CHAPTER 135

Sustainable Construction Supply Network Optimization: An Empirical Analysis

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ABSTRACT

Construction industry contributes significantly to global carbon emissions and resource consumption. Integration of sustainable practices into supply network operations including logistics operations for order quantity allocation decisions offers a pathway to reduce impact of these activities on environment. This paper explores the inventory optimization decisions in supply network by considering logistics operations with an objective of minimizing supply network cost and its impact on the environment. A detailed methodology is developed to allocates optimal order quantity (OQA) to the suppliers considering the logistics cost. The model developed for OQA is a Mixed Integer Nonlinear Programming (MINLP) model which considers the practical project constraints. Design of Experiments (DOE) concept is used to gauge the sensitivity of input variables on supply network cost. Identification of significant variables can help practitioners design appropriate sourcing strategy for the construction organizations to minimize impact of sourcing activities on environment. The methodology has been verified with the help of numerical case.

Keywords: Order quantity allocation; Sustainability cost; Design of experiments (DOE); Supplier selection; Supply network cost optimization; Mixed integer Non-Linear programming.

1.0 Introduction

The building sector is among the globe's biggest carbon producers and consumers of resources, accounting for almost 40% of the world's energy-related CO_2 emissions and 36% of total energy use. With the ongoing urbanization and infrastructure needs, the environmental impact of construction activities keeps increasing, driving climate change, resource consumption, and environmental degradation. Under such circumstances, the need for sustainable construction supply chain practices has never been more critical. The combination of green logistics and maximum supply network sustainability is a revolutionary approach to reduce these effects without compromising its economic feasibility. Recent studies highlight the key role of sustainable supply chain management (SSCM) in reducing the environmental impact of construction activities (Lazer *et al.*, 2021).

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The transition towards sustainability in the construction industry is also accelerated by regulatory forces, stakeholder pressure, and long-term cost savings. The businesses embracing sustainable supply chain strategies can lower costs of operations by as much as 16% and achieve a 20% reduction in carbon emissions. However, the fragmented and practical nature of the construction industry often prevents the implementation of new solutions (Guerlain *et al.*, 2019). Although green logistics and sustainable materials are progressively used, the practise is uneven, especially in developing economies, where technology and access to capital are limited. Moreover, the absence of standardized metrics for sustainability makes it harder to track progress and drive industry-level transformation.

This research fills existing gaps by considering supply network optimization from a sustainability perspective. The paper tries to unify logistics operations, supplier choice, and order quantity allocation within a Mixed Integer Nonlinear Programming (MINLP) model to achieve low costs and environmental footprint (Kanáliková *et al.*, 2019). The approach employs Design of Experiments (DOE) to determine major variables that affect sustainability performance and provide recommendations to practitioners (Bagul & Mukherjee, 2018). By linking to global sustainability targets, this study emphasizes the role of centralized sourcing, green logistics, and technological innovation in attaining economic performance and environmental stewardship. The results offer a blueprint for the construction sector to minimize its environmental impact while building long-term resilience and sustainability.

2.0 Literature Review

Centralized sourcing has emerged as a critical strategy for enhancing supply chain performance and sustainability. Bagul & Mukherjee (2020) explore the impact of centralized sourcing on supplier selection and order quantity allocation (SSOQA) in multi-tier supply networks. Their study, using mixed-integer nonlinear programming (MINLP) models, demonstrates that centralized sourcing reduces inventory costs by 1.69%, improves product quality, and enhances environmental sustainability compared to decentralized approaches. The study also highlights the cost advantages of centralized sourcing in price-uncertain environments and recommends supplier consolidation and local procurement to reduce emissions. In a related study, Bagul & Mukherjee (2020) propose a framework for optimizing sourcing strategies in centralized, multi-tier supplier networks, emphasizing demand uncertainties and supplier failure risks (SFR). Their findings underscore the benefits of centralized supply chains, including improved resource utilization, risk reduction, and transparency, which collectively contribute to waste reduction and sustainability. Torres-Ruiz & Ravindran (2018) address supplier selection through a multi-objective optimization model that integrates sustainability criteria such as greenhouse gas (GHG) emissions, lead times, and supplier risks. Their approach, which employs a Supplier Sustainability Risk Score (SSRS) and goal programming, demonstrates significant reductions in lead times, logistics costs, and carbon footprints by prioritizing local suppliers.

