture, while the Announcer does not show a significant effect. This suggests that visual monitoring technologies and leadership roles are more effective in shaping a safety culture compared to voice-based communication. Meanwhile, OHS Culture

itself has not shown a significant influence on Accident Prevention, indicating the need for stronger internalization of safety values to produce a tangible impact in the field.

Regarding the Accident Prevention variable, significant influence is shown by the Real-Time CCTV System, Announcer, and Safety Leadership Program 4.0, whereas the Work Environment does not have a significant impact and even shows a negative relationship direction. This indicates that accident prevention efforts are more influenced by monitoring systems, real-time alerts, and leadership involvement than by the physical conditions of the environment alone. Therefore, safety-related technology and leadership play a crucial role in creating a disciplined and safe work culture.

Expert Validation

Expert validation was conducted to ensure that the research instruments and model are conceptually and practically appropriate in the context of implementing technology-based occupational safety in construction projects. Five experts from the oil and gas and construction industries, with a minimum educational background of a bachelor's degree and over 10–20 years of work experience, were involved in evaluating the indicators of six main variables: Real-Time CCTV System, Announcer, Safety Leadership Program 4.0, Work Environment, OHS Culture, and Accident Prevention.

The validation process used an indicator assessment sheet with agree/disagree options and a comment section. The results showed that all indicators were deemed appropriate and approved by all experts without any rejection. The experts stated that each indicator aligns with field safety practices, is relevant to technological developments, and can effectively support the strengthening of OHS culture. This validation reinforces that the research model can serve as both an evaluative and implementative framework in the development of modern, data-driven construction safety systems.

The results of this study show that the Safety Leadership Program 4.0 has the most significant influence on the formation of OHS Culture. This finding is consistent with the study by Senthamizh Sankar and Anandh (2024), which emphasized that safety leadership involving direct supervision, leading by example, and inspirational communication can enhance workers' collective awareness of the importance of OHS. Project leaders who actively engage with their teams serve as catalysts in shaping safe work behavior. Technology-based and participatory leadership programs have proven effective in reinforcing sustainable safety values in workers' daily routines.

In addition to leadership, the work environment also contributes significantly to the development of a safety culture. This result aligns with the findings of Robbins and Judge (2017), who stated that physical and social conditions in the workplace—such as lighting, ventilation, noise levels, and interpersonal relationships—directly influence attitudes toward safety. A comfortable and supportive work environment encourages the creation of a safe and productive atmosphere. In the context of construction projects, where physical risks are quite high, creating a conducive work environment becomes a crucial factor in strengthening compliance with OHS procedures.

The significant impact of the Real-Time CCTV System on both OHS Culture and Accident Prevention also supports previous findings. Seong et al. (2023) showed that integrated visual monitoring systems can identify violations of safety procedures and potential hazards in

real time, thereby promoting more disciplined work behavior. In this context, CCTV not only functions as a monitoring tool but also as a visual reminder that encourages compliance. This is reinforced by the implementation of similar systems in Pertamina's HSSE Eagle Eyes program, which relies on the integration of CCTV and announcers to directly intervene in unsafe behaviors from the control room. This real-time monitoring has proven to increase worker discipline and facilitate quick preventive actions without having to wait for the physical presence of field officers.

In contrast to CCTV, the Announcer shows a significant influence only on Accident Prevention, but not on OHS Culture. This result is supported by the research of Lee et al. (2020) and Xie et al. (2019), who found that audio-based warning systems are more effective in raising awareness and prompting quick responses, especially in emergency situations. This is also reflected in the use of announcers in the Eagle Eyes project, where HSSE officers can deliver direct voice warnings to workers who are observed violating safety procedures through project speakers. Although effective in situational contexts, this approach is considered insufficient in instilling long-term safety values, as the interaction is one-way and does not foster reflective awareness.

OHS Culture itself does not show a significant direct effect on Accident Prevention, reinforcing the argument made by Irwansyah and Widanarko (2023) that safety culture tends to be symbolic if not genuinely implemented in daily work systems. A strong safety culture requires consistency in supervision, incident reporting, and risk-based training in order to have a real impact on preventive actions. This finding is also consistent with field experiences such as in the Eagle Eyes project, where the effectiveness of safety culture is strengthened through visual documentation systems, monitoring dashboards, and intervention SOPs implemented in a disciplined manner.

CONCLUSION

This research demonstrates that Safety Leadership Program 4.0 and work environment significantly influence OHS culture development, while Real-Time CCTV and announcer systems directly impact accident prevention through immediate hazard detection mechanisms. The mediating role of OHS culture was limited, indicating that technological interventions provide more immediate safety benefits than cultural transformation approaches. The results show that Safety Leadership Program 4.0 and work environment are fundamental pillars for building safety awareness and behavior. Real-Time CCTV systems have near-significant influence on OHS culture but demonstrate direct effectiveness in accident prevention along with announcer systems. This indicates that technology-based interventions excel in early detection and risk monitoring, while leadership and environmental factors are more effective for long-term cultural development. This research contributes by establishing the first empirical framework for integrated technology-leadership safety interventions in construction. Future research should examine: (1) longitudinal safety culture development studies, (2) comparative analysis across project types, (3) cost-benefit analysis of integrated safety systems, (4) AI enhancement for real-time monitoring, and (5) cross-cultural validation of safety leadership effectiveness. For practical implementation, construction management should optimize Real-Time CCTV and announcer integration, enhance safety leadership training, and create comprehensive technology-leadership-environment approaches. Workers should improve safety compliance and actively participate in training programs. Future researchers should incorporate new variables, use mixed-methods approaches, and broaden

research scope for more comprehensive results.

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