

A COMPUTATIONAL DEA-BASED DECISION SUPPORT FRAMEWORK FOR GREEN SUPPLY CHAIN MANAGEMENT IN CONSTRUCTION

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Abstract

In construction, greening supply chains requires balancing economic performance with environmental impact, making systematic evaluation and comparison difficult. Current approaches rely on single indicators or subjective assessments, limiting their ability to identify relatively efficient configurations. This paper proposes a Data Envelopment Analysis (DEA)-based framework to computationally evaluate green supply chain management (GSCM) scenarios. Economic and environmental parameters are treated as inputs and outputs in the DEA model. An application to 81 scenarios identifies supply chain configurations that achieve environmental improvements without disproportionate economic penalties, addressing a key challenge in implementing GSCM in the construction sector.

Introduction

The construction industry plays an important role in the world's economic growth and infrastructure development. Apart from construction activities, a substantial amount of construction-related environmental and economic impact is embedded in upstream material production, transportation, and logistics decisions (Wibowo, Handayani and Farida, 2022). As a result, attention has increasingly shifted toward construction supply chains as a key leverage point for improving overall project performance. In response, green supply chain management (GSCM) has emerged as an approach that integrates conventional supply chain decisions with environmental considerations, while maintaining economic and operational performance (Farida, Handayani and Wibowo, 2019). In construction, GSCM practices include reducing material wastage, improving energy efficiency, lowering carbon emissions, and optimising transportation and logistics operations (Castellano *et al.*, 2023). However, these strategies rarely improve all performance dimensions simultaneously.

A primary challenge in implementing GSCM in construction lies in managing trade-offs among multiple, often conflicting parameters, including cost, emissions, waste generation, time, and profitability (Wibowo, Handayani and Farida, 2022). Therefore, evaluating alternative options in GSCM configurations is a complex multi-criteria decision-making problem. Existing practices focus on a single dimension or a descriptive

comparison, such as cutting emissions or reducing costs and time. Because of focusing on one dimension, these approaches often fail to capture the multidimensional nature of supply chain performance and typically require subjective weighting of criteria.

These constraints are particularly evident in project-based construction contexts where total material demand is fixed, and variations among alternative supply chain configurations arise primarily from differences in resource utilisation efficiency rather than scale. Under such conditions, conventional evaluation methods struggle to provide objective benchmarking across green supply chain scenarios. There remains a lack of structured, scenario-based analytical frameworks tailored to project-level construction supply chains, capable of simultaneously capturing economic, environmental, and operational performance while enabling objective efficiency benchmarking under constant material demand conditions. Addressing this gap requires an efficiency-based evaluation approach that can handle multiple inputs and outputs concurrently, avoid subjective weighting of performance criteria, and benchmark alternatives relative to best-performing configurations.

Data Envelopment Analysis (DEA) offers a comprehensive solution to this issue. DEA is a non-parametric method for evaluating efficiency that measures the relative performance of similar entities by examining their capacity to convert various inputs into preferred outputs, without the necessity for predetermined weights (Charnes, Cooper and Rhodes, 1978; Banker, Charnes and Cooper, 1984). DEA has shown potential applications in supply chain studies as well as environmental and sustainability research to evaluate performance independently (Zhou, Ang and Poh, 2008). These attributes make DEA particularly suitable for assessing GSCM in construction projects that involve competing economic and environmental objectives.

Therefore, this study proposes a structured, scenario-based DEA framework for assessing GSCM efficiency in project-level construction supply chains under constant demand conditions. Alternative supply chain configurations are systematically developed using literature-based economic and environmental parameters and evaluated as decision-making units within a variable returns to scale (VRS) DEA model. By focusing on project-oriented supply chain contexts where material

quantities are design-driven, the study provides a targeted analytical approach for comparing green supply chain configurations and identifying improvement pathways. The findings contribute methodological support for efficiency-based decision-making in construction supply chains and offer practical insights for managers and policymakers evaluating sustainable supply chain interventions.