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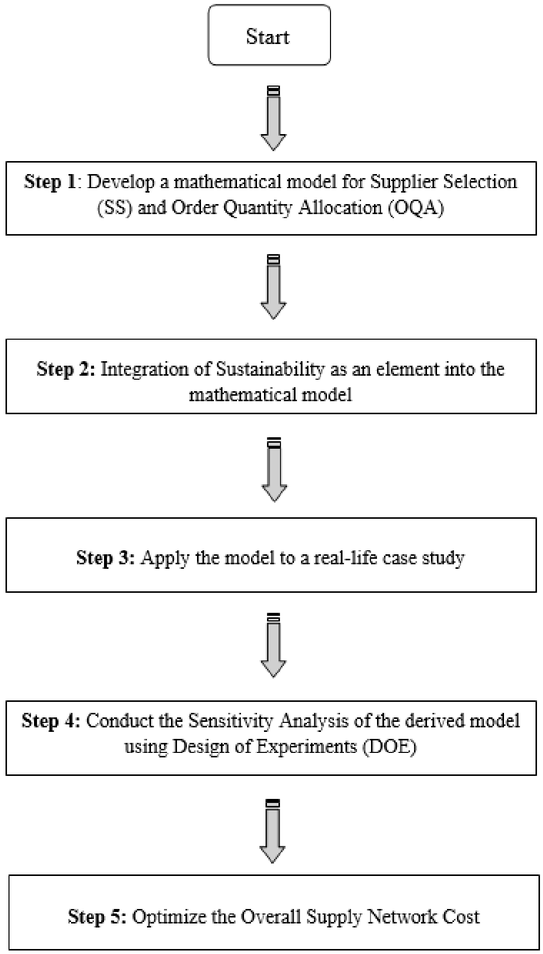
Tiwari *et al.* (2014) highlight the challenges of applying supply chain management (SCM) in construction, including risk management, information sharing, and organizational issues. They advocate for cultural change, education, and enhanced knowledge sharing to improve SCM performance. Patella *et al.* (2020) examine the adoption of green vehicles in last-mile logistics, focusing on incentives and autonomous vehicles.

Figure 1: Methodology for Optimal Supply Network Cost Optimization



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Despite the progress in sustainable logistics and GSCM research, several challenges remain. Many studies, such as those by Benmamoun *et al.* (2017) and Sato *et al.* (2022), are limited by small sample sizes, self-reported data, and a lack of empirical evidence. Additionally, the focus on specific industries or regions, as seen in the work of Cheng *et al.*

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(2023) and Trivellas *et al.* (2020), restricts the generalizability of findings. The reviewed literature underscores the importance of centralized sourcing, green logistics, and technological innovations in enhancing supply chain sustainability and performance. While significant progress has been made, the limitations of existing studies highlight the need for more comprehensive, empirically validated research. By addressing these gaps, future studies can provide actionable insights for industries striving to balance economic, environmental, and social sustainability in their logistics and supply chain operations.

3.0 Methodology

The methodology for optimal supply network cost optimization is shown in Figure 1.

3.1 Development of the mathematical model for SS and OQA

The mathematical model developed in the study addresses supplier selection (SS) and order quantity allocation (OQA) through a structured approach that optimizes inventory costs in a multi-tier supply network. The inventory cycle for this model follows a single-stage supply system as depicted in Figure 2. This illustrates the relationship between order quantities and time periods in a simplified supply chain. For more complex networks, Figure 3 presents the multi-tier supplier system, which forms the basis of our MINLP optimization approach. The optimization process involves calculating the number of orders to be placed with each supplier based on demand and capacity as well as allocating order quantities to minimize total costs while adhering to constraints.

Figure 2: Inventory Cycle for Single Stage Supply System

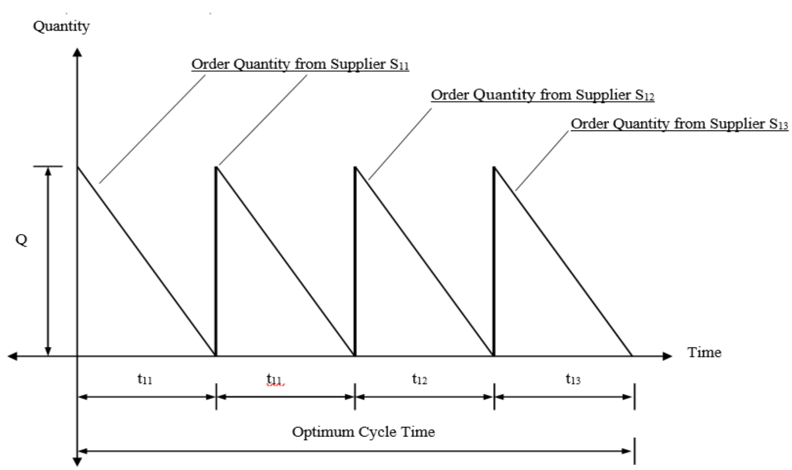

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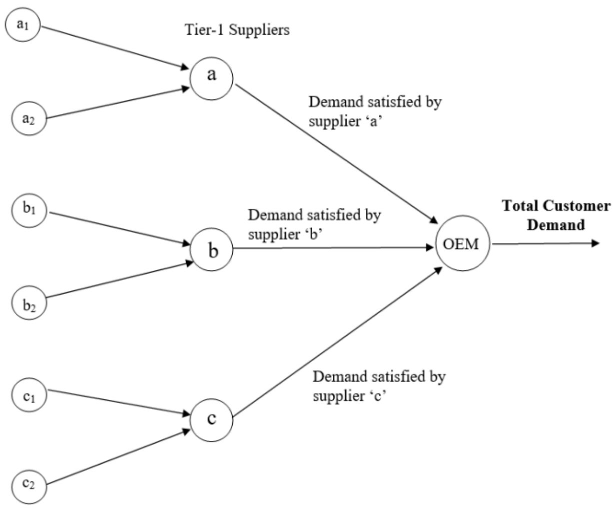
Figure 3: Multi-Tier Supplier System



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3.2 Multi-objective optimization model

The proposed multi-objective optimization model addