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Review

Impact of AI on triple bottom line performance and economic sustainability in megaprojects: a systematic review and conceptual framework

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A B S T R A C T

Megaprojects have significant impacts on global infrastructure development, yet they continue to face sustainability challenges, including high costs, environmental damage, and social conflict. Artificial intelligence (AI) technologies are transforming construction management, but there is little literature examining the integration of AI into construction and megaproject sustainability. This gap is addressed through a comprehensive literature review on the impact of AI on the triple bottom line (TBL) performance and economic sustainability of megaprojects and by proposing a conceptual framework supported by research propositions. A Boolean combination of three keywords in the Scopus database resulted in 348 initial articles, from which 18 key articles were selected for further analysis. All three keyword categories identified only five articles pertinent to the current research topic, highlighting a clear knowledge gap. Analysis shows that AI research has matured in economic performance areas such as cost estimation and resource optimization, with 87% of reviewed papers addressing economic aspects. Research on environmental performance, particularly carbon emissions and waste management, has progressed but remains limited. Social performance, including stakeholder management and community impact assessment, is the least explored dimension. Based on the Technology-Organization-Environment (TOE) framework and stakeholder theory, this study develops a theoretical model with three layers: AI technology inputs, TOE conditions, and TBL performance outputs, in which economic sustainability serves as a higher-level outcome. Four propositions are developed to identify how AI impacts each TBL dimension and economic sustainability. This study contributes to the theoretical groundwork and direction for future empirical studies.

1. Introduction

Megaprojects are major initiatives that require an investment of more than US$1 billion, take several years to develop and construct, and affect economic, environmental, and social factors. Common types include transportation infrastructure (e.g., high-speed rail, airports), energy systems (e.g., nuclear power plants), and urban development programs (e.g., smart cities). Examples include the Hong Kong-Zhuhai-Macao Bridge, the NEOM smart city initiative in Saudi Arabia, the Crossrail Project in London, and other renewable energy initiatives, such as offshore wind farms in the North Sea. These megaprojects are important in promoting social and economic development. Given the rapid global increase in infrastructure investments, the challenges of implementing megaprojects have become a growing concern. Research shows that cost overruns in megaprojects average above 50% [1]. These issues include carbon emissions, excessive resource use, environmental impacts, and social problems related to land ownership, community issues, and labor conditions, posing significant obstacles to sustainable management practices. Several variables that contribute to poor performance in megaprojects have been highlighted in an exhaustive literature review, including ineffective governance, asymmetric information, and conflicting stakeholder objectives. The existing management systems are unable to satisfactorily balance economics, environment, and society in their considerations [2]. The Triple Bottom Line (TBL) framework provides an evaluation method that extends beyond economic parameters to consider environmental and social dimensions, thereby ensuring sustainable development for "people, planet, and profit" [3]. In this study, economic performance and economic sustainability are distinguished. Economic performance refers to short-term or project-stage financial performance, which includes accurate cost estimation, budget management, and efficient use of resources. In contrast, economic sustainability refers to financial performance over time and throughout the project, including operational revenue stability, return on investment, and resilience to financial risk [4, 5]. While economic performance is one aspect of TBL, economic sustainability is viewed in this research as an outcome that depends on the combined development of the three TBL aspects. In relation to megaprojects, which are characterized by considerable capital expenditures and long-term operations, this consideration becomes particularly relevant, thereby providing a major reason to investigate economic sustainability separately.

The application of AI results in changes to the management practices in the construction industry. For instance, cost predictions using machine learning and safety monitoring systems powered by computer vision are becoming common and are revolutionizing existing processes. Despite the marked increase in the number of publications on the topic of interaction between AI and architecture, engineering, and construction (AEC) during the past ten years, no agreement has been reached yet concerning the sustainability evaluation frameworks or the association between the use of AI technology and sustainability achievements [6]. Although the potential of AI to support the United Nations Sustainable Development Goals (SDGs) has been recognized [7], this benefit is mitigated by risks such as the digital divide and resource imbalances, which can be further exacerbated in resource-heavy megaprojects. The limitations identified include a lack of data, ambiguity in causality, and an absence of industry specificity, among others, as well as a failure to advance theories alongside technological advancements [8]. A review of the extant literature indicates a clear-cut gap in research. Specifically, literature examining the implementation of AI technology in the AEC sector tends to analyze particular tasks performed by the technology without considering the TBL impact of the entire process. Studies on sustainability in megaprojects ignore the role of AI as a variable to consider. Indeed, a systematic search in Scopus using three keywords yielded only five relevant publications.

To fill this gap, this study performs a systematic review of the literature on AI technology and its impact on sustainability performance in the construction sector. This review leads to the development of an explanatory conceptual model that shows the connections between AI, TBL, and economic sustainability in megaprojects. This study makes three primary contributions. Theoretically, the study adopts an innovative methodology combining the TOE framework and stakeholder theory to explore the impact of AI on the sustainability performance of megaprojects. Structurally, the suggested conceptual model provides a framework for systematically synthesizing scattered empirical studies that explore the relationship between AI and TBL performance. In practice, the implications of this paper can inform project managers' decisions about investing in AI technology.

