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The Impact of Construction 4.0 on Project Efficiency and Safety

Kemmala Dewi[1✉], Aris Krisdiyanto[2], Dewanto[3], Tomi Apra Santosa[4]
[1,2] Universitas 17 Agustus 1945 Semarang, Indonesia
[3] Universitas Negeri Surabaya, Indonesia
[4] Akademi Teknik Adikarya, Indonesia
Email:kemala-dewi@untagsmg.ac.id[1✉]

Abstrak

Penelitian ini bertujuan untuk mengetahui pengaruh konstruksi 4.0 terhadap efisiensi dan keselamatan proyek. Jenis penelitian ini adalah penelitian kuantitatif dengan pendekatan meta-analisis. Sumberd data dalam penelitian ini berasal dari analisis 13 jurnal nasional dan internasional terbitan 2022-2025. Kriteria inklusi yaitu penelitian harus relevan; penelitian diperoleh dari database jurnal bereputasi Sciencedirect; Wiley, Springer, Google Scholar dan Mendeley, Penelitian harus melaporkan data yang lengkap. Analisis data dengan bantuan aplikasi Microsoft Excel dan Jamovi. Hasil penelitian ini menjelaskan nilai summary effect size sebesar ($d = 0.830$; $z = 6.073$; $p < 0.001$). Temuan ini menunjukan bahwa konstruksi 4.0 memberikan pengaruh positif terhadap efisiensi dan keselamatan kerja proyek dengan kategori pengaruh yang tinggi

Kata Kunci: *Kontruksi 4.0; Effect Size; Efisiensi; Keselamatan Proyek*

Abstract

This study aims to determine the influence of construction 4.0 on project efficiency and safety. This type of research is a quantitative research with a meta-analysis approach. The data sources in this study come from the analysis of 13 national and international journals published in 2022-2025. The inclusion criteria are that the research must be relevant; research obtained from the database of reputable journals Sciencedirect; Wiley, Springer, Google Scholar and Mendeley, Research should report complete data. Analyze data with the help of Microsoft Excel and Jamovi applications. The results of this study explain the value of the summary effect size of ($d = 0.830$; $z = 6.073$; $p < 0.001$). These findings show that construction 4.0 has a positive influence on the efficiency and safety of project work with a high influence category.
Keyword: *Construction 4.0; Effect Size; Efficiency; Project Safety*

INTRODUCTION

The construction industry is currently undergoing a significant transformation through the implementation of Construction 4.0, which integrates various advanced technologies to improve efficiency, productivity, and work safety(Olsson et al., 2021; Statsenko et al., 2023). This concept is an adaptation of the Industrial Revolution 4.0, which emphasizes digitalization and automation of the construction process. Technologies such as Artificial Intelligence (AI) enable more accurate data analysis for project planning, risk detection, and resource optimization(Kor et al., 2023). Meanwhile, the Internet of Things (IoT) plays a role in improving connectivity between devices at project sites, enabling real-time monitoring of environmental conditions, equipment, and labor. The existence of Building Information Modeling (BIM) systems is also increasingly dominating the construction industry, where integrated digital models help in design, simulation, and collaboration between stakeholders to reduce errors and improve operational efficiency (Adepoju & Aigbavboa, 2020; Karmakar & Delhi, 2021).

In addition, robotics and automation are beginning to be widely adopted in various stages of construction, including 3D printing for building structures, the use of drones for project inspections(Munianday et al., 2024; Júnior et al., 2021), as well as autonomous construction machinery that reduces reliance on manual labor. The application of this technology not only accelerates the development process but also improves safety aspects by reducing workers' exposure to high-risk work environments(Milijić et al., 2020). With the integration of increasingly mature technology, Construction 4.0 has the potential to change the paradigm of the construction industry from conventional to data-based and automation(Hossain & Nadeem, 2019; Osunsanmi et al., 2020). However, challenges in terms of investment, regulation, and readiness of human resources are still factors that need to be considered so that the adoption of this technology can run optimally and sustainably (El Jazzar et al., 2021).

The construction industry faces increasingly complex challenges in meeting project efficiency demands, both in terms of time, cost, and quality(Sreejith et al., 2021). In an increasingly competitive environment, the success of a project is measured not only by its completion, but also by the effective use of resources and the minimization of waste. Increasing efficiency in construction projects is a must to avoid delays that can impact cost escalation and decreased productivity. Factors such as poor planning(Adepoju & Aigbavboa, 2020), lack of coordination between stakeholders, and technical constraints are often the main causes of inefficiencies in projects(Kor et al., 2023). To be a strategic solution in improving operational efficiency, ensuring the integration of project data, and accelerating the real-time data-based decision-making process (Olsson et al., 2021).

