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DIGITAL SUPPLY CHAIN AND PROJECT MANAGEMENT PRACTICES FOR SMART INFRASTRUCTURE AND EPC ENGINEERING PROJECTS

Sardorbek Isroilov[1*], Azibaev Akhmadkhon Gulomjon ugli[2], Abdurakhimova Zulaykho Ikromjon kizi[3], Rashidkhon Uulu Atabek[4], Ismoilov Ravshanjon Yakubjon ugli[5]

[1]Vice-rector for Strategic Development and International Cooperation, Faculty of Business Administration, Business Administration, IT, Math, Turan International University, Namangan, Uzbekistan. e-mail: s.isroilov@tiu-edu.uz, orcid: https://orcid.org/0000-0003-3782-1534*
[2]Senior Lecturer of Mathematics, Faculty of Business Administration, Business Administration, Math, IT, Turan International University, Namangan, Uzbekistan. e-mail: ahmadxonazibayev@gmail.com, orcid: https://orcid.org/0000-0002-4431-3151
[3]Senior Lecturer of Mathematics, Faculty of Business Administration, Business Administration, Math, Turan International University, Namangan, Uzbekistan. e-mail: zulaykhoabdurakhimova96@gmail.com, orcid: https://orcid.org/0009-0006-1885-4102
[4]Senior Lecturer of Mathematics, Faculty of Business Administration, Business Administration, Math, Turan International University, Namangan, Uzbekistan. e-mail: atabekrashidxonugli@gmail.com, orcid: https://orcid.org/0009-0009-3327-4909
[5]Director of IC&DT Department, Faculty of Business Administration, Business Administration, IT, Math, Turan International University, Namangan, Uzbekistan. e-mail: ravshan.ismoilov77@gmail.com, orcid: https://orcid.org/0009-0007-5608-8733

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SUMMARY

The smart infrastructure construction projects implemented under the Engineering-Procurement-Construction (EPC) model have been growing more complicated with the globalized supply chains, the technology-induced complexity of the components employed, and the increased sustainability and risk management demands. Conventional EPC supply chain and project management have been highly divided, resulting in a lack of real-time visibility, reactive decision-making, and inefficiencies in performance. This paper opposes this by analyzing how digital supply chain practices can be incorporated into project management functions to enhance performance in EPC-based smart infrastructure projects. The research follows a conceptual and analytical course, integrating the latest literature on digital supply chains, project delivery of EPC, and technologies of smart infrastructure. It is on this synthesis that a Digital Supply Chain- Project Management Integration Framework is created with the aim of matching digital capabilities in terms of engineering, procurement, construction, and governance. Analyses of comparative performance based on literature-synthesized measures prove that digitally enabled EPC supply chains obtain significant improvements in comparison with the traditional practice in terms of approximately 35-40 % procurement lead time, 45-50 % cost variance, and 45-60 % risk response time. Other benefits can be seen in schedule reliability and supply chain visibility; the largest performance improvements can be seen within the construction phase and the project governance phase. The results indicate that digital integration contributes to the proactive management of risks, enhanced coordination, and performance-based project governance. The current study is an addition to the literature by filling the gaps between digital supply chain management and project management in the EPC setting and providing a practical understanding in furthering the resilience, transparency, and sustainability of smart infrastructure provision.

Key words: *digital supply chain, EPC projects, smart infrastructure, project management, BIM, digital twin.*

INTRODUCTION

The growing urbanization, sustainability needs, and requirement of intelligent and resilient systems have created Smart infrastructure development as a critical priority for governments and industries. Urban facilities that make use of digital services like smart transportation networks, energy delivery systems, and digitally empowered infrastructures are largely manufactured under the Engineering-Procurement-Construction (EPC) contracting models, providing one contracting organization with the entire lifecycle responsibility [2][20]. Although EPC arrangements enhance accountability and clarity of contracts, it also creates considerable managerial complexity due to large-scale coordination, international procurement, and strict scheduling and cost requirements [3][14]. Regarding the project management, EPC project performance is highly connected with the efficiency of supply chain integration and governance systems. Nevertheless, in a traditional EPC setting, supply chain management and project management are usually regarded as independent and lightly interrelated processes. The main difference between project management and supply chain management lies in the definition of the scope, project schedule, project budget, and the control of project risks, and the definition of the supplier, buyer logistics, and coordination of the material flow, respectively [3][18]. If there is a functional separation, it often leads to poor decision-making, poor real-time visibility, and slow reaction to disruption, heightening the risk of cost overrun and time delay in complex infrastructure projects [12]. The increased usage of digital technologies provides new possibilities to solve these constraints. Three applications of digital supply chain practices through Building Information Modeling (BIM) and Internet of Things (IoT) platforms increase information sharing and coordination of engineering, procurement, and construction stages [6][11].

Moreover, cloud services and blockchain-based procurement systems enhance the transparency, traceability, and accessibility of the data in the EPC supply chains [4][15]. Such digital solutions are complemented by proactive risk management, better schedule compliance, and more informed managerial decision-making in case they are aligned with project management processes [5][10]. Although digital supply chains and smart construction have accelerated academic and industrial attention, research on the topic is still divided. Numerous studies concentrate on single digital solutions or single functional enhancements, e.g., procurement efficiency or construction monitoring [6][11]. Conversely, project management studies in EPC settings tend to focus on scheduling methods, collaboration, or contract-government without necessarily considering the digitalization of the supply chain [9][18]. Consequently, end-to-end management-based strategies involving systemic incorporation of digital supply chain functions with project management, throughout the EPC lifecycle, are scarcely integrated, especially in smart infrastructure undertakings [7]. To fill this gap in research, the given paper will consider how digital supply chain practices can be applied to project management functions to boost the performance and resilience of EPC-based smart infrastructure projects. The research takes conceptual and analytical forms developed out of a systematized review and synthesis of current literature, which allowed determining key digital enablers and aligning them with EPC phases and project management knowledge areas [2].

This study will achieve the following objectives: (i) the constraints of conventional supply chain and project management practice in EPC infrastructure projects will be analyzed; (ii) the significance of digital supply chain technologies in enhancing project management functions at engineering, procurement, and construction stages will be examined; (iii) a combined Digital Supply Chain-Project Management framework to achieve effective governance and decision-making. The paper findings, such as an integrated synthesis of the current body of digital supply chain management literature, a proposed comprehensive framework specific to EPC smart infrastructure delivery, and practical managerial implications to support digital transformation efforts, are all contributions of the paper. Digital supply chain and project management applied in smart infrastructure and EPC engineering projects are transforming the science and educational world and offering students with practical learning experiences that will bridge the gap between theoretical knowledge and practical skills and equip them with the changing needs of the industry [21].

The rest of the paper is presented in the following way. Section 2 reviews related literature on digital supply chains, EPC projects, and project management integration. Section 3 explains the research methodology. Section 4 presents the proposed digital supply chain project management integration framework. Section 5 discusses the results and performance analysis. Section 6 provides discussion and managerial implications. Section 7 highlights practical implications, and Section 8 concludes the paper with key findings and future research directions.

LITERATURE REVIEW

Digital Supply Chain Management in EPC Projects

The complex supply chain management of EPC projects is project-based and engineer-to-order, which implies excellent coordination between the activities of engineering, procurement, and construction. In contrast with the manufacturing supply chain, the EPC supply chain is characterized by customized parts, long lead times in procurement, and high reliance on the reliability of suppliers, which directly impacts the schedule of projects and the costs of projects [1][3]. According to review studies, the lack of alignment of procurement planning and project scheduling is a significant contributor to delays and cost overruns in infrastructure projects [2]. Global sourcing, contractual relationships, and material criticality also add complexity to procurement. The old procurement processes usually have disjointed information systems and manual processes, which hamper transparency as well as real-time decision making [3]. Digital supply chain approaches have been receiving more focus in order to deal with these challenges. Procurement systems based on blockchains increase the traceability and trust of the stakeholders in the EPC [4], and data-driven integration of supply chains helps to improve the performance and coordination efficiency of procurement in international EPC projects [5]. Although these have taken place, EPC supply chains are also susceptible to upsets through supplier delays and design amendments, which is why integrated digital solutions are a necessity [12].

Digital Technologies for Smart Infrastructure Projects

The second section is about digital technologies to use in smart infrastructure projects. Digital technologies are a key tool to ameliorate the performance of the EPC project and provide the delivery of smart infrastructure. Design coordination, information consistency, and early conflict detection across EPC phases are facilitated by Building Information Modeling (BIM) in minimizing rework and schedule disruptions [11]. Digital twin technologies build upon this functionality and provide real-time bidirectional monitoring and optimization of the lifecycle performance of infrastructure assets [6]. Internet of Things (IoT) and cloud computing provide additional possibilities to make digital integration happen through real-time data collection and dissemination among distributed project teams [15]. Monitoring based on IoT enhances visibility of the sites and tracking of progress, and cloud platforms facilitate collaborative workflows and centralized information control [17]. According to the previous research, the positive side of these technologies is always maximized when they are introduced as complex systems and not as isolated tools [8].

Integration of Supply Chain and Project Management Practices

The combination of supply chain management and project management is becoming increasingly understood as a necessary factor in enhancing the EPC project results. Project management regulates scope, schedule, cost, and risk, whereas supply chain decisions directly affect material availability and time of procurement [7]. Lack of compatibility between these functions usually results in poor use of resources and project risk. This is facilitated by digital project management structures and platforms of cross-platform collaboration that allow tracking of progress in real-time and making decisions based on the data [9][10]. Nevertheless, the practice of complete integration is still curtailed by organizational silos and contractual restraints [18]. Moreover, the issues of sustainability and governance are starting to influence EPC project management and confirm the significance of the integrated digital approaches, capable of facilitating the long-term performance and resiliency [16][19]. The reviewed papers indicate that although digital technologies and developed practices in the supply chain present tremendous advantages to the delivery of EPC projects, their implementation is still very fragmented and functional. The current literature focuses on separate tools or managerial activities without offering a holistic approach to harnessing digital supply chain capabilities and project management activities throughout the EPC lifecycle. This disparity explains why the development of a management-centric framework that attempts to systematically integrate digital supply chain technologies into project management knowledge domains is needed to improve performance, resilience, and sustainability in smart infrastructure projects. The inference directly inspires the development of the methodology and the framework, which is introduced in the following sections.

RESEARCH METHODOLOGY

This research uses a conceptual and analytical approach to design an integrated Digital Supply Chain-Project Management model for smart infrastructure projects based on EPCs. The Existing method lacks methods of collecting empirical data, hypothesis testing, and statistical modeling. According to this conceptual synthesis, the Digital Supply Chain-Project Management Integration Framework is created to facilitate coordinated decision-making and project management at the engineering, procurement, and construction stages. The general steps of the research that will be used in the case are depicted in Figure 1.

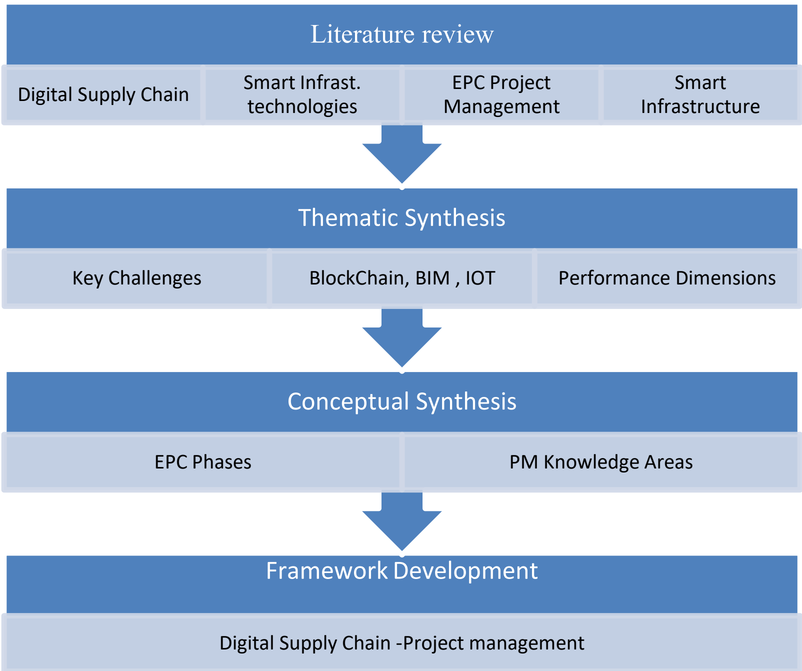

Figure 1. Research Process for Framework Development

A narrow literature review on digital supply chain management, smart infrastructure technologies, EPC project management practices, and smart infrastructure delivery is the working start of the research process. The studied articles are summarized in such a way that they reveal the main challenges, prevailing digital technologies (Blockchain, BIM, and IoT), and the appropriate dimensions of performance that affect the EPC project results. This is then conceptually mapped to phases of the EPC project and areas of project management knowledge to form the relationship between the digital supply chain capabilities and managerial functions. Research method that has been followed in the development of the Digital Supply Chain-Project Management integration framework on EPC-based smart infrastructure projects.

DIGITAL SUPPLY CHAIN–PROJECT MANAGEMENT INTEGRATION FRAMEWORK

This section gives the proposed Digital Supply Chain-Project Management Integration Framework of EPC-based smart infrastructure projects. The framework is based on the combination of digital supply chain technologies with project management functions throughout the EPC lifecycle to assist in the coordinated planning, execution, monitoring, and governance within the complex infrastructure delivery environments.

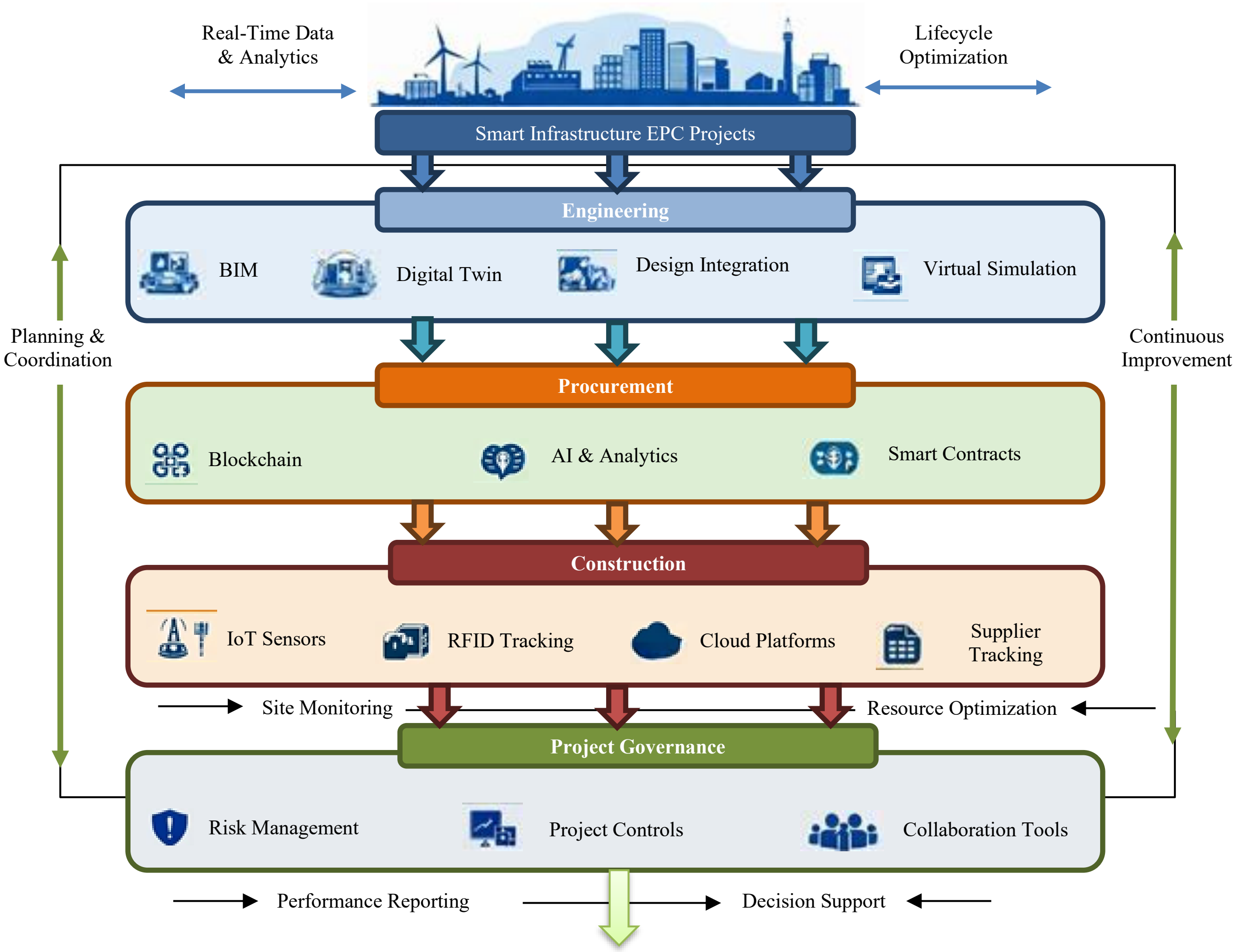

Figure 2. Digital Supply Chain–Project Management Integration Framework for EPC-Based Smart Infrastructure Projects

The framework establishes smart infrastructure EPC projects as digital-enabled systems that have a continuous exchange of data, real-time analytics, and lifecycle optimization. It brings about formal connections between the engineering, procurement, and construction operations and overriding project governance systems, which allow timely and informed managerial choices.

The framework is focused on integrated design and early-stage decision support at the engineering level. Building Information Modeling (BIM) and digital twins technologies can be used to ensure design integration, virtual simulation, and validation to enhance the clarity of the scope and minimize design-related risks prior to the commencement of the procurement and construction process. The procurement level concerns transparency, coordination, and contractual efficiency. The procurement systems based on blockchain improve the traceability and confidence in the sourcing operations, and AI-based analytics are used to help assess the supplier and predict demand. Smart contracts also match the procurement implementation to project schedules and project cost controls. The construction level deals with the monitoring of the real-time execution and optimization of resources. IoT sensors, RFID-based tracking, and cloud platforms will allow monitoring the location of the site continuously, where the material is moving, and coordinating the workforce, thereby facilitating the process of schedule compliance, quality control, and the effective use of resources. The level of project governance offers cross-cutting to all EPC stages. Project controls, risk management systems, collaboration systems, and decision-support systems integrate engineering, procurement, and construction layers of information. This allows reporting of the performance, mitigation of risks proactively, and the ability to coordinate stakeholder engagement. In general, the framework aligns the digital capabilities of the supply chain with the main areas of knowledge of project management, such as scope, time, cost, risk, quality, and stakeholder management. The framework facilitates the increased performance and effectiveness in lifecycle and managerial aspects of EPC-based smart infrastructure projects by enabling planning and coordination, real-time information and analytics, and constant improvement, as summarized in Figure 2.

RESULTS AND PERFORMANCE ANALYSIS

This part examines the performance implications of phasing in digital supply chain activity with project management functionalities in EPC-based smart infrastructure undertakings. The performance trends analyzed rely on a comparative synthesis of the previously reported trends of performance using the main managerial performance dimensions and not by empirical measurement.

Traditional versus Digital EPC Supply Chain Performance

The traditional EPC supply chains are generally described as having a lack of information flow, limited project-phase visibility, and a reactive coordination process. The consequences of these restrictions usually include long procurement lead times, increased cost variance, schedule variances, and slow reaction to risks. Conversely, EPC supply chains enable digital use of integrated data platforms and real-time information interchange to facilitate proactive planning and execution. The values reported in Table 1 are synthesized from performance ranges and comparative trends documented in prior studies on EPC supply chains and digital project management. Baseline values for traditional EPC practices reflect commonly reported outcomes under document-driven and non-integrated supply chain environments [1-3]. The digitally enabled EPC values are derived from reported improvements associated with the adoption of BIM, blockchain-based procurement, IoT-enabled monitoring, digital twins, and data-driven analytics in EPC and smart infrastructure projects [4-6][10][11]. The improvement percentages are calculated using normalized comparative differences to illustrate relative performance trends rather than empirical project-specific measurements, consistent with conceptual and analytical research approaches [7][12].

Table 1. Comparison of Traditional and Digital Supply Chain Practices in EPC Projects

Performance Metric	Traditional EPC SCM	Digital EPC SCM	Improvement (%)
Procurement Lead Time (weeks)	14.5	9.1	37.2
Cost Variance (%)	±12.0	±6.2	48.3
Schedule Delay Incidence (%)	28.0	15.0	46.4
Risk Response Time (days)	18.0	7.5	58.3
Supply Chain Visibility (0–100)	42	82	95.2

Table 1 is a comparison of key performance measures of traditional and digitally enabled EPC supply chain practices. The comparative evaluation indicates that the digital supply chain integration results in reduced procurement lead times, better cost predictability, schedule compliance, and quicker risk response. These have been made possible mainly by the enhanced coordination between engineering, procurement, and construction processes and the availability of real-time project information.

Phase-Wise Performance Impact of Digital Integration

The results are disaggregated by phase of the project to determine the areas of performance gains in the EPC lifecycle. This stage-by-stage evaluation puts emphasis on the role of digital technologies in improving performance in the process of engineering, procurement, construction, and project governance.

Table 2. Impact of Digital Integration Across EPC Project Phases

EPC Phase	Key Digital Enablers	Primary Performance Focus	Performance Improvement Range (%)
Engineering	BIM, Digital Twin	Scope clarity, design coordination	30–45
Procurement	Blockchain, AI analytics	Cost control, procurement transparency	35–50
Construction	IoT, RFID, Cloud platforms	Schedule adherence, quality control	40–55
Project Governance	Analytics dashboards, collaboration tools	Risk mitigation, decision speed	45–60

Table 2 provides an overview of the digital integration effect on performance in phases throughout the EPC lifecycle. The findings indicate that the main increase in performance is associated with the engineering phase of digitalization, but the greatest improvement is achieved in the construction and project governance phases. This stage-by-stage allocation complies with the available literature emphasizing the significance of real-time tracking and analytics on enhancing execution control and responsiveness of managers in EPC projects.

Multi-Dimensional Performance Comparison

Multi-dimensional comparative analysis is used in order to visualize the overall performance impact on the multiple management dimensions. This visualization compares the traditional and the digitally enabled EPC supply chain practices in terms of schedule compliance, predictable costs, reduction of risks, visibility of supply chains, and efficiency of coordination.

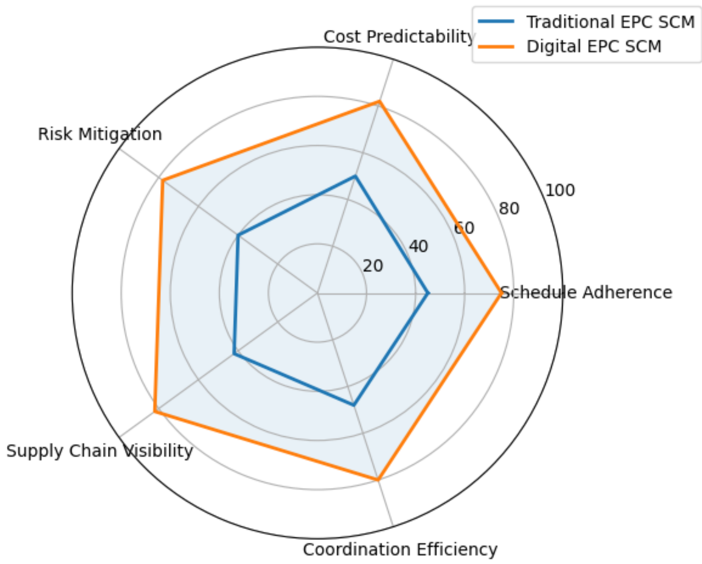

Figure 3. Comparative Performance Profile of Traditional and Digital EPC Supply Chains

Figure 3 shows a multi-dimensional analysis of traditional and digitally enabled EPC supply chain practices in the core managerial performance dimensions. The visualization concentrates on the higher levels of performance that are always present under the digital integration, especially in the areas of supply chain visibility, risk mitigation, and efficiency in coordination. These trends indicate the results within the literature that highlight the importance of combined digital solutions and real-time information streams in multi-faceted EPC setups. On the whole, the analysis of the performance shows that the digital integration assists in the shift from reactive to predictive and performance-oriented project management. The findings give a quantitative explanation of the suggested structure and will be used to discuss the subject of risk reduction, sustainability, and managerial implications in the following section.

DISCUSSION

The implications of the proposed framework and the performance analysis are discussed in this section, focusing on reducing the risk, digital maturity, sustainability, and managerial relevance in the EPC-based smart infrastructure projects. The numbers shown in this part are theoretical images based on normalized trends that were reported in earlier research and help substantiate rather than validate empirically.

Risk Reduction and Digital Maturity

Online coordination between engineering, procurement, and construction stages would allow a stepwise decrease in the project risk as EPC organizations become increasingly digital-mature. Information visibility and reporting are the main functions of digital tools at the lower levels of maturity. With the rise in the level of integration, real-time data transmissions and analytics allow for detecting the risk earlier, responding quicker, and coordinating the activity of project stakeholders better. The performance analysis shows that digitally integrated supply chains contribute much to a shorter time of risk response and better schedule reliability due to the proactive monitoring and decision-making based on the information.

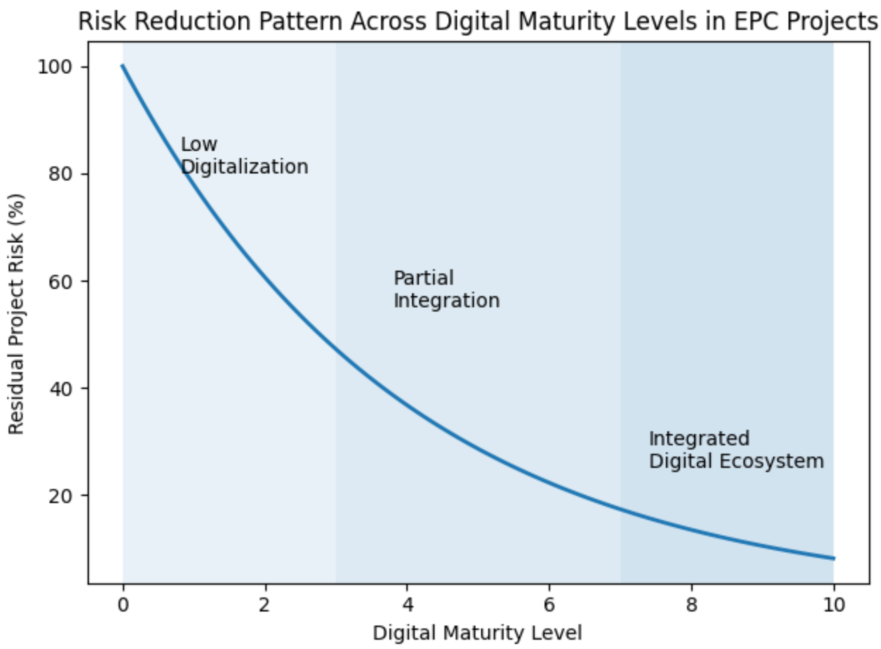

Figure 4. Risk Reduction Trend with Increasing Digital Maturity in EPC Projects

Figure 4 illustrates a conceptual risk reduction pattern as digital maturity increases in EPC projects. The nonlinear relationship reflects findings in prior studies showing that isolated digital tools provide limited risk mitigation, while integrated digital ecosystems significantly enhance risk anticipation, response speed, and coordination effectiveness in EPC and construction supply chains [6,12]. The nonlinear risk reduction trend illustrates that incremental digital adoption yields moderate benefits initially, while integrated digital ecosystems generate substantially higher risk mitigation outcomes. This observation supports the need to have digital transformation on a coordinated basis and not through individual adoption of technology.

Sustainability and Smart Infrastructure Implications

In addition to operational performance, there is integration of the digital supply chain and project management that assists in smart infrastructure project sustainability goals. Digital technologies allow better resource planning, decrease the number of reworks, increase logistics and lifecycle monitoring, which in turn helps to decrease environmental impact. Specifically, BIM and digital twins technologies allow conducting sustainability evaluation in the early stage, whereas the IoT-based monitoring will assist with energy efficiency and waste minimization throughout the construction process and operation.

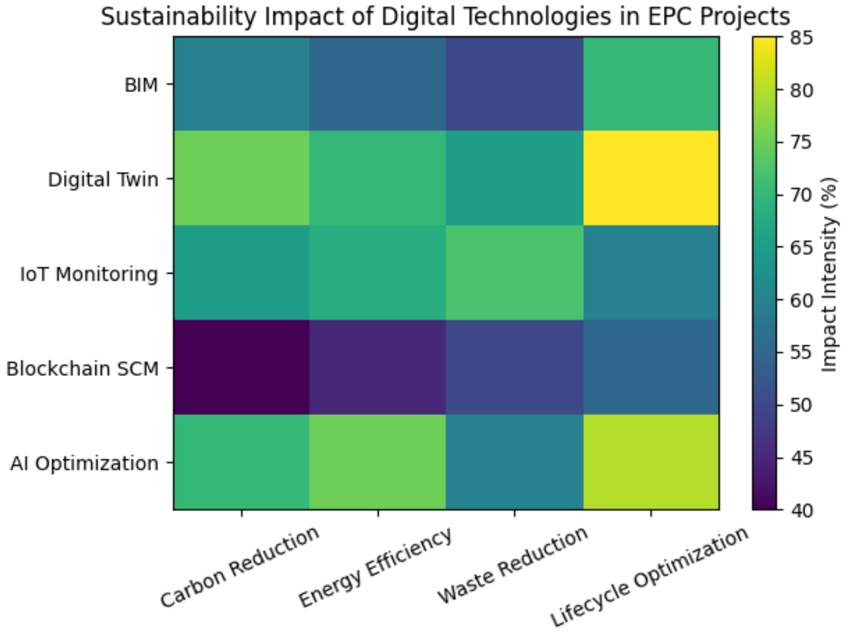

Figure 5. Contribution of Digital Technologies to Sustainability Performance

Figure 5 contains a comparative graphic illustration of the sustainability contribution of key digital technologies in infrastructure projects based on EPC in smart environments. The intensities of the impacts are aggregated by the previous research that reported the contribution of BIM, digital twins, IoT, and AI-based optimization in infrastructure delivery through lessening the rework, enhancing the energy efficiency, and ensuring the lifecycle sustainability [6,13]. In the sustainability comparison, it is noted that digital twins, AI-optimization, and BIM-based planning have the best potential in terms of carbon minimization and eco-efficient infrastructure delivery. Such results coincide with the sustainability and development goals of smart infrastructure systems in general.

Managerial and Strategic Implications

On the managerial front, the findings put emphasis on the fact that EPC organizations need to view digital supply chain integration as a strategic capability and not as a technological supplement. The implementation needs to be successful, and this can only be achieved by synchronizing digital tools, project management practices, and organizational processes. To achieve the full advantage of the integration, EPC contractors need to invest in digital capabilities, data management controls, and interdisciplinary coordination. Infrastructure owners and policymakers can use digitally integrated EPC structures to enhance the transparency, accountability, and long-term performance of assets at the strategic level. The suggested framework facilitates sound decision-making, better governance, and resilience, making digital integration one of the key facilitators of efficient smart infrastructure provision.

PRACTICAL IMPLICATIONS

The results of the research have a number of practical implications for EPC contractors, project managers, and infrastructure stakeholders in the smart infrastructure delivery. To begin with, EPC organizations need to consider the digital supply chain-project management integration as a strategic initiative and not a technology upgrading project. The findings also show that there is maximum maximization of performance gains when the digital tools are aligned between the engineering, procurement, construction, and governance functions. Isolated implementation of single technologies will hardly provide long-term gains. Second, the suggested integration framework can serve as a decision-support base for project managers in order to structure digital capabilities in accordance with the major fields of project management knowledge (scope, time, cost, risk, quality, and stakeholder management). Such coordination facilitates proactive planning, enhanced coordination, and response to disruption in a quicker fashion throughout the EPC lifetime.

Third, procurement and supply chain managers need to focus on technologies that can contribute to the improvement of transparency, traceability, and coordination, including BIM-enabled quantity alignment, blockchain-based procurement solutions, and real-time logistics monitoring. The practices have a direct positive impact on enhanced cost predictability and schedule reliability. Fourth, in terms of governance, EPC companies are advised to invest in integrated analytics dashboards, data control systems, and cross-functional collaboration systems. With such investments, the senior management is able to shift from reactive control to predictive and performance-driven project governance. Lastly, digitally integrated EPC frameworks can enable infrastructure owners and policymakers to make projects more transparent, accountable, and perform well in the long run. Promoting standard digital implementation and interoperability between EPC contracts would enhance the speed of smart infrastructure provision and sustainability goals.

CONCLUSION

This paper examined how digital supply chain practices could be incorporated with project management functions in a smart infrastructure project based on EPC. The paper has been able to discover the major gaps that exist in the traditional EPC delivery, such as disjointed coordination, poor real-time visibility, and reactive control mechanisms, through a systematic review of the current literature. To manage these issues, a Digital Supply Chain- Project Management Integration Framework was presented to synchronize digital capabilities at the engineering, procurement, construction, and governance stages. The findings show that EPC supply chains that are digitally enabled offer consistent performance benefits in comparison to traditional practices. Comparisons synthesized in the literature indicate that there are decreases of about 35-40 % in lead time of procurement, 45-50 % in cost variance, and 45-60 % in risk response time, and significant improvement of schedule reliability (about 45 %) and supply chain visibility (about 90 %). The phase-wise analysis further shows that the highest level of performance improvements is witnessed at the construction and project governance stages, where real-time monitoring and analytics with integrated decision support dominate. These numerical trends represent systematic backup of the suggested framework and emphasize its applicability in dealing with complexity in the delivery of smart infrastructure. Practically, the results focus on the idea that digital integration must be regarded as a strategic management capability, but not as an independent technological upgrade. The proposed framework may help EPC organizations to increase the level of coordination, proactive risk management, and performance-based project governance. There are some limitations in this study. The evaluation is based on literature-synthesized and normalized measures of performance, instead of primary empirical measures, and the framework proposed has not been tested on real-life EPC case-studies. Moreover, there were no specific contextual considerations like organizational preparedness and regulatory limitations modeled. Future studies ought to be aimed at the empirical validation of the framework based on case studies or project-level data, consider the technology-specific integration routes, and consider organizational, human, and cybersecurity aspects that impact digital adoption in EPC projects.

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