2. Analysis of the problems

2.1 The sustainability dilemma of megaprojects

The same attributes that make megaprojects strategically important in terms of considerable investments, long periods of time, advanced technologies, and many participants also make megaprojects some of the toughest environments for sustainability management. The examination of success factors in the management of megaprojects in China illustrates this conflict: efficient organizational coordination is often considered indispensable, yet megaprojects cannot achieve their goals due to coordination issues, skewed communication, and lengthy decision-making processes. Cost and time overruns are inevitable across sectors and countries due to a capability gap stemming from the inherent complexity of megaprojects and traditional project management approaches [9].

Management for sustainability in megaprojects faces several difficulties. For example, in infrastructure development projects, there are different stages: planning, design, construction, and operation; at each stage, economic viability, environmental, and social aspects must be balanced. This can be observed, for example, in the fact that maximizing economic benefits might negatively impact the environment, while accelerating construction might affect workers. Research on sustainable management in infrastructure development reveals that control mechanisms play a vital role in achieving sustainability goals. But the main emphasis of control measures lies in time and cost rather than in environmental and social aspects [4]. The mismatch between control systems and sustainability goals has led to a high demand for innovative approaches, especially those involving AI.

2.2 Triple bottom line theory and its application in the construction sector

The TBL theory is recognized as a key theoretical paradigm in sustainability and has been considered important both theoretically and practically since the late 1990s. While reviewing the 25-year development of TBL theory, Elkington argued that TBL could be seen as a paradigm shift rather than a performance measure [10]. After performing a bibliometric analysis of TBL literature from 2001 to 2023, the findings show a trend towards an increasing number of studies in this area, but the research focus shifts from corporate social responsibility to the evaluation of industry sustainability. This shows that keywords have shifted toward the environment over economics and society, signifying a trend towards economic sustainability [11]. Various attempts to integrate sustainability into project management have been undertaken in the project management literature. However, various studies reveal many problems, such as terminological confusion, non-uniform assessment criteria, and differing organizational perspectives. People working in project management have difficulty practicing TBL [5]. This gap between concepts and execution highlights the need for technology such as AI to make sense of data and enable intelligent decision-making.

2.3 Current status of AI technology application in construction

The application of AI in the construction industry has advanced from theory to practice across various settings. A systematic review of the use of AI in infrastructure development shows that machine learning, deep learning, computer vision, and natural language processing are increasingly used in areas such as project decision-making, construction management, quality control, and document management. Maturation in these regards varies greatly from one stage to another. Construction safety planning and prediction during construction are considered fairly mature processes. However, generative design optimization and predictive maintenance are becoming more mature processes, but they still need large-scale deployment [12]. Combining Building Information Modeling (BIM) with AI has enabled intelligent construction management by integrating three-dimensional digital models with AI-powered software for clash detection, scheduling, and energy simulation. However, many barriers remain in this respect [13].

Two key issues posed by the current state of technology can be identified. From a dimensional perspective, previous research has focused more on economic performance dimensions, such as costing, planning, and scheduling. Research into environmental performance dimensions such as carbon emissions, waste management, and energy efficiency has made significant progress, though it remains relatively underdeveloped. Social performance research on AI-based safety-warning risks, workforce management, and community impact assessment is relatively scarce. Regarding the integration of theory, most research demonstrates the effectiveness of specific AI techniques for particular tasks but does not provide a tool for evaluating the influence of AI on construction projects in the context of sustainability. Based on the reviewed literature, topics concerning economic performance dominate existing research, with a systematic review showing that 87% of AI decision-support applications in construction organizations focus solely on economic performance [14]. Environmental performance studies have expanded, but their scope remains narrower than that of social performance, the least-focused pillar among the three components of TBL.

2.4 Research gap and positioning of this study

In the analysis above, three levels of systemic issues emerge from the extant literature. From a practical standpoint, cross-disciplinary research on AI and sustainability primarily focuses on SMEs and construction projects. The following empirical study examines the use of AI and its effects on performance from a sustainability perspective in SMEs, using a mixed-methods approach. In particular, the study applies structural equation modeling and artificial neural networks to demonstrate the benefits of AI for performance. Although the study is methodologically sound, the applicability of its results is hindered by differences between SMEs and megaprojects [15]. In terms of theory, most research follows an SDG approach or focuses on a single aspect of sustainability, while few studies examine the TBL approach comprehensively. At the level of dimensional coverage, the gap between abundant economic research and relatively less environmental and social research is evident in megaprojects, given their broad environmental impacts and more complex stakeholder interactions. The gap generated after the literature review is presented in Table 1. This research study is based on three distinct focal perspectives. First, this study is conducted from the perspective of megaprojects, which have generally been overlooked in earlier research. Second, the TBL approach is employed as a broad perspective within which economic sustainability is considered independently. Third, this research attempts to integrate various streams of literature and develop propositions from the literature review.

2.5 Theoretical foundations

The conceptual model is grounded in two complementary theories: the TOE framework and stakeholder theory. The TOE model helps explain how technology adoption occurs within firms, as it depends on factors related to technology, the organization itself, and the environment [25]. Regarding the use of AI in megaprojects, the technological aspects include the intelligence of the algorithms used, the availability of high-quality data, and the feasibility of implementation. In terms of the organizational aspect, important considerations include digital skills, adaptability to technological change, and infrastructure improvements. Environmental factors cover industry standards, government rules, and competitive conditions. As evidenced by a meta-analysis of factors influencing BIM, the TOE framework is effective for analyzing construction technology, and organizational factors, including management commitment and organizational readiness, have the greatest influence on implementation decisions [26].

The TOE framework helps identify the circumstances that trigger AI adoption; however, understanding the impact of AI on performance from various perspectives can only be achieved through a stakeholder approach. According to the stakeholder approach, any strategic actions and performances ought to take into account the needs of all those parties concerned [27]. Megaprojects involve multiple stakeholders with distinct concerns- government agencies, investors, contractors, communities, and employees- whose diverse demands correspond to the three TBL dimensions. As noted in a systematic review of stakeholder management in large construction projects, stakeholder conflict and coordination are critical to achieving sustainable success, with information transparency and stakeholder participation as key tools for mitigating conflict [28].

Given the capabilities of AI in processing data, making predictions, and decision-making, the position that can be taken by AI in regard to the three important elements in TBL is the improvement of decision-making and transparency in information, among others, depending on the stakeholder. Together, these two theories form the foundation of the conceptual framework, supporting a "condition–application–performance" analytical sequence in which TOE identifies adoption antecedents and stakeholder theory explains the channels through which performance is impacted.

Table 1. Literature gap analysis

Author(s) / Year	Research Context	AI Technology	Sustainability Dimension	Method	Key Findings	Gap with This Study
Regona et al. (2024) [16]	Construction industry (full lifecycle)	ML, DL, CV, robotics, predictive analytics	SDGs (Goals 6–9, 11–13, 15, 17)	SLR (PRISMA)	AI contributes to construction sustainability with 10–15% carbon reduction potential	SDGs framework, not TBL; general construction, not megaprojects
Smith & Wong (2022) [14]	Construction projects (full lifecycle)	ANN, fuzzy logic; 46% hybrid models	Economic (87%), environmental, social	SLR (3 databases, 77 articles)	50% of studies focus on early-stage prediction; economic dimension dominates	General construction, not megaprojects; no conceptual framework proposed
Akbari et al. (2018) [17]	Large-scale construction projects	Rough sets	Sustainable success index	Predictive model	Organizational, technical, and environmental factors jointly affect sustainable success	Custom sustainability index, not TBL framework; dated AI technique
Greiman (2020) [18]	Megaprojects	AI (general)	Not explicitly addressed	Conceptual discussion	AI is the "next frontier" for megaproject management	Conference paper; no TBL or sustainability analysis
Ahmed et al. (2025) [19]	Megaprojects (CPEC)	Generative AI tools	Operational efficiency (indirect)	Qualitative (grounded theory)	Leadership support is critical for AI-driven knowledge management	Focuses on knowledge management, not TBL performance
Waqar et al. (2023) [20]	Oil and gas projects	ML, DL, expert systems, fuzzy logic	Environmental protection, operational efficiency	SLR	AI enhances operational efficiency and safety while reducing environmental impact	Single industry; no TBL framework; no economic sustainability concept
Singh et al. (2023) [21]	Construction supply chains	AI (general)	Sustainability management (broad)	Literature review + fuzzy DEMATEL	Core barriers: data integration, lack of standards, organizational resistance	Focuses on adoption barriers, not performance impact; not megaprojects
Adebayo et al. (2025) [22]	Construction PM (1985–2024)	ML, DL, expert systems, NLP, CV	Sustainability as adoption driver	Structured literature review	AI most applied in planning and monitoring; sustainability drives adoption	Focuses on AI evolution, not sustainability performance impact
Kulejewski & Rosłon (2023) [23]	Construction scheduling	Metaheuristic algorithms + AI	Economic (cost) + environmental (ecological index)	Computational experiment	AI enables simultaneous optimization of ecological and economic objectives	Covers two TBL dimensions but omits social; general construction projects
Sánchez et al. (2024) [24]	Linear infrastructure projects	Industry 4.0 (IoT, AI, BIM, digital twin)	Sustainable development (broad)	SLR	Industry 4.0 promotes sustainability but adoption is constrained by funding and talent	Covers Industry 4.0 broadly, not AI specifically, not megaprojects

3. Materials and methods

3.1 Literature search strategy

In this study, a systematic review method was employed in conjunction with the development of a conceptual framework through literature analysis across three major areas: AI, megaprojects, and sustainability [29]. The literature review was undertaken using the Scopus database by applying Boolean cross-conditions based on terminology selected from the following three groups. The precise search query used for the same was:

TITLE-ABS-KEY (("artificial intelligence" OR "machine learning" OR "deep learning" OR "AI-driven" OR "AI-based") AND ("mega project" OR "megaproject" OR "large-scale construction" OR "infrastructure project" OR "major project" OR "construction project") AND ("sustainability" OR "sustainable" OR "triple bottom line" OR "economic performance" OR "environmental performance" OR "social performance")).