Research background

Conventionally, construction supply chains have been designed primarily to minimise costs, improve efficiency, ensure on-time deliveries, and maintain sufficient inventory to prevent construction delays. However, these priorities often conflict with sustainability goals, leading to overproduction, excessive transport, and material wastage (Cataldo *et al.*, 2022).

The rising urgency of climate change and resource scarcity has placed sustainability at the forefront of supply chain management. Governments, investors, and clients now demand construction projects that reduce carbon emissions, minimise waste, and adopt circular practices (Chen, Feng and Garcia de Soto, 2022). For cement, reducing emissions is a global priority, as its production contributes significantly to overall greenhouse gas levels (GCCA India-TERI, 2025). But project stakeholders cannot ignore cost pressures, productivity requirements, and delivery deadlines. This dual pressure creates a fundamental tension over whether to focus on environmental outcomes or efficiency-focused measures (Golpîra, 2021).

This tension is especially evident in decisions around production and inventory (Castellano *et al.*, 2023). For example, producing and storing more material than immediately needed helps prevent material shortages on site, but increases emissions, costs, and risks of wastage (Chen, Feng and Garcia de Soto, 2022). In construction, the problem is more constrained to the project level. Total material demand is often fixed by design, and performance differences among alternatives arise from differences in per-unit costs, emissions intensity, and operational losses, such as material wastage. Transportation choices further complicate the trade-off, as frequent deliveries may improve responsiveness but generate higher emissions (Suhaib, Amir Babak Rasmi and Türkay, 2023).

In response, GSCM enhances conventional supply chain management by including environmental impacts into procurement, production, transportation, and waste management decisions. In the construction industry, GSCM methods typically encompass the adoption of low-carbon resources, energy-efficient technology, optimal logistics planning, and minimisation of material waste (Farida, Handayani and Wibowo, 2019; Wibowo, Handayani and Farida, 2022).

A variety of techniques have been utilised to assess green supply chain effectiveness. Life Cycle Assessment (LCA) is extensively employed to measure environmental consequences throughout the supply chain and identifies

emission hotspots in construction materials and processes (Backes and Traverso, 2022). However, LCA predominantly emphasises environmental factors but does not explicitly include economic efficiency or the trade-offs among various performance metrics.

Multi-Criteria Decision-Making (MCDM) methodologies, like the Analytic Hierarchy Process (AHP), TOPSIS, have been widely utilised to assess green supply chain options by consolidating various criteria into a singular score (Paul *et al.*, 2021). Although these systems provide flexibility, they depend on predetermined or gathered weights to reflect decision-making preferences. Numerous assessments indicate that MCDM outcomes are significantly influenced by weighting methods, potentially introducing subjectivity and constraining transparency, especially when objective benchmarking is necessary (Paul *et al.*, 2021).

In project-based construction environments, where possibilities are evaluated under set demands and standardised functional units, dependence on subjective weighting is a considerable constraint. Thus, there is a necessity for performance evaluation methodologies that may objectively assess many options based on empirical performance data without necessitating prior determination of preference weights.

DEA gives a non-parametric framework for assessing the relative efficiency of analogous decision-making units utilising various inputs and outputs without predetermined weights (Charnes, Cooper and Rhodes, 1978; Banker, Charnes and Cooper, 1984). The DEA formulates an efficiency frontier based on observable data, designating efficient units as benchmarks for their inefficient counterparts, while also measuring prospective improvement objectives.

DEA has been extensively utilised in energy, environmental, and sustainability research to evaluate eco-efficiency by including costs, energy consumption, emissions, and resource losses as inputs, while financial performance indicators serve as outputs (Zhou, Ang and Poh, 2008). In supply chain research, DEA has been employed to assess companies, logistics networks, and supply chain designs, providing insights about efficiency rankings and opportunities for enhancement (Zhou, Ang and Poh, 2008).