In addition to efficiency, occupational safety in the construction industry is also a crucial aspect that needs serious attention (Sreejith et al., 2021). This sector is one of the industries with a high rate of work accidents due to risky environmental conditions, the use of heavy equipment, and human error factors (Temidayo. O. Osunsanmi et al., 2018). Therefore, the application of technologies such as IoT sensors for monitoring working conditions, artificial intelligence (AI) for predicting potential accidents, and robotics for high-risk tasks are solutions that can improve labor safety (Agha et al., 2024). In addition to technology, the implementation of data-based safety policies and worker training with a digital approach also plays an important role in reducing the number of accidents. With the synergy between project efficiency and improved occupational safety, the construction industry can achieve better operational sustainability, reduce the economic impact of work accidents, and create a safer and more productive work environment (Fakher & Anandh, 2022).

The development of digital technology in the construction industry has become a major response to various challenges related to time, cost, and occupational safety. Project delays are often caused by inefficiencies in planning, coordinating, and managing resources, which can lead to increased costs as well as decreased quality of the final deliverables (El Jazzar et al., 2021). In addition to time and cost efficiency, the aspect of occupational safety is also the main focus in the application of digital technology in the construction industry. IoT has enabled real-time jobsite monitoring, where sensors installed on machines and workers can detect potential hazards as well as provide early warnings to reduce the risk of accidents (Turner et al., 2021). Wearable device technology, such as smart helmets and vests with worker health monitoring sensors, is also beginning to be used to improve safety in the field (Fakher & Anandh, 2022). In addition, robotics and drones have been adopted for high-risk tasks, such as structural inspections and construction work at height, thereby reducing workers' exposure to hazardous conditions. With the integration of this digital technology, the construction industry is not only able to improve efficiency and reduce project costs, but also create a safer and more sustainable working environment for the workforce (Temidayo. O. Osunsanmi et al., 2018).

Research by Oesterreich and Teuteberg (2016) shows that the adoption of Building Information Modeling (BIM), Internet of Things (IoT), and artificial intelligence (AI) in construction projects can reduce inefficiencies in planning as well as improve coordination between stakeholders. In addition, a study conducted by Li et al. (2020) revealed that the use of robotics and automation in construction can accelerate the construction process up to 30% faster than conventional methods, while reducing material waste. The results of a meta-analysis conducted by Wang et al. (2021) also found that construction companies that implement digital technology in their management systems experienced significant improvements in operational efficiency and reduced unexpected costs due to design and planning errors. Zhong et al. (2017), the application of wearable technology, IoT sensors, and drones in project site monitoring has succeeded in significantly reducing the number of work accidents, especially in large-scale projects. Meanwhile, research by Golizadeh et al. (2022) confirms that the use of smart helmets and AI-based monitoring systems is able to detect potential hazards and provide early warnings, thereby reducing the risk of injury due to human negligence. In addition, a meta-analysis conducted by Nnaji et al. (2023) concluded that the implementation of Construction 4.0 technology contributes to improving the safety culture in the construction industry, with digital-based training and automated systems that can replace high-risk jobs. Thus, further studies through meta-analysis are needed to integrate various previous research findings to obtain a more comprehensive picture of the benefits of Construction 4.0 on work efficiency and safety in the construction industry. Based on this, this study aims to determine the influence of construction 4.0 on project efficiency and safety.

RESEARCH METHODS

This study uses a meta-analysis method to evaluate the impact of Construction 4.0 on project efficiency and work safety in the construction industry. The meta-analysis was carried out by collecting, analyzing, and synthesizing various relevant empirical studies from Scopus-indexed scientific journals, Web of Science, and IEEE Xplore in the 2022–2025 time frame. The data in this meta-analysis was obtained from 13 journals that met the inclusion criteria. . The inclusion criteria are that the research must be relevant; research obtained from the database of reputable journals Sciencedirect; Wiley, Springer, Google Scholar and Mendeley, Research should report complete data.