The search was carried out on January 15, 2025, and included English-language peer-reviewed journals and reviews from 2015 to 2025. The upper limit of the search year was set to 2026 in the Scopus filter to capture any early-indexed publications; however, no 2026 publications were retrieved during the search. Selection and screening procedures followed the PRISMA statement on Preferred Reporting Items for Systematic Reviews and Meta-Analyses [30].

The initial search yielded 348 publications after removing duplicates using Scopus's duplicate removal tool. The inclusion criteria required selecting only English-language articles from the engineering, computer science, environmental sciences, and business management disciplines. The exclusion criteria included conference proceedings, book sections, and editorials irrelevant to megaprojects and AI, as well as studies that focused on predicting material properties or structure without any relation to AI. After applying filters for both research areas and document types, 107 sources remained. In total, 107 documents were analyzed for relevance based on their titles and abstracts, and 18 key articles were identified as relevant to the topic. Figure 1 illustrates this entire review process.

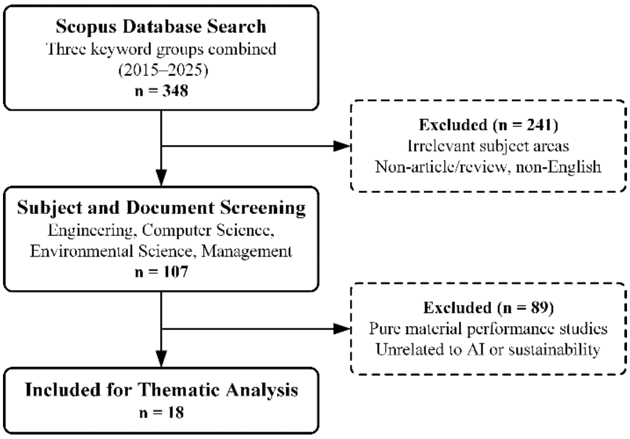

Figure 1. PRISMA-guided literature screening and selection process

Concurrent use of all three sets of keywords yielded only five articles in Scopus. Such a result provides clear bibliometric evidence of a significant knowledge gap across AI, TBL efficiency, and megaprojects, thereby underscoring the relevance of current research.

3.2 Literature analysis method

The thematic approach was used to analyze and interpret the 18 core publications [31]. Each publication was coded by the first author and verified by the corresponding author along six predefined dimensions: research context (project type and industry), AI technology type (machine learning, deep learning, computer vision, natural language processing, etc.), sustainability dimension coverage (economic, environmental, social, and combinations), research method (systematic review, computational experiment, quantitative modeling, etc.), core findings, and gaps relative to the present study. Discrepancies in coding were resolved through discussion until consensus was reached. The coding results were organized in a structured extraction matrix using Microsoft Excel, which facilitated the identification of themes, recognition of patterns, and detection of gaps. To avoid conceptual overlap between the economic performance theme (Section 4.2) and the economic sustainability theme (Section 4.5), studies addressing short-term, project-phase financial outcomes were coded under economic performance, whereas studies addressing long-term financial viability or life-cycle economic resilience were coded under economic sustainability. In the synthesis process, the existing literature was divided into four themes based on the coding results: the effects of AI on economic, environmental, and social performance, and the association between AI and economic sustainability. The four categories mentioned above are based on the dimensions of TBL and the concept of economic sustainability. The theme analysis served as a tool for guiding the development of theories using the TOE framework and stakeholder theory, thereby leading to the creation of the conceptual framework and the proposition. Conceptual research entails developing a new framework and a proposition from the literature review, without necessarily conducting primary data collection [32].

4. Results

The systematic search yielded 18 core articles for thematic analysis. Most (15) were published between 2022 and 2025, with systematic literature reviews as the predominant method (7 publications). Construction emerged as the predominant context of study (11 publications), but only three focused on megaprojects, and no empirical studies were conducted in this context. The uneven balance is clear: Economic analysis is dominant, environmental analysis is growing but relatively small, and social analysis is clearly understudied across the reviewed studies. Table 2 summarizes the characteristics of the reviewed articles in detail.

4.1 Theme 1: AI's impact on economic performance in megaprojects

Economic performance has become the key focus of academic literature, where the link between AI and construction sustainability is explored. According to a review of AI decision-making systems that have been developed to support construction sustainability, there were 77 publications, out of which 87% of studies were concerned about economic sustainability, 50% stressed the importance of forecasting, artificial neural networks and fuzzy logic prevailed among AI models used in such research, and 46% involved hybrid AI algorithms [14]. This indicates that AI-based predictive methods in construction economics have reached considerable sophistication. For megaprojects, such predictive capability is critical given the scale of investment, where even a one-percentage-point error can cost millions of dollars. To study megaprojects, a model based on the rough set approach has been proposed to achieve sustainability in large-scale construction projects by integrating organizational, technical, and environmental considerations, thereby extending sustainability analysis beyond purely economic terms [17].

Table 2. Characteristics of included studies

No.	Author(s)/ Year	Research Context	AI Technology	Sustainability Dimension	Method	Key Findings
1	Regona et al. (2024) [16]	Construction industry (full lifecycle)	ML, DL, CV, robotics, predictive analytics	SDGs (Goals 6–9, 11–13, 15, 17)	SLR (PRISMA)	AI contributes to construction sustainability; 10–15% carbon reduction potential
2	Waqar et al. (2023a) [20]	Oil and gas projects	ML, DL, expert systems, fuzzy logic	Environmental protection, operational efficiency	SLR	AI enhances efficiency and safety while reducing environmental impact
3	Singh et al. (2023) [21]	Construction supply chains	AI (general)	Sustainability management (broad)	Literature review + fuzzy DEMATEL	Core barriers: data integration, lack of standards, organizational resistance
4	Smith & Wong (2022) [14]	Construction projects (full lifecycle)	ANN, fuzzy logic; 46% hybrid models	Economic (87%), environmental, social	SLR (3 databases, 77 articles)	50% focus on early-stage prediction; economic dimension dominates
5	Waqar et al. (2023b) [33]	Construction projects (AI drones)	AI-based drone systems	Project success (efficiency, safety, environment)	Quantitative modeling	AI drones improve monitoring accuracy and safety management
6	Adebayo et al. (2025) [22]	Construction PM (1985–2024)	ML, DL, expert systems, NLP, CV	Sustainability as adoption driver	Structured literature review (135 articles)	AI most applied in planning and monitoring; sustainability drives adoption
7	Alshboul et al. (2022) [34]	Green building cost prediction	XGBoost	Economic (cost prediction) + environmental (green building)	Computational experiment	XGBoost outperforms traditional methods in green building cost estimation
8	Hetemi et al. (2020) [35]	Sustainability-oriented infrastructure	BIM and digital extensions	Sustainability (institutional perspective)	Institutional theory analysis	Digital tools alone are insufficient; institutional and organizational support needed
9	Sánchez et al. (2024) [24]	Linear infrastructure projects	Industry 4.0 (IoT, AI, BIM, digital twin)	Sustainable development (broad)	SLR	Industry 4.0 promotes sustainability but constrained by funding and talent
10	Akbari et al. (2018) [17]	Large-scale construction projects	Rough sets	Sustainable success index	Predictive model	Organizational, technical, and environmental factors jointly affect success
11	Shahnavaz & Akhavian (2022) [36]	Construction equipment emission	ML (with inertial sensors)	Environmental (carbon emission)	Experiment	ML automates emission estimation with real-time sensor data
12	Bang & Andersen (2022) [37]	Construction site waste	AI (image recognition, data analytics)	Environmental (waste reduction)	Qualitative	AI shows significant potential for waste identification and reduction
13	Mésároš et al. (2024) [38]	Construction industry carbon footprint	AI (data analysis and prediction)	Environmental (carbon footprint)	Analytical study	AI improves carbon footprint analysis efficiency; data availability is a challenge
14	Lin et al. (2025) [39]	Construction engineering and management	Smart techniques (AI, IoT, BIM, digital twin)	Sustainability (broad)	Review	Smart techniques show broad potential, but lab-to-practice transfer remains challenging
15	Ahmed et al. (2025) [19]	Megaprojects (CPEC)	Generative AI tools	Operational efficiency (indirect)	Qualitative (grounded theory, 6 interviews)	Leadership support is critical for AI-driven knowledge management
16	Greiman (2020) [18]	Megaprojects	AI (general)	Not explicitly addressed	Conceptual discussion	AI is the "next frontier" for megaproject management
17	Srivastava et al. (2022) [40]	LNG mega project	Digital control tower (AI-assisted)	Operational efficiency (indirect)	Industry case report	Digital control tower enables real-time visibility and decision support
18	Kulejewski & Rosłon (2023) [23]	Construction scheduling	Metaheuristic algorithms + AI	Economic (cost) + environmental (ecological index)	Computational experiment	AI enables simultaneous optimization of ecological and economic objectives

The AI method used in this research currently seems outdated, but applying AI classification and prediction methods to forecast sustainability is relevant to megaprojects. Notably, there is significant variation in the methods used in these studies. While certain studies used systematic literature reviews to draw generalizable assumptions from an extensive collection of articles [14], others used computational predictive models in their respective project setups [17] or employed machine learning techniques tested on limited datasets [34]. All these variations make generalizing the results difficult because megaprojects involve significantly large amounts of data. One limitation of much of this research is its focus on the short-term impact of AI on the economic efficiency of megaprojects, with little discussion of its potential long-term effects on their economic well-being. This gap is discussed in section 4.5.

4.2 Theme 2: AI's impact on environmental performance in megaprojects

Environmental performance ranks second in the reviewed literature, covering carbon emission assessment, waste management, and multi-objective environmental optimization. As for carbon emissions assessment, the application of AI to assess construction carbon footprints has led to more efficient and accurate results, but the lack of available data and inadequate standards pose challenges to this area of research [38]. From a more detailed technological perspective, the use of machine learning systems trained on inertial sensor data would enable the automation of carbon emissions quantification from construction equipment, a practical approach for real-time monitoring at construction sites [36]. However, their current use is limited to individual pieces of equipment or even to single construction-site operations, with scaling to megaprojects remaining an unaddressed problem.

Within the environmental management needs of megaprojects, carbon emissions and waste are two criteria that have received the most attention from researchers to date. Other important aspects, such as water resource management, ecosystem effects, noise reduction, and changes in land use, have yet to be considered within the scope of AI research. Most of the current literature focuses on a single environmental concern at the construction stage, while no studies have considered the environmental contribution of AI across the entire project life cycle. The above review shows methodological heterogeneity among the studies analyzed. Experimental methods that use sensors, in addition to quantitative analysis [36] and qualitative designs [37], have been used in environmental AI research. In contrast, carbon footprint analysis was hampered by a lack of data [38]. None of these studies attempted cross-site or cross-project validation, which limits the scalability of their findings to megaprojects involving multiple construction sites and extended timelines. The environmental consequences of megaprojects are experienced in the long run, across large geographical areas, and through complex causal chains, thus calling for an analytical framework that extends beyond a single life cycle stage and indicator.

4.3 Theme 3: AI's impact on social performance in megaprojects

Social performance is the least developed of the three TBL pillars in the reviewed literature. Research on knowledge management using AI within the China-Pakistan Economic Corridor project found that leadership support is crucial for successful AI use. Furthermore, the analysis and prediction capabilities of AI can be leveraged to make the information-processing process more transparent, which may help mitigate the trust gap among stakeholders in megaprojects [19]. In terms of the social performance sub-dimension concerning construction safety, studies have indicated that drones powered by AI technology can help increase monitoring effectiveness in safety management [33].

The social implications of megaprojects extend beyond safety and knowledge management problems to include community displacement due to land acquisition, construction disruptions that interfere with community members' daily activities, labor-related issues, and employment impacts. Nevertheless, there is considerable unexploited potential for AI in this domain. Potential applications include natural language processing techniques to evaluate public opinion generated on social media and in public consultation records, predictive machine learning models to forecast the consequences of community dislocation, and AI-enabled stakeholder mapping systems that can identify potential conflicts from the outset of the planning process. Future studies should consider operationalizing the social performance metric using various performance indicators, such as stakeholder satisfaction, worker welfare and safety measures, levels of public approval, social equity, and community resilience. The scarcity of scholarly literature in this area stems from the persistent focus on economic and technological considerations in AI implementation and sustainable construction research. Given that megaprojects involve more stakeholders than other projects and entail far-reaching social considerations, filling this gap is especially important.

4.4 Theme 4: AI and economic sustainability in megaprojects

Drawing on the distinction outlined in Section 2.2, this section reviews the literature on AI and economic sustainability in megaprojects. A study on the use of Industry 4.0 approaches in linear infrastructures reveals that, through digital technologies, sustainable life cycle management can be achieved by providing relevant data. In contrast, inadequate funding and a lack of technical expertise make it difficult to adopt technology, especially in megaprojects, which require substantial investment [24]. Similarly, a study on the use of AI technologies in oil and gas projects revealed that increased efficiency could yield favorable economic outcomes, but the issue of economic sustainability was not considered separately [20].

4.5 Conceptual framework construction and proposition formulation

A conceptual framework was developed through thematic analysis that synthesized the TOE framework and stakeholder theory, as illustrated in Figure 2.

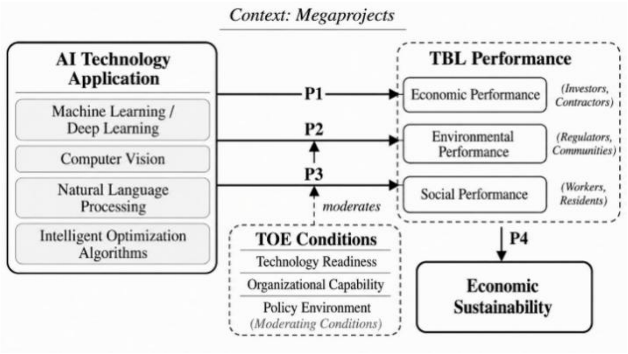

Figure 2. Conceptual framework: impact of AI on TBL performance and economic sustainability in megaprojects

This framework includes three levels: the input level with four types of AI technologies (machine learning and deep learning, computer vision, natural language processing, and optimization algorithms), the conditioning level with TOE moderating factors, and the output level, which is made up of TBL performance dimensions with economic sustainability as extended results. The key issue is that this approach relies on theory-driven argumentation rather than empirical data, so that all connections between layers imply directionality but not necessarily any empirically tested findings. Further research may be conducted using an empirical analysis of the impact of digitalization on sustainable performance [41] to quantify the relationships within this path.

The causal mechanism of the theoretical framework works as follows. AI technologies at the input stage develop analytical capabilities, including prediction, recognition, and optimization. Nonetheless, these analytical abilities alone do not guarantee improved performance, since their effectiveness depends on TOE criteria. Specifically, the technology readiness criterion dictates the degree to which AI technologies are mature enough to be used in the existing environment. Organizational capability is the set of skills and knowledge an organization possesses for using information technology in its operations. The policy framework encompasses regulatory and other measures that may hinder or facilitate the uptake of artificial intelligence technology. In contrast, the stakeholder theory examines the impacts that the advantages derived from innovation relating to the use of AI have on the different aspects of the TBL from the output standpoint. Specifically, the economic aspect benefits investors and contractors, the environmental aspect affects regulators and the local community, and the social aspect concerns employees and the local community. Economic sustainability is the second most important, given its favorable effects on all three TBL aspects. The framework gives rise to four research propositions:

Proposition P1: The use of AI technology positively impacts economic performance in megaprojects. The existing literature suggests that there are economic gains from AI, such as better cost estimates, improved resource optimization, and permanent classification. However, fulfilling certain prerequisites is necessary to achieve those economic gains, including reliable data, the right algorithms, and organizational willingness to change, depending on the characteristics of a particular megaproject. Specifically, technologies that incorporate AI, such as cost-forecasting techniques and machine-learning-powered resource management algorithms, have the greatest impact on performance, with the extent of this impact varying with the company's digital maturity level and data quality.

Proposition P2: The use of AI technology positively impacts environmental performance in megaprojects. Evidence for this proposition mainly comes from studies conducted in regular construction settings, such as carbon emissions measurement, waste handling, and ecological-economic optimization. Applying this evidence to megaprojects raises issues regarding data integration and the comprehensiveness of environmental performance measures. The strength of this correlation will probably depend on regulations and standardization of environmental data collection.

Proposition P3: The application of AI technology positively impacts social performance in megaprojects. This hypothesis receives the least empirical support among the four theories. There is some information supporting this theory, but it comes from research on the use of AI in relation to worker safety at the site and project-related knowledge management. The use of AI in relation to social aspects remains uncertain, with potential negative side effects. The impact of AI on social performance may be shaped by stakeholder involvement and the quality of governance within the project, particularly in megaprojects, where multiple organizations and diverse community interests are involved.

Proposition P4: The application of AI technology promotes economic sustainability in megaprojects by enhancing TBL performance. This theory suggests that better short-run economic performance, together with better performance in environmental and social arenas, is a necessary prerequisite for achieving sustained long-run economic performance. However, the achievement of this prerequisite depends on certain governance, contractual, and policy issues, leading to the highest level of uncertainty for proposition P4 among the four propositions. Furthermore, the substantial financial outlay required to deploy AI technologies may negatively affect economic sustainability in the short run, posing a trade-off that needs to be carefully managed through a phased deployment approach and an enabling policy framework. A summary of research propositions is given in Table 3.

4.6 Discussion

The literature review indicates that, across the academic discourse, there is a consistent bilateral disparity. This is because only 3 of the 18 articles studied discuss megaprojects, while the other 15 address general construction environments. In essence, this means that the theoretical propositions put forward in this study are partly supported by information drawn from the general construction literature, and further testing is required to validate them for megaprojects. An analysis of intelligent technologies used in sustainable construction indicates that, while there is tremendous scope for applying intelligent technologies and AI in sustainable development, the transition from research to practical implementation poses considerable challenges [39]. The conflict is further complicated by megaprojects due to the complexity associated with projects.

Table 3. Summary of research propositions

Proposition	Content	Theoretical Basis	Supporting Literature	Level of Support
P1	AI positively influences economic performance in megaprojects through improved cost prediction, resource optimization, and decision efficiency	TOE (technology readiness) + Stakeholder theory (owner/contractor interests)	[14, 17, 34, 40]	Moderate
P2	AI positively influences environmental performance in megaprojects through emission monitoring, waste management, and ecological optimization	TOE (technology capability) + Stakeholder theory (community/regulatory interests)	[23, 36-38]	Moderate
P3	AI positively influences social performance in megaprojects through safety monitoring, stakeholder analysis, and labor management	TOE (organizational readiness) + Stakeholder theory (community/labor interests)	[19, 33, 35]	Weak
P4	AI promotes economic sustainability through the mediating pathway of improved TBL performance	Integrated TOE + Stakeholder theory	[18, 20, 24]	Weak

In fact, research on the challenges to adopting AI in the construction industry's supply chain also supports this discussion from a different perspective. Data interoperability issues, lack of technological standardization, and resistance to change are the most common hindrances to the deployment of artificial intelligence [21]. Such difficulties could be amplified in megaprojects involving more than one organization and international collaboration. From a theoretical perspective, the theory advanced in this research addresses the problem of "fragmented theories" in the current literature. Incorporating the TOE approach with stakeholder theory yields an all-encompassing model that connects "adoption conditions" and "performance outcomes," allowing studies across different technical settings to be interpreted within a single theory. It should be noted that the TOE framework was originally designed for organizational-level technology adoption. Megaprojects, as temporary multi-organizational entities, differ fundamentally from traditional firms, which may affect how TOE constructs operate in this context. Empirically, the findings suggest that AI offers advanced capabilities for economic and environmental performance, whereas applications for social performance require further research. Based on current research on the ethical considerations in using AI for optimization in the supply chain process, the use of AI technologies on the basis of insufficient knowledge can lead to future social risks that have not been recognized [42]. Advocates for the wise implementation of large projects need to ensure that information on evaluation and rewards related to environmental and social performance is available to avoid purely economically driven decisions.

Moreover, incorporating AI into megaprojects presents some risks. Discrimination by algorithms that support decision-making may lead to an unequal distribution of resources and an undervaluation of their impact on disadvantaged groups. Other risks include data breaches associated with handling sensitive data, cybersecurity risks to AI-enabled systems, and social unrest due to job losses.

In addition, the energy consumed during the training and usage of such large AI systems becomes an environmental cost that somewhat offsets the sustainability advantages. The aforementioned dangers highlight the importance of developing ethical governance for the use of AI in megaprojects, including ethical considerations, data protection, and stakeholder participation [42].

5. Conclusion

This study explored the effects of AI on megaproject performance, considering the triple bottom line framework and economic sustainability. Based on the thematic analysis of 18 relevant sources, two main research gaps are identified: first, a dimension gap, where the economic dimension is prioritized over the environmental and societal dimensions; and second, a lack of consideration of megaprojects as a research context. By applying the organizational environment paradigm and stakeholder theory, a theoretical framework can be established, and four propositions can be proposed to provide a strong theoretical basis. The major theoretical contribution lies in integrating the TOE framework with stakeholder theory in a coherent theoretical construct. Under this theoretical construct, variables that influence the adoption of AI are linked to organizations' TBL performance, with economic sustainability viewed as a higher-order variable. The four propositions define the relationship between AI and organizational performance on the economy, environment, and society. From a practical perspective, managers need to focus on how AI can be used to estimate costs, manage energy, and reduce emissions. In the social context, experimentation is advisable as a means of protection against potential negative consequences. Policymakers should create an incentive system that encourages efficiency and social and environmental excellence through AI. Several limitations should be mentioned when interpreting these findings. Methodologically, this theory is based on arguments made by various scholars in the literature and has not been validated by empirical studies using primary data. The P3 (social performance) and P4 (economic sustainability), which are theoretically justified by a relatively thin body of literature, still need to be validated empirically. The use of Scopus as the sole database may have excluded relevant studies indexed in other databases such as Web of Science. Additionally, megaprojects were treated as a single category without differentiating by type, sector, or geographic context. Several approaches can be adopted for future empirical validation. The proposed framework and propositions could be tested using partial least squares structural equation modeling (PLS-SEM) with survey data collected from megaproject stakeholders or through multi-case comparative analysis of megaprojects at different stages of AI adoption. Longitudinal project data analysis tracking AI implementation and sustainability outcomes over time would be particularly valuable for testing P4. Multi-criteria decision-making techniques such as fuzzy AHP or TOPSIS could be applied to evaluate the relative importance of TOE conditions in different megaproject contexts. Future studies could also disaggregate AI into specific technology types and extend the framework through cross-cultural, cross-sector investigations and incorporation of technologies such as digital twins and BIM-AI integration.

Ethical issue

The authors are aware of and comply with best practices in publication ethics, specifically regarding authorship (avoidance of guest authorship), dual submission, manipulation of figures, competing interests, and compliance with research ethics policies. The authors adhere to publication requirements that the submitted work is original and has not been published elsewhere.

Data availability statement

The manuscript contains all the data. However, additional data will be provided by the corresponding author upon reasonable request.

Conflict of interest

The authors declare no potential conflict of interest.

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