In contrast to LCA and MCDM methodologies, DEA is especially appropriate for objective benchmarking scenarios that need the simultaneous assessment of numerous quantitative metrics. Its capacity to eliminate subjective weighting and to offer reference sets and proportional improvement metrics renders it very appropriate for assessing the green supply chain for the construction industry, contexts defined by fixed demand and various efficiency determinants. Despite existing contributions, a distinct vacuum persists in the systematic benchmarking of various GSCM scenarios within construction project-based frameworks. Current research predominantly applies descriptive comparisons, utilises MCDM methods with subjective weighting, or focuses on firm-level efficiency

assessments instead of scenario-based evaluations under constant project demand.

This paper proposes a DEA-based framework for assessing the efficiency of green supply chains to solve this gap. The approach utilises an input-oriented VRS-DEA model to benchmark literature-informed scenarios, facilitating objective comparisons of economic and environmental performance, identification of efficient configurations, and quantification of prospective improvements. This enhances both the theoretical and practical aspects of decision-making in GSCM for the construction industry.

Methodology

This study proposes a structured, DEA-based multi-stage framework to address the need for systematic, objective benchmarking methods for assessing GSCM scenarios in the context of project demand. The methodology aims to facilitate transparent scenario construction, minimise dependence on subjective performance weighting, and promote quantitative efficiency benchmarking across various supply chain configurations.

The proposed methodological framework shown in Figure 1 combines literature-informed parameter identification, scenario development, DEA model formulation, computational implementation, improvement potential analysis, and decision support interpretation to facilitate a comprehensive and replicable assessment of GSCM efficiency.

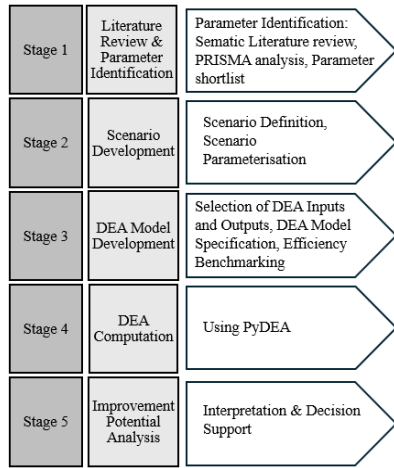


Figure 1: DEA-Based Methodological Framework

Stage 1: Literature Review & Parameter Identification

A systematic literature review using the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) was performed to identify performance parameters associated with the efficiency of GSCM (Page *et al.*, 2021). Relevant studies were sourced from prominent academic databases such as Google Scholar, Web of Science, and Scopus. Based on their applicability to construction supply chains and their utilisation of quantitative performance indicators. From the collected literature, economic, environmental, and operational

parameters frequently used to assess green supply chain performance were extracted and categorised. Table 1 represents the shortlisted Economic, Environmental, and Operational parameters with their sources. The selection of parameters was guided by their relevance to GSCM objectives, the availability of quantitative benchmarks, and their appropriateness for efficiency-based evaluation. This approach ensures that scenario development and subsequent DEA analysis are anchored in established literature rather than arbitrary assumptions.

Table 1: Shortlisted Parameters

Category	Parameter	Description	Source
Economic	Production cost (₹/t)	Costs associated with material manufacturing and processing	1,2,3
	Transport cost (₹/t)	Cost of conveying materials from the origin to the site	1,2,3,4
	Carbon cost/Tax (₹/t)	Costs related to carbon pricing or emissions Taxes	7,8
	Net profit (₹/t)	The financial worth produced per unit of material provided	1,2,3
Environmental	CO ₂ emissions (production) (tCO ₂ /t)	Emissions produced during the manufacturing of materials	4,5,6
	CO ₂ emissions (transport) (tCO ₂ /t)	Emissions produced during the transportation of materials	4,5,6
Operational	Material wastage (%)	Percentage of material wasted due to handling and inefficiencies	9,10

1.(Khaiyum, Sarker and Kabir, 2023), 2.(Castellano *et al.*, 2023), 3.(Bhagwat and Sharma, 2007), 4.(Francis and Thomas, 2020a), 5.(GCCA India-TERI, 2025), 6.(Okay, Sencer and Taskin, 2024), 7. (Pan *et al.*, 2024), 8.(Santos, 2022), 9.(Gulghane and Khandve, 2015), 10.(Golzarpoor and González, 2013)

Stage 2: Scenario Development

This study characterises a scenario as a unique construction supply chain configuration distinguished by varying operational and environmental management approaches, with each scenario considered as a Decision Making Unit (DMU) within the DEA framework. Scenarios are designed deterministically to represent realistic and comparative supply chain options. A case study construction project is utilised to ensure practical relevance, with the corresponding cement demand serving as the analytical foundation. All scenarios are constructed with regard to this case study.

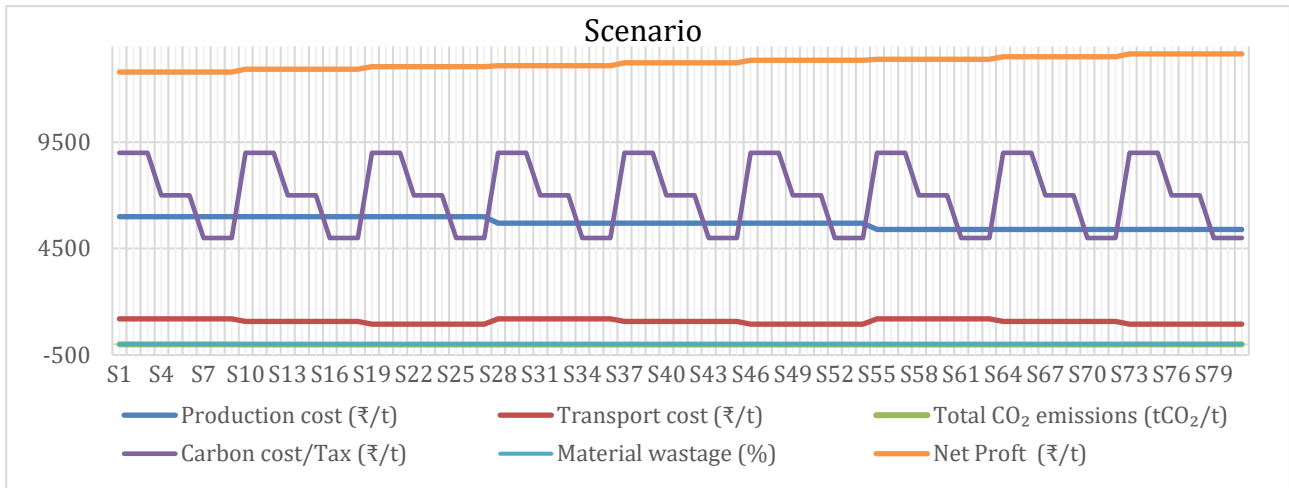


Figure 2: GSCM Scenario Design for DEA-Based Evaluation

A constant project demand assumption is used across all scenarios, representing standard construction conditions in which material quantities are dictated by design and scheduling limitations. This guarantees that the observed discrepancies in efficiency stem from differences in resource utilisation rather than scale effects. A total of 81 scenario archetypes are developed to assess performance across various management strategies, reflecting systematic differences in cost structure, emission intensity, material waste, logistics efficiency, and carbon cost internalisation. Figure 2 shows a graphical representation of all developed scenarios.

Table 2: Parameter Range Summary Table

Parameter	Max	Mid	Min
Production cost (₹/t)	6000	5700	5400
Transport cost (₹/t)	1200	1075	950
Carbon cost/Tax (₹/t)	9000	7000	5000
CO ₂ emissions production (tCO ₂ /t)	0.9	0.65	0.54
CO ₂ emissions transportation (tCO ₂ /t)	2.02	1.9	0.65
Material wastage (%)	5	3.5	2

Table 2 provides a parameter-range summary used in scenario development. The parameter values were selected from industry evidence and published studies. Wastage percentages were defined using industry evidence. Gulghane and Khandve (2015) report that cement wastage in Indian construction typically ranges from 2–3% in well-managed sites, while poorly managed projects experience higher levels. Other studies note wastage levels of 2.6–4% on active projects, which justifies a maximum assumption of 5% and a reduction to 2% for scenarios (Golzarpoor and González, 2013). Cost assumptions were anchored in UltraTech Cement's financials for 2025, which report an average realisation of ₹5,052 per tonne and logistics costs of ₹1,167 per tonne (UltraTech Cement Limited, 2025). Scenarios apply 5–

10% premiums in line with early adoption of low-carbon cement, which global benchmarks suggest may be 50–45% more expensive. Finally, CO₂ emission parameters were aligned with sectoral roadmaps.

Francis and Thomas (2020b) shows that Indian housing can achieve up to 40% reductions through material substitution and policy measures, while the Decarbonization Roadmap for the Indian Cement Sector: Net-Zero CO₂ by 2070 (GCCA India-TERI, 2025), outlines feasible reductions of 35–50% by mid-century. Accordingly, the parameter value applies a 50% reduction for both production and site consumption emissions, with incremental reductions at Low and Medium levels.

Carbon cost numbers were articulated in Indian Rupees per tonne of CO₂ to ensure compatibility with project cost data. International carbon tax rates and emissions trading prices indicate that carbon pricing levels often vary from below USD 1/tCO₂ to over USD 100/tCO₂ (Santos, 2022; Pan *et al.*, 2024; United Nations Environment Programme and Global Alliance for Buildings and Construction, 2025). Utilising a realistic currency rate, this equates to around ₹100–₹10,000 per tCO₂. Consequently, low, medium, and high carbon cost levels were established within this spectrum to represent voluntary carbon markets, average compliance pricing, and stringent policy scenarios, respectively. While India does not presently enforce a comprehensive carbon tax, this study incorporates carbon costs to account for evolving international carbon pricing frameworks and prospective regulatory conditions, facilitating a forward-looking assessment of the efficiency of GSCM.

Stage 3: DEA Model Development

The selection of DEA inputs and outputs is based on GSCM concepts and the attributes of project-based construction systems. Inputs signify unfavourable economic, environmental, and operational constraints that need to be reduced, and outputs denote favourable economic results.

Each construction supply chain scenario is regarded as a DMU defined by a vector of inputs and outputs. The DEA input set comprises production cost (₹/t), transport cost (₹/t), carbon cost/tax (₹/t), total CO₂ emissions (tCO₂/t),

and material wastage (%). Net profit (₹/t) is designated as the primary output variable as it represents an aggregate performance indicator reflecting the combined effects of production cost, transport cost, carbon cost, and material wastage, which are explicitly modelled as inputs. The quantity of material is omitted as an output variable because project demand remains constant across all scenarios and therefore does not influence efficiency differentiation. All variables are articulated on a per-tonne basis to guarantee comparability and eliminate scale-induced error. Table 3 represents inputs and outputs used in DEA.

Table 3: DEA Inputs and Outputs

Variable type	Parameter	Unit	DEA role
Input	Production cost	₹/t	Minimized
Input	Transport cost	₹/t	Minimized
Input	Carbon cost	₹/t	Minimized
Input	Total CO ₂ emissions	tCO ₂ /t	Minimized
Input	Material wastage	%	Minimized
Output	Net profit	₹/t	Maximized

An input-oriented DEA model is used to assess the relative efficiency of green supply chain scenarios. The aim is to reduce economic and environmental burdens while sustaining the same level of revenue generation. This viewpoint aligns with construction project conditions, where output quantities are limited by fixed demand and efficiency enhancements are primarily realised through reductions in costs, emissions, and waste.

VRS are assumed using the Banker–Charnes–Cooper (BCC) DEA model, which allows efficiency to vary with scale and isolates pure technical efficiency from scale effects (Charnes, Cooper and Rhodes, 1978; Banker, Charnes and Cooper, 1984).

DEA Multiplier Formulation,

For a given scenario, the DEA efficiency score is obtained by solving the following linear programming problem:

$$\text{Max } E_o = \sum_{r=1}^s u_r y_{ro}$$

Subject to,

$$\begin{aligned} \sum_{r=1}^s v_i x_{io} &= 1 \\ \sum_{r=1}^s u_r y_{rj} &\leq \sum_{i=1}^m v_i x_{ij}, \quad \forall j = 1, 2, \dots, n \\ u_r &\geq 0, \quad v_i \geq 0 \end{aligned}$$

The objective function maximises the weighted sum of outputs for scenario o, normalised by the weighted sum of its inputs. The second constraint ensures that the identical combination of weights does not yield an efficiency score exceeding 1 in any other scenario, thereby establishing the efficiency frontier.

For computational implementation, the equivalent input-oriented VRS envelopment model is used:

$$\text{Min } \theta_o$$

Subject to,

$$\sum_{j=1}^n \lambda_j x_{ij} \leq \theta_o x_{io}, \quad \forall i = 1, 2, \dots, m$$

$$\sum_{j=1}^n \lambda_j x_{y_{ij}} \leq y_{ro}, \quad \forall r = 1, 2, \dots, s$$

$$\sum_{j=1}^n \lambda_j = 1$$

$$\lambda_j \geq 0$$

This study employs DEA formulations based on the basic input-oriented multiplier and envelopment models initially introduced by Charnes et al., (1978) and then modified to VRS by Banker et al., (1984). Table 4 shows a description of the notation.

Table 4: Notation and Variable Description

Symbol	Description	Unit	Corresponding parameter
n	Number of scenarios (DMUs)	–	81 scenarios
m	Number of inputs	–	5 inputs
s	Number of outputs	–	1 output
x_{1j}	Production cost of scenario (j)	₹/t	Production cost
x_{2j}	Transport cost of scenario (j)	₹/t	Transport cost
x_{3j}	Carbon cost of scenario (j)	₹/t	Carbon cost
x_{4j}	Total CO ₂ emissions of scenario (j)	tCO ₂ /t	Total CO ₂ emissions
x_{5j}	Material wastage of scenario (j)	%	Material wastage
y_{1j}	Net profit of scenario (j)	₹/t	Net profit
u_r	Weight assigned to output (r)	–	DEA output weight
v_i	Weight assigned to input (i)	–	DEA input weight
λ_j	Intensity variable	–	Peer contribution
θ_o	Efficiency score of scenario (o)	–	DEA efficiency

Stage 4: DEA Computation Using PyDEA

The DEA model outlined in the preceding part is executed using PyDEA, a Python-based application for data envelopment analysis (PyDEA Developers, 2023). PyDEA calculates efficiency scores by resolving a linear programming problem for each scenario and determines efficient benchmarks and reference sets. These outputs serve as the foundation for later efficiency benchmarking

and analysis of improvement possibilities, which will be addressed in the upcoming section.

Validation and Robustness Checks

This study emphasises the credibility and robustness of the proposed DEA-based framework over prediction accuracy. Conceptual validity is achieved by basing scenario development and parameter selection on recognised literature in GSCM and construction supply chains. All scenarios represent realistic and comparable configurations under constant project demand.

A sensitivity study was performed to evaluate the robustness of the DEA results by adjusting key input parameters within $\pm 10\%$ of their baseline values. The efficiency rankings and benchmark scenario identifications were predominantly consistent, suggesting that the DEA results are not affected by slight data fluctuations. These evaluations increase confidence in the reliability of the proposed framework and its relevance for decision assistance in GSCM planning for construction projects.

Stage 5: Improvement Potential Analysis

The next phase of the methodology focuses on synthesising DEA outputs to facilitate decision-making in GSCM planning for the construction industry. Efficient scenarios are recognized as benchmark configurations exemplifying best practices under constant project demand, whereas inefficient scenarios are assessed in comparison to their reference counterparts and their potential for improvement. The next part discusses detailed efficiency scores, benchmarking correlations, and opportunities for improvement.

Results and Discussion

The proposed DEA-based framework assessed 81 scenario-based DMUs representing different green supply chain configurations in the construction industry. Figure 3 represents the efficiency score across all scenarios with the considered parameters. All scenario configurations were developed within constrained and literature-informed parameter ranges to ensure realistic techno-economic and environmental relationships across production and transport stages. Production costs, transportation costs, transportation and production carbon emissions, carbon cost levels, and material wastage levels for the economic and environmental inputs are integrated into each scenario. Performance is evaluated using an economic outcome indicator under uniform functional assumptions. With scenarios S1–S27 obtaining an efficiency score of roughly 0.727, scenarios S28–S54 achieving an intermediate efficiency of roughly 0.88, and scenarios S55–S81 forming the efficient frontier with an efficiency score equal to 1, the resulting DEA efficiency scores indicate a structured pattern.

Scenarios S1–S27 exhibit high-intensity production configurations, featuring a production cost of ₹8,800 per tonne and production-related emissions of 0.90 tCO₂ per tonne, reflecting typical high-emission production regimes where higher emissions are associated with less

efficient and more resource-intensive processes. Despite the reduction of wastage from 5% to 2% and decreasing the carbon tax from ₹9,000 to ₹5,000 per tCO₂e, these scenarios continue to exhibit relative inefficiency in terms of DEA. An efficiency score of 0.727 indicates that, on average, these scenarios necessitate a 27% decrease in their aggregate economic and environmental inputs to align with the performance of frontier scenarios. From a GSCM perspective, this outcome suggests that downstream green practices, such as waste minimisation and logistics optimisation, enhance absolute performance by reducing material losses and carbon emissions; however, their efficacy is limited when upstream production technologies are significantly carbon- and resource-intensive.

Scenarios S28–S54 indicate medium-intensity, characterised by a production cost of ₹7,200 per tonne and decreased production emissions of 0.65 tCO₂ per tonne. These scenarios attain an efficiency score of roughly 0.88, indicating the synergistic impact of moderate emission intensity and enhanced cost structure. This also reflects a realistic transition regime where improvements in emission intensity are accompanied by more efficient cost structures rather than conflicting trade-offs. Within this cohort, fluctuations in wastage and transportation emissions result in quantifiable enhancements in net profit and carbon cost liability. For instance, a 3 % point reduction in waste effectively reduces material losses and associated carbon costs, thereby improving economic performance even at elevated carbon tax rates. The results closely align with GSCM principles, indicating that operational greening and emission-control strategies significantly enhance supply chain performance when industrial systems are not overly carbon-intensive. Nevertheless, despite these advancements, none of the scenarios under this category attain the efficiency frontier, showing that even incremental greening cannot entirely offset the lack of low emissions during production.

Scenarios S55–S81 constitute the DEA efficient frontier, characterized by low-intensity production configurations, with a production cost of ₹6,400 per tonne and production emissions of 0.54 tCO₂ per tonne, alongside relatively reduced transport emissions. These configurations represent technologically feasible low-emission production pathways rather than idealised or unconstrained combinations of low cost and low emissions. Across all examined policy and operational situations, these configurations currently encompass various aspects of optimal green supply chain practices. Under this system, slight alterations in wastage or carbon tax do not lead to shifts in dominance, as the scenarios function near the least viable combination of economic and environmental costs within the specified scenario space. In the context of GSCM, these scenarios exemplify advanced, cohesive green supply chains where technological decisions, operational rigour, and regulatory readiness together enhance eco-efficiency.

The analysis shows that waste reduction and carbon taxes affect supply chain performance through production and logistics frameworks rather than as standalone efficiency

