

LEAN-GREEN SUPPLY CHAIN FRAMEWORK FOR CONSTRUCTION USING VSM AND DES

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ABSTRACT

Construction supply chains are often affected by inefficiencies, delays, material wastage, and carbon emissions, with implications for both project performance and sustainability. Although lean and green supply chain management (GSCM) approaches have been studied extensively, evidence on their integrated, project-level application in construction remains limited, especially in developing economies. This study proposes a comprehensive framework designed to enhance operational efficiency while promoting sustainability within the construction sector by integrating Lean and GSCM. The framework integrates Value Stream Mapping (VSM) to identify and redesign inefficient processes, with VSM-based Discrete Event Simulation (DES) to quantitatively demonstrate how lean interventions translate into environmental benefits across the construction supply chain. The proposed framework is validated through a real-world case study of a water supply pipeline distribution project in India. The results demonstrate that lean-driven supply chain redesign leads to an 8% reduction in total cycle time and inventory levels, while simultaneously achieving 7% decrease in carbon emissions. The integration of VSM and simulation enables construction practitioners and project managers to evaluate the operational and environmental implications of lean supply chain redesign in advance, reducing implementation risk and supporting informed decision-making at the project level.

KEYWORDS

Lean Construction practices, construction supply chains, green supply chain management, Value Stream Mapping, Discrete Event Simulation.

INTRODUCTION

The construction sector in India is one of the largest contributors to the country's GDP and a cornerstone of its economic development. Despite its economic significance, the sector is responsible for a substantial portion of the country's greenhouse gas emissions, resource consumption, and waste generation (Francis and Thomas, 2020), making it a significant contributor to national carbon emissions and resource depletion. In addition to these environmental concerns, the construction sector faces persistent challenges in supply chain management. The construction supply chain is highly complex, involving multiple stakeholders such as suppliers, subcontractors, and vendors. This complexity leads to a lack of coordination, causing delays and disruptions in material flows, thereby impacting the project's cost and timelines. Furthermore, the wide variety and large volumes of materials required in large-scale projects create significant challenges for inventory planning and control. To manage

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uncertainty, construction teams frequently maintain excessive buffer inventories, leading to inefficiencies, increased costs, and additional environmental burdens.

In response to persistent inefficiencies in construction supply chains, lean construction has gained attention as a means to improve process flow, reduce non-value-adding activities, minimise excess inventory, and enhance coordination among project stakeholders (Francis and Thomas, 2020). Beyond operational improvements, these lean interventions have the potential to deliver environmental benefits by reducing material wastage, unnecessary transportation, and idle time, which are key contributors to energy use and carbon emissions in construction projects. To counter these challenges, lean practices offer promising approaches to enhance the environmental performance and efficiency of construction projects, making them more sustainable (Engin et al., 2019). While lean tools such as Value Stream Mapping (VSM) helps identify inefficiencies and propose lean improvements, it does not capture the dynamic interactions and variability inherent in construction supply chains (Seth * and Gupta, 2005). Simulation approaches would enable proposed lean-based changes to be tested in advance, reducing uncertainty about their operational performance and associated environmental outcomes (Golzarpoor and González, 2013; Seth et al., 2017). However, existing studies largely examine lean and environmental performance either at a conceptual level or through static analyses, with limited focus on quantitatively evaluating Lean–Green interactions under dynamic, project-level conditions in construction supply chains (Bortolini et al., 2023; Garcia-Buendia et al., 2021).

Therefore, this paper presents a Simulation-Supported Lean–Green Framework that integrates VSM with DES to enable quantitative, project-level evaluation of the operational and environmental implications of lean interventions in construction supply chains. VSM is used to diagnose material and information flows and identify sources of waste and inefficiency, while DES enables proposed lean interventions to be evaluated under project-specific and dynamic conditions prior to implementation. Environmental impacts are derived from operational parameters such as material flow, transportation, and handling activities Through a case study application, the framework demonstrates how environmental benefits, including reduced material waste and carbon emissions, can emerge as secondary outcomes of lean supply chain redesign. The study contributes by explicitly linking lean-driven supply chain improvements with environmental outcomes through simulation, enabling a shift from conceptual Lean–Green discussions to a quantitatively grounded, project-level analysis. The framework is intended to support industry practitioners and decision-makers in evaluating lean interventions prior to implementation, while contributing a structured analytical approach for researchers studying Lean–Green supply chains.