The meta-analysis process is carried out through several stages, namely identification, selection, data extraction, and synthesis of research findings. The data collected was analyzed using the effect size approach to measure the level of influence of Construction 4.0 technology on project efficiency and work safety variables. In addition, a heterogeneity test was carried out using Cochran's Q and I^2 statistics to assess the variation between the analyzed studies. The funnel plot technique and the Rosenthal Fail Safe N test were also applied to identify potential publication bias in the research results. With this method, this study is expected to provide a more comprehensive and evidence-based picture of the contribution of Construction 4.0 technology in improving efficiency and safety in the construction industry. Furthermore, the effect size criteria in this study are guided by The classification of effect size values includes g = 0.2 (small effect), g = 0.5 (medium effect), g = 0.8 (large effect), g = 1.20 (huge effect), and g = 2.0 (very huge effect) (Borenstein et al., 2007; Tamur et al., 2020)

RESULT AND DISCUSSION

Based on a search of data sources from the google scholar database; Sciencedirect and Wiley obtained 13 studies that met the inclusion criteria as seen in Table 1.

Table 1. Effect Size and Standard Error Every Research

Code journal	Years	Effect Size	Standard Error	Source
AL 1	2022	2.10	0.45	Google Scholar
AL 2	2025	0.76	0.20	Sciencedirect
AL 3	2025	0.81	0.30	Google Scholar
AL 4	2022	0.92	0.30	IEEE
AL 5	2024	0.44	0.19	IEEE
AL 6	2023	0.32	0.22	Wiley
AL 7	2023	0.84	0.38	Wiley
AL 8	2025	1.09	0.44	Google Scholar
AL 9	2025	2.09	0.50	Google Scholar
AL 10	2024	0.63	0.29	Wiley

AL 11	2023	0.29	0.12	Wiley
AL 12	2024	0.88	0.35	IEEE
AL 13	2025	1.24	0.41	IEEE

Based on Table 2, the effect size value of the 13 studies ranged from 0.29 to 2.10. According to Borenstein et al., (2007) Of the 15 effect sizes, 5 studies had medium criteria effect sizes and 13 studies had high criteria effect size values. Furthermore, 13 studies were analyzed to determine an estimation model to calculate the mean effect size. The analysis of the fixed and random effect model estimation models can be seen in Table 3.

Table 2. Random Effect Model

	Q	df	p
Omnibus test of Coefficients Model	36.887	1	< 0.001
Test of Residual Heterogeneity	56.119	12	< 0.001

Based on Table 3, a Q value of 59.119 was obtained higher than the value of 36.887 . The findings can be concluded that the value of 15 effect sizes analyzed is heterogeneously distributed. Therefore, the model used to calculate the mean effect size is a random effect model. Furthermore, checking publication bias through funnel plot analysis and Rosenthal fail safe N (FSN) test (Tamur et al., 2020; Badawi et al., 2022; Ichsan et al., 2023b; Borenstein et al., 2007; Zulkifli et al., 2022; Dewanto et al., 2023). The results of checking publication bias with funnel plot can be seen in Figure 2.

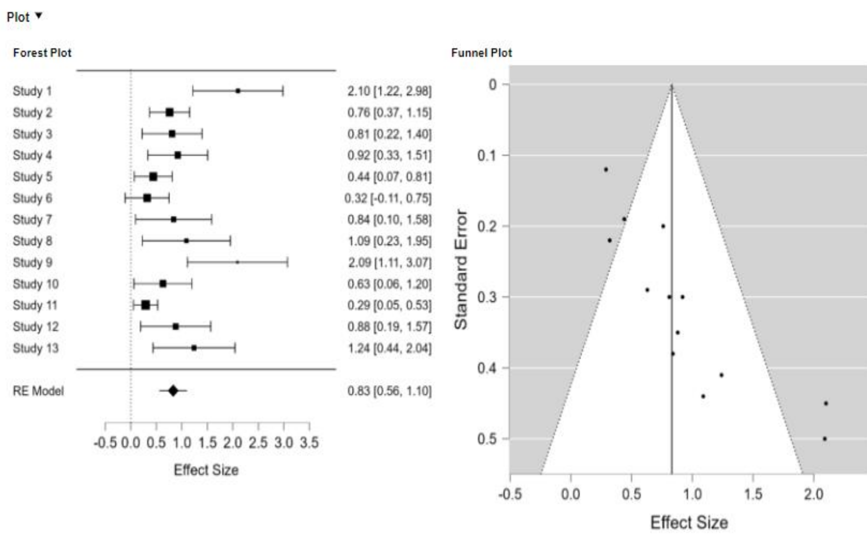

Figure 2. Funnel Plot Standard Error And Forest Plot

Based on Figure 2, the analysis of the funnel plot is not yet known whether it is symmetrical or asymmetrical, so it is necessary to conduct a Rosenthal Fail Safe N (FSN) test. The results of the Rosenthal Fail Safe N calculation can be seen in Table 4.