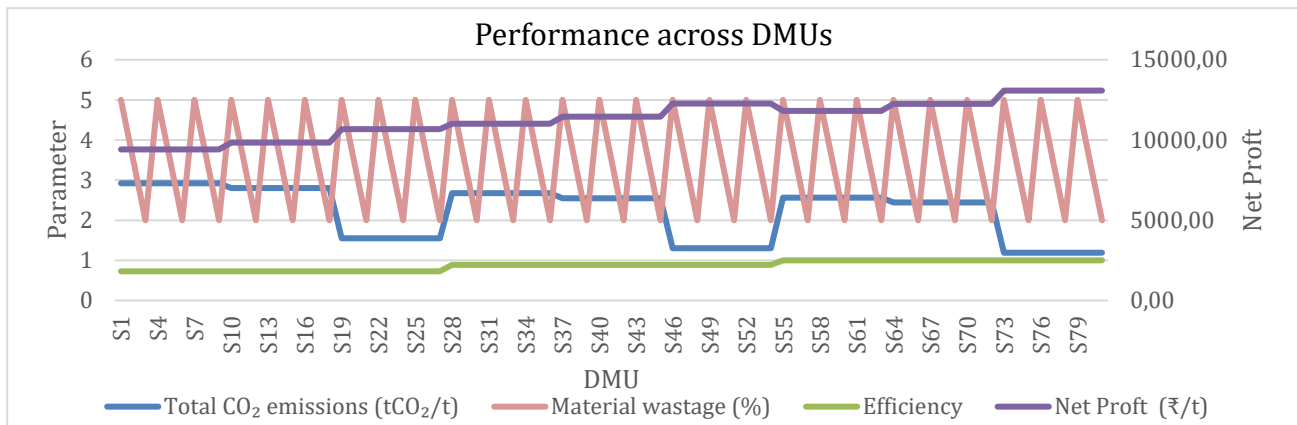


Figure 3: Integrated Environmental, Operational, and Economic Performance across DMUs

drivers. Under the fixed-revenue assumption, wastage and emission reductions improve absolute profitability and regulatory resilience but may not always improve relative efficiency scores compared to fundamentally cleaner setups. This supports GSCM theory, which distinguishes between incremental efficiency improvements within a technological regime and frontier-shifting transformations through low-carbon production and sourcing.

The results support the GSCM principle that technological, operational, and regulatory choices must align to sustain environmental advances. Performance and resilience improve with incremental greening, while structural investments in low-emission manufacturing and logistics redefine the efficiency frontier. This multi-scenario, multi-input-output framework ranks scenarios and reveals structural efficiency drivers, allowing decision-makers to compare supply chain configurations, identify non-dominated pathways, and understand how technology, operations, and policy changes may affect performance in a complex, sustainability-oriented decision environment.

Conclusions

This study proposes a structured, scenario-based DEA framework designed for project-level green construction supply chain decision-making under constant demand conditions. The primary contribution lies not merely in the application of DEA, but in the systematic development and benchmarking of alternative supply chain configurations using multi-dimensional economic, environmental, operational, and regulatory parameters. By organising scenario-based supply chain strategies as decision-making units within a consistent functional boundary, the framework enables objective efficiency comparison without requiring subjective weighting of sustainability indicators. This project-oriented perspective provides a targeted analytical approach for evaluating green supply chain strategies in construction contexts where material demand is design-driven and efficiency improvements must be assessed across feasible operational and technological alternatives.

The framework is useful for decision-makers in complex green supply chains where cost efficiency, carbon emissions, material waste, and regulatory demands are

interdependent. Managers and policymakers can examine how production technology, transport emissions, wastage, and carbon taxation affect efficiency and net profit using multi-scenario analysis. Instead of offering a single solution, the framework shows dominance relationships and improvement potentials, helping stakeholders distinguish between operational and fundamental technology inefficiencies. This helps decide whether greening should focus on incremental operational improvements or deeper transitions to low-emission industrial technology.

The results are relative efficiency outcomes under fixed modelling assumptions and scenario-based inputs; therefore, they enable decision-making rather than prescriptive optimization for real-world implementation. While the use of a single output simplifies the analysis, it enables clearer interpretation of relative efficiency, with scope for extending the framework to multi-output DEA formulations in future work. In practice, demand variability due to design changes or schedule pressure can alter resource utilisation, cost structures, and emission intensity, potentially affecting relative efficiency rankings. Future research can address this limitation by extending the model using stochastic or dynamic DEA approaches that incorporate probabilistic demand variation, time-dependent resource allocation, and uncertainty in economic and environmental parameters.

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