RESEARCH BACKGROUND

The construction supply chain is characterised by fragmentation, variability, and significant non-value-adding activities, resulting in inefficiencies such as excessive waiting time, rework, inventory accumulation, and poor coordination among stakeholders. These activities also affect the environmental impact. These inefficiencies not only affect project cost and schedule performance but also contribute to increased resource consumption, waste generation, and environmental impacts (Degani, 2002). Lean thinking, originating from the Toyota Production System, was developed to improve efficiency by eliminating waste and enhancing value through improved flow and process optimisation (Ohno and Bodek, 2019). The adoption of lean principles in the construction sector led to the development of lean construction, which focuses on reducing variability, improving coordination, and minimising non-value-adding activities across project processes (Koskela, 1996). Lean construction has demonstrated potential in addressing operational inefficiencies inherent in construction projects by improving planning reliability, workflow continuity, and stakeholder collaboration (Koskela, 1992).

Extending lean principles beyond project operations, Lean Supply Chain Management (LSCM) focuses on streamlining material and information flows across the supply chain (Garcia-Buendia et al., 2021; Reyes et al., 2023). In construction, LSCM practices such as just-in-time delivery, continuous improvement, and VSM have been used to reduce excess inventory, minimise waiting times, and improve coordination among suppliers, contractors, and subcontractors. Studies indicate that the application of LSCM in construction projects can enhance operational efficiency, improve project performance, and increase customer satisfaction (Garcia-Buendia et al., 2021; Kosasih et al., 2023b).

In parallel, Green Supply Chain Management (GSCM) within the construction sector is to incorporate environmental considerations at every phase of the construction supply chain, encompassing material procurement through to waste management (Oyefusi et al., 2024). The primary objective of GSCM is to achieve economic efficiency while minimising environmental impacts. This method includes the use of sustainable materials, the practice of recycling, and the minimisation of waste. Recent studies indicate that GSCM can lead to considerable cost savings and positive environmental impacts in construction initiatives (Badi and Murtagh, 2019). Prior research has shown that GSCM can lead to positive environmental outcomes and potential cost savings; however, its adoption in construction is often hindered by limited stakeholder coordination, regulatory constraints, and uncertainty regarding economic feasibility (Martínez and Mathiyazhagan, 2020).

Recognising the complementary nature of lean and green paradigms, recent studies highlight the benefits of combining lean and green approaches into an integrated Lean-Green Supply Chain Management (LG-SCM) model (Bortolini et al., 2023). This integration offers operational and environmental advantages, such as reduced costs, improved sustainability, and enhanced competitiveness (Govindan et al., 2015; Kosasih et al., 2023a). Tools such as VSM are widely used to support lean supply chain improvement; however, they provide a static view of processes and do not capture the dynamic and uncertain nature of construction supply chains (Francis and Thomas, 2020). VSM is a useful lean technique for visualising and analysing the materials and information required to deliver a product or service (Francis and Mahalingam, 2012; Seth et al., 2017). VSM is implemented to identify and eliminate waste, streamline processes, and improve the overall efficacy of case studies. It involves creating a detailed map of the process's current state, identifying areas of waste, and developing a future state map that outlines the necessary improvements. However, the actual performance of proposed lean interventions at the project level remains uncertain, since implementation is often delayed and affected by variability in site conditions, resources, and coordination.

Although VSM offers a systematic method for pinpointing inefficiencies and formulating enhanced future-state supply chain designs, its static characteristics limit its capacity to reflect the dynamic behaviour and unpredictable nature inherent to construction projects. However, DES facilitates the assessment of proposed lean initiatives across diverse operational contexts by simulating stochastic material flows, resource limitations, and coordination delays (Beck, 2008; Mostafa et al., 2016; Omogbai and Salonitis, 2016; Salas-Navarro et al., 2024). The integration of VSM and DES provides a synergistic decision-support framework, in which VSM directs the identification and reconfiguration of process enhancements, while DES enables the assessment of their operational viability and efficacy prior to execution. Recent studies further emphasise the need for combining lean analytical tools with simulation techniques to better address system variability and improve decision-making in complex supply chains (Goienetxea Uriarte et al., 2020). This integrated approach is especially pertinent in construction supply chains, as fluctuations in demand, delivery timelines, and site efficiency can greatly impact the success of lean projects. Thus, there is an increasing demand for cohesive analytical frameworks that combine the diagnostic advantages of VSM with the predictive

functionalities of simulation to enhance operational optimisation and related environmental performance advancements.

METHODOLOGY

The study follows a structured, four-phase methodology to examine how lean interventions in construction supply chains translate into operational and environmental improvements. A case study-based approach is adopted to ensure practical relevance and to validate the proposed Lean–Green framework under real project conditions. Figure 1 presents an overview of the research methodology.

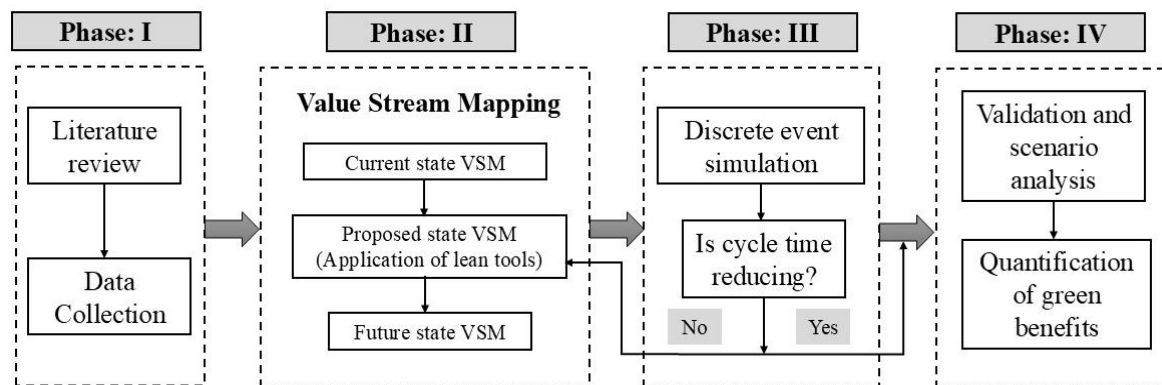


Figure 1: Flowchart illustrating the research methodology adopted in this study

PHASE 1: CASE STUDY-BASED DATA COLLECTION

A focused literature review on lean construction, supply chain management, VSM, and lean and green integration was conducted, followed by primary data collection from a rural water supply pipeline project in India. The project covers 375 villages and includes intake works, treatment facilities, reservoirs, pumphouses, head tanks, approximately 3,798 km of pipelines, and 1,46,129 household connections. Pipes were selected as the focal supply chain element due to their high material intensity, multiple handling stages, and transport dependence. The supply chain involves MS, DI, GI, and HDPE pipes for raw water, clear water, and distribution networks. A typical pipe supply chain is shown in Figure 2.

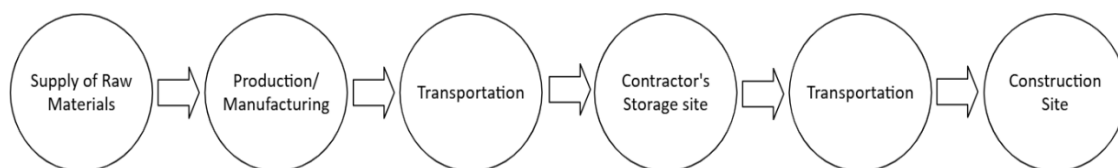


Figure 2: A typical flow of components of the supply chain of pipes

Based on the literature review and preliminary understanding of site practices, key sources of material-related inefficiencies in the pipe supply chain were identified. These include theft, rusting due to open storage, mishandling during transportation and unloading, damage during cutting and bending, and lack of coordination between supply and site activities. To systematically structure these issues and understand their root causes, a cause–effect (fishbone) diagram was developed, as shown in Figure 3. This analysis informed the selection of focus areas for subsequent value stream mapping.

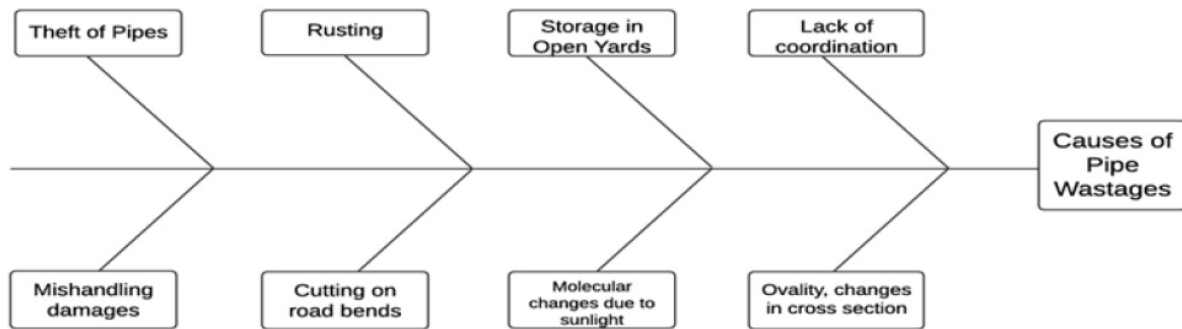


Figure 3: Fishbone diagram illustrating the common causes of pipe wastage at the site

PHASE 2: DRAWING OF VSM

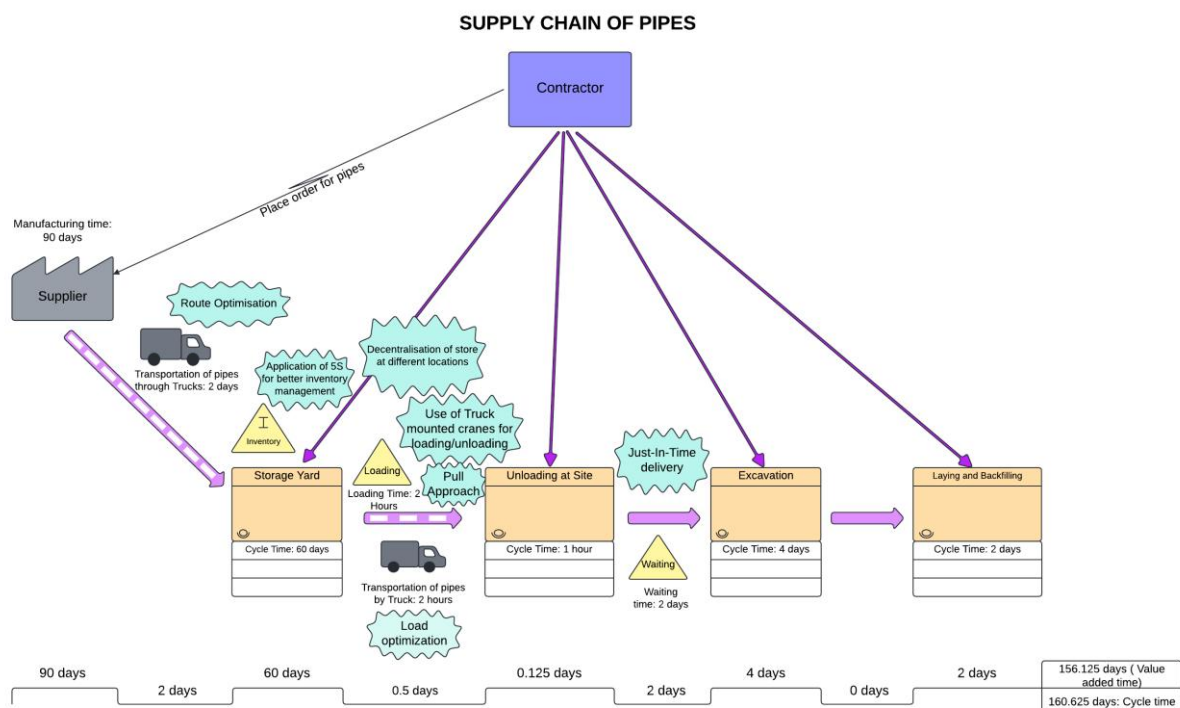


Figure 4: Current and proposed state Value Stream Map of the supply chain

Building on the insights from Phase I, VSM was applied to translate the literature-derived lean principles and case-specific data into a visual representation of material and information flows across the pipe supply chain. The analysis assumes 100 mm diameter pipes, with 35 pipes transported per truck (420 m per trip), mobile cranes for loading and unloading, an 8-hour workday, and excavation productivity of 120 m/day.

Based on these assumptions, a current-state VSM was developed to map the entire pipe supply chain from order placement to pipe laying at the site (Figure 4). The current-state map highlights extended manufacturing lead times, excessive inventory, waiting at the site, and inefficient transportation. Based on this analysis, a set of lean tools, including 5S, route optimisation, decentralised storage, just-in-time delivery, load optimisation, and pull-based planning, was identified. The identification of these lean interventions was guided by prior lean construction studies (Engin et al., 2019; Francis and Mahalingam, 2012; Francis and Thomas, 2020) and insights from field observations and discussions with project stakeholders during the case study. This combined approach helped ensure that the VSM assumptions and proposed

improvements reflect both theoretical principles and practical site conditions. These interventions were incorporated into a proposed-state VSM (Figure 4), followed by the development of a future-state VSM. The future-state VSM indicates potential reductions in cycle time, as shown in the results section (Table 1). It remains deterministic and does not account for process variability, uncertainty in logistics, or resource constraints. Therefore, the proposed lean interventions are treated as hypothetical improvement scenarios requiring further evaluation.

PHASE 3: DES FOR PERFORMANCE EVALUATION

VSM is effective for identifying lean wastes, but its static nature limits the ability to assess whether the improvement measures it proposes will work under real project conditions. Construction supply chains are subject to variability in logistics, resource availability, and site operations, which cannot be adequately represented using VSM alone. To address this limitation, DES was used to evaluate the performance of VSM-derived improvement measures before implementation. DES enables the modelling of process interactions, resource constraints, and time-dependent variability, allowing the behaviour of the supply chain to be examined under realistic conditions. In this study, simulation models were developed using FlexSim software based on the current and future-state VSMs.

The simulation model was developed to represent the operational characteristics of the existing pipe supply chain using activity durations, transportation distances, and resource configurations derived from site records and discussions with project personnel. Where direct measurements were unavailable, reasonable assumptions consistent with construction planning practice were adopted, and simplified variability was incorporated to reflect uncertainty in logistics and site productivity. The current-state model was first constructed based on the current-state VSM to estimate key performance indicators such as cycle time, lead time, and waiting time. A lean-enhanced future-state model was then developed by incorporating the proposed improvement measures identified in Phase 2. Model validation was carried out through structural verification and face validation with practitioners to ensure realistic representation of process sequences and expected system behaviour. Comparison of simulation results from the two models enabled assessment of whether the proposed measures led to measurable performance improvements. Figure 5 illustrates the simulation model developed for the pipe supply chain.

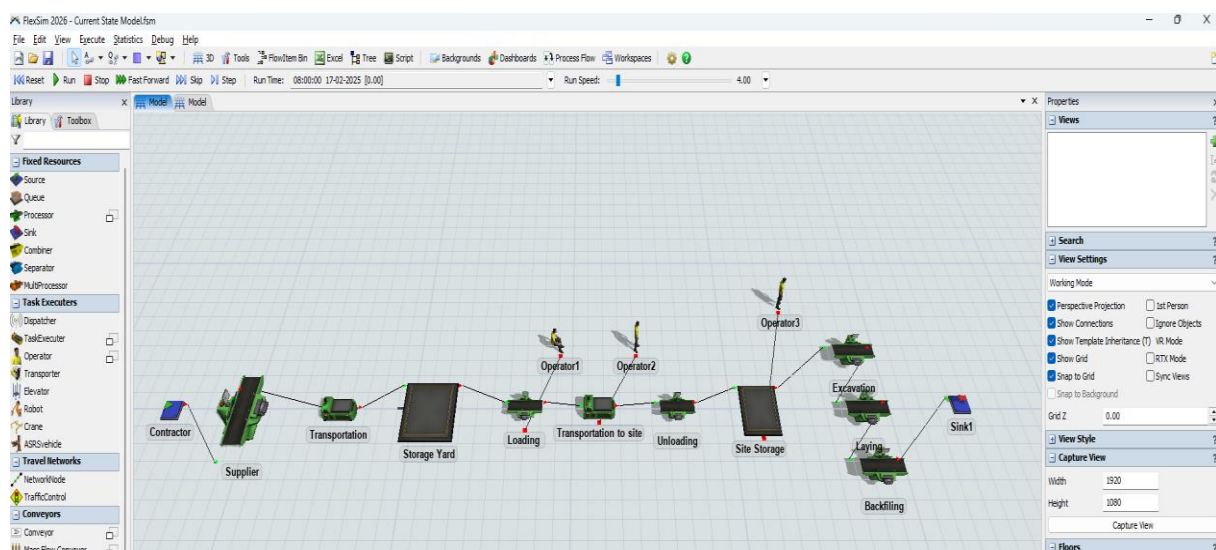


Figure 5: Snapshot of the Flexsim software showing the simulated supply chain model

PHASE 4: VALIDATION OF LEAN-GREEN LINKAGES AT THE PROJECT LEVEL

Phase 4 focuses on estimating and quantifying the environmental (green) outcomes resulting from the implementation of lean principles in the construction supply chain. Simulated operational improvements obtained from the DES models are translated into environmental performance indicators, allowing the environmental implications of lean interventions to be assessed in a systematic manner. Reductions in transportation, waiting, and inventory holding are mapped to key environmental metrics, including lower transportation-related emissions due to optimised delivery schedules, reduced material wastage, and decreased energy consumption associated with material handling and on-site storage. Environmental benefits are thus evaluated as consequential outcomes of lean-induced efficiency improvements, rather than as independent optimisation objectives.

This phase plays a critical role in validating whether lean practices applied at the project level can effectively support environmental goals. By explicitly linking operational performance improvements to measurable environmental outcomes, the phase addresses a key research gap in Lean-Green synergy within construction supply chains and provides the basis for the proposed Lean-Green supply chain framework.

RESULTS AND DISCUSSION

In line with the adopted methodology, the results combine lean diagnosis using VSM, dynamic evaluation using VSM-based DES, and assessment of environmental outcomes as consequences of operational improvements. The VSM analysis highlights substantial inefficiencies in the current state, particularly related to inventory holding, transportation, handling, and waiting at the site.

Table 1 compares cycle times across supply chain activities for the current and future states. The comparison between the current and future states reveals notable improvements in both operational and environmental performance. The total cycle time is reduced from 160.625 days to 147.375 days, corresponding to an 8% reduction, which indicates enhanced process efficiency achieved through the elimination of non-value-adding activities. In parallel, carbon emissions decrease from 2363.2 kg CO₂e to 2198 kg CO₂e, reflecting a 7% reduction in the environmental footprint.

Table 1: Reduction in cycle time between current state and future state of VSM

Activities	Current State Cycle Time (Days)	Future State Cycle Time (Days)	Percentage Reduction
Manufacturing	90	90	0%
Transport Supplier to Site	2	1	50%
Warehousing (Electricity)	60	50	17%
Loading	0.25	0.125	50%
Unloading	0.125	0.125	0%
Local Transport to Site	0.25	0.125	50%
Waiting time at Site	2	0	100%
Excavation	4	4	0%
Laying and Backfilling	2	2	0%
TOTAL	160.625	147.375	8%

The operational improvements achieved through lean interventions are reflected in environmental performance. Carbon emissions were estimated for individual supply chain

activities based on fuel and electricity consumption using standard emission factors. Figure 6 presents a comparison of carbon emissions between the current and future state VSMs. For the calculations of carbon emissions, the assumptions and standard emission factors that are being taken are mentioned in Table 2. The carbon emissions were calculated using standard emission factor-based formulations, where activity data (distance, fuel consumption, electricity use) were multiplied by the corresponding emission factors. Reductions are observed in emissions associated with transportation, warehousing, electricity use, loading, and local transport. Emissions from excavation and laying remain unchanged, consistent with the operational results. This indicates that environmental benefits arise as a consequence of reduced logistics, inventory holding, and material handling, rather than through direct environmental optimisation.

Table 2: Assumptions and standard emission factors for calculations of carbon emissions

Distance from the supplier to the site storage yard	737 kms
Truck Load	5 Tonnes
Truck emission factor (Smart Freight Centre India, 2025)	0.12 kg CO ₂ e/ton-km
Warehouse electricity emission factor (Bhawan and Puram, 2025)	0.82 kg CO ₂ e/kWh
Fuel emission factor (Intergovernmental Panel on Climate Change (IPCC), 2019)	2.68 kg CO ₂ e/litre
Electricity and lighting usage at Warehouse/Store	1 kW, 10 hours/day
Excavator fuel consumption rate	10 litres/ hour
Hydraulic Crane fuel consumption rate	15 litres/ hour

These results demonstrate that VSM of the entire pipes supply chain enables systematic identification of inefficiencies and non-value-added activities, which can be directly addressed through targeted lean interventions. The application of lean tools leads not only to reductions in cycle time but also to measurable reductions in carbon emissions, thereby contributing to a greener supply chain configuration.

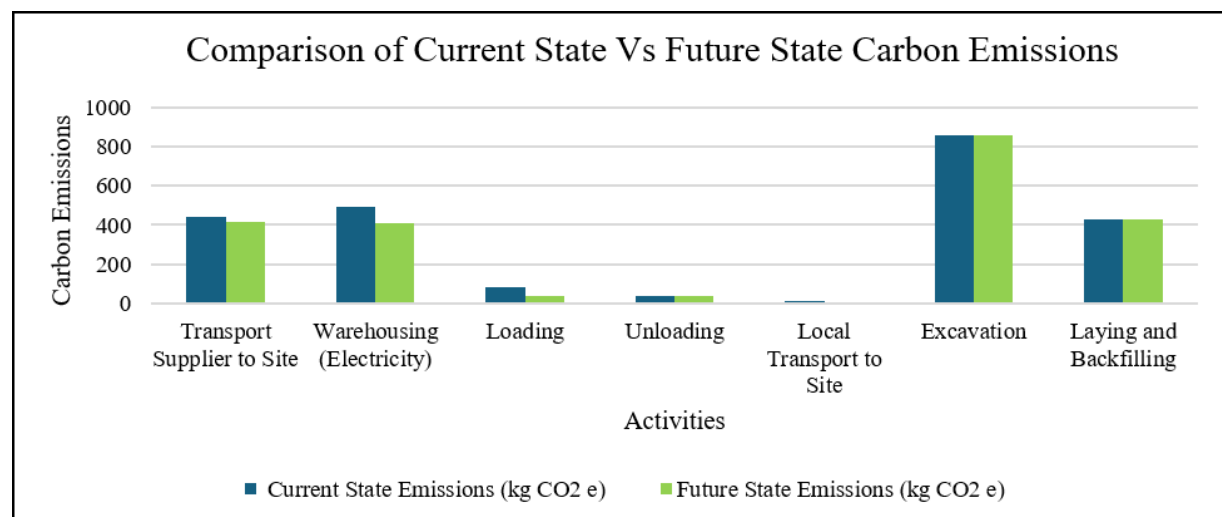


Figure 6: Carbon emissions comparison of current state and future state VSMs

ANALYSIS OF VSM-BASED DES

To account for process variability and to test whether the improvements identified through VSM would perform as intended under realistic conditions, the supply chain was further

analysed using DES. The simulated current state reproduces a total cycle time of 160.62 days, closely matching the VSM-based estimate and confirming the validity of the baseline model. The simulated future state yields a total cycle time of 147.38 days, as shown in Figure 7, demonstrating that the proposed lean interventions remain effective when dynamic interactions are considered.

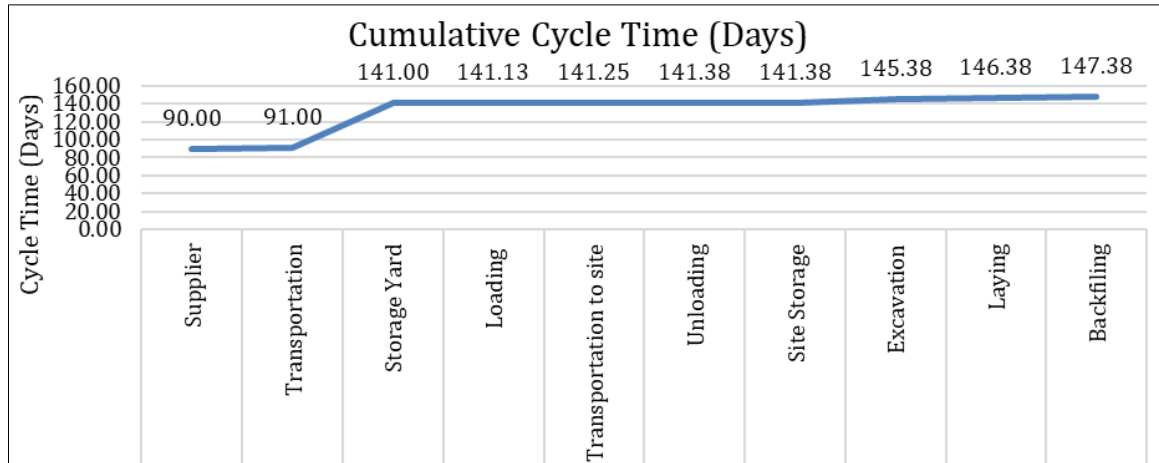


Figure 7: Graphical representation of cumulative cycle time by stage from future state simulation model

Scenario-based simulations provide additional insights into the robustness of the proposed improvements. Figure 8 compares optimistic, most-likely, and pessimistic future state scenarios reflecting variations in inventory holding, transportation efficiency, and coordination. The optimistic scenario achieves the lowest cycle time due to reduced inventory levels and improved coordination, while the pessimistic scenario exhibits higher cycle times driven by increased transportation and inventory durations. These findings highlight the sensitivity of supply chain performance to the degree of lean implementation and illustrate the value of simulation for exploring alternative configurations, which cannot be achieved using VSM alone.

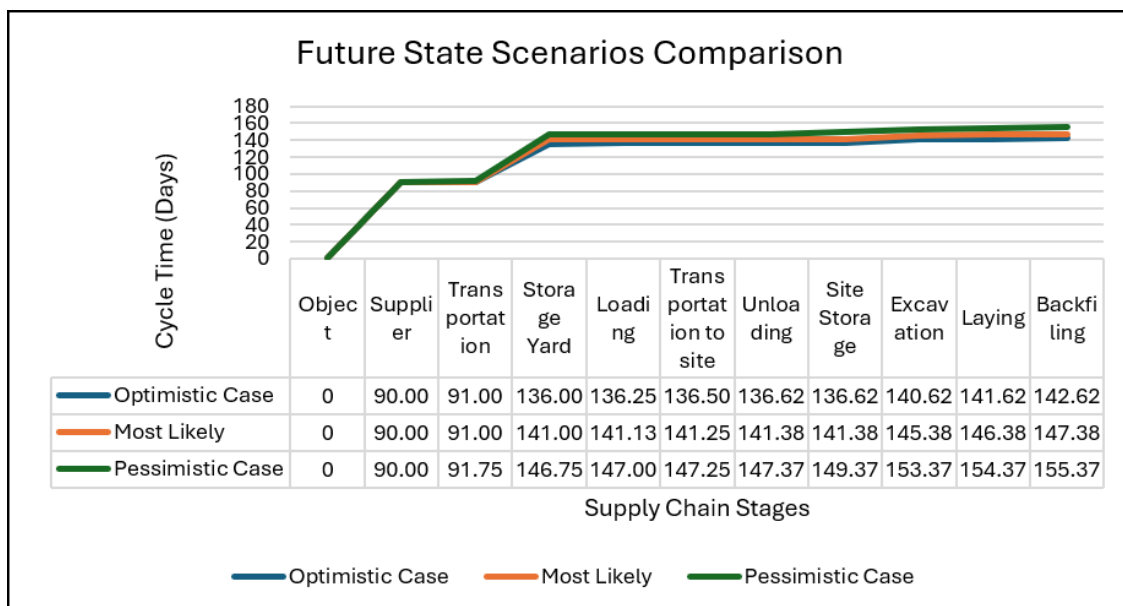


Figure 8: Comparison of the multiple scenarios of the future state model

Although permissible wastage in such projects is typically 1–2%, the case study indicates that poor inventory management and logistics can increase actual wastage by an additional 2–3%.

For a project of this scale, even a 1% wastage corresponds to approximately 40 km of pipe, resulting in an estimated 1.2 million kg CO_{2e} of additional emissions due to remanufacturing and transport. These findings highlight the broader environmental and economic consequences of supply chain inefficiencies beyond what is captured in direct process emissions.

Overall, the results show that lean interventions targeting logistics and inventory management lead to measurable reductions in both cycle time and carbon emissions. The integration of VSM and DES enables systematic evaluation of lean-driven improvements and their environmental implications, providing empirical support for the proposed Simulation-Supported Lean–Green Framework in construction supply chains. In the context of India's growing emphasis on sustainable infrastructure and resource-efficient development, such integrated approaches offer a practical pathway towards more resilient, cost-effective, and environmentally responsible construction supply chains.

From a theoretical perspective, this study substantiates that lean-driven enhancements in material flow and resource coordination can yield environmental advantages as a secondary result of operational optimisation (Garcia-Buendia et al., 2021). Lean interventions enhance system flow reliability and diminish unpredictability by minimising non-value-adding logistics operations, excessive buffering, and material handling requirements, hence reducing energy consumption and related emissions throughout supply chain stages. This corroborates the expanding Lean–Green supply chain literature, indicating that operational efficiency and environmental performance frequently enhance one another when improvement initiatives prioritise waste reduction and flow stabilisation (Bortolini et al., 2023; Engin et al., 2019). Simulation-based validation further strengthens this understanding. It shows how the environmental effects of lean interventions become visible under dynamic, uncertain conditions in construction projects. This helps move Lean–Green integration beyond conceptual discussion to a quantitatively evaluated, project-level application.

CONCLUSION

This study demonstrates that integrating Lean and GSCM practices can deliver simultaneous operational and environmental benefits in construction supply chains. A key contribution of this work is the development of a Simulation-Supported Lean–Green Framework that integrates VSM with DES. While VSM supports systematic identification of improvement opportunities, DES enables these lean interventions to be tested under dynamic and uncertain project conditions, allowing their operational and environmental implications to be assessed before implementation. By linking lean-driven efficiency gains to environmental outcomes and enabling a case-study validation, the framework provides a structured and evidence-based approach for evaluating Lean–Green strategies, thereby reducing implementation risk and supporting more informed decision-making.

From a practitioner's viewpoint, the suggested simulation-assisted Lean–Green framework provides a systematic decision-support methodology for enhancing construction supply chain performance at the project level. The framework facilitates project teams in visualising material flow inefficiencies via VSM and assessing alternative planning strategies through DES, thereby optimising delivery schedules, inventory levels, and resource utilisation under diverse site conditions. This can mitigate delays, minimise superfluous buffer stocks, and reduce operating emissions associated with transportation and handling activities. Thus, the methodology facilitates a more proactive and data-informed supply chain strategy, enabling construction managers to reconcile efficiency, cost, and environmental factors in actual project settings.

The study is limited by its reliance on a single case study and its focus on operational and logistics-related emissions, rather than a comprehensive life-cycle assessment. Future research can extend the framework across multiple projects and material supply chains, incorporate richer data inputs, and integrate life-cycle and behavioural considerations. Overall, the findings

indicate that simulation-supported lean approaches offer a practical and scalable pathway for improving efficiency and sustainability in construction supply chains, with relevance for both practitioners and researchers.

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