Tabel 4. Fail Safe N

File Drawer Analysis			
	Fail Safe N	Target Significance	Observed Significance
Rosenthal	493	0.050	< 0.001

Based on Table 4, the Fail Safe N value of 493 is greater than the value of 5k + 15 = 5(13) + 10 = 75, so it can be concluded that the analysis of 15 effect sizes in this data is not biased by publication and can be scientifically accounted for. Next, calculate the p-value to test the hypothesis through the random effect model. The results of the summary effect model analysis with the random effect model can be seen in Table 5.

Tabel 5. Mean Effect Size

Coefficient				
	Effect Size	Standard Error	z	p
Intercept	0.83	0.137	6.073	< 0.01

Based on Table 5, the results of the analysis with the random . The effect size category in this study is included in the high category. Furthermore, the results of the Z test to determine the significance were obtained 6.073 and the p value < 0.01, so it can be concluded that the application Construction 4.0 has a positive influence on the efficiency and safety of project work with a high influence category. In addition. The implementation of Construction 4.0 contributes significantly to improving the efficiency of construction projects, especially in terms of time, cost, and labor productivity. The analyzed study indicates that the use of Building Information Modeling (BIM), Artificial Intelligence (AI), and Internet of Things (IoT) allows for real-time optimization of project planning and management, thereby reducing inefficiencies and improving coordination between stakeholders. In addition, robotics and automation technology has been proven to be able to speed up the construction process, reduce material waste, and improve the accuracy of work in the field. These findings are in line with the research of Li et al. (2020), which showed that construction projects that apply digital technology experienced up to 30% higher efficiency improvements compared to conventional methods. In addition to efficiency, the adoption of Construction 4.0 technology also plays a role in improving work safety in the construction sector. Data analysis shows that the use of IoT sensors, drones, and wearable technology allows real-time monitoring of worker conditions and work environments, so that potential accidents can be identified early. Some of the studies analyzed also highlighted the role of smart helmets and AI-based monitoring systems in detecting worker fatigue and providing early warning of accident risks. This is reinforced by the findings of Zhong et al. (2017), who reported that the use of IoT-based technology can reduce the number of work accidents by up to 25%, especially in large-scale projects that have a high level of risk.

Although Construction 4.0 technology offers many benefits, there are several challenges in its implementation, especially related to high initial investment costs, limited skilled labor, and resistance to technological change (Statsenko et al., 2023). Some of the studies in this meta-analysis show that small and medium-sized construction companies still face difficulties in fully adopting this technology due to budget constraints and lack of workforce training (Milijić et al., 2020). In addition, the compatibility of digital systems with existing infrastructure is also an obstacle that is often faced. Therefore, a more comprehensive strategy, such as policy support from the government and increased workforce training programs, is needed to accelerate the adoption of Construction 4.0 technology in the construction industry (Hossain & Nadeem, 2019; Osunsanmi et al., 2020). Overall, this meta-analysis confirms that Construction 4.0 has a significant positive impact on project efficiency and work safety. However, the effectiveness of its implementation is highly dependent on the readiness of the industry in adopting technology, including in the aspects of human resources, regulations, and digital infrastructure (El Jazzar et al., 2021). With the increasing need for work efficiency and safety in the construction sector, the use of digital-based technology will become the new standard in the industry. Therefore, further research is needed to explore optimal strategies in addressing implementation challenges as well as evaluating the long-term impact of Construction 4.0 technology on the sustainability of the construction industry (Kor et al., 2023).

CONCLUSION

From the results of this study, it can be concluded that the value of the summary effect size is ($d = 0.830$; $z = 6.073$; $p < 0.001$). These findings show that construction 4.0

has a positive influence on the efficiency and safety of project work with a high influence category. The application of technologies such as Building Information Modeling (BIM), Artificial Intelligence (AI), Internet of Things (IoT), robotics, and automation has been proven to increase planning effectiveness, reduce resource waste, and accelerate the development process. In addition, IoT-based technology and real-time monitoring systems also contribute to improving work safety by detecting the risk of accidents early. However, the implementation of this technology still faces various challenges, such as high investment costs, limited skilled labor, and resistance to technological change. Therefore, broader efforts are needed, including policy support, workforce capacity building, and the development of more adaptive digital infrastructure. With the right strategic steps, Construction 4.0 has the potential to be the main solution in creating a more efficient, safe, and sustainable construction industry in the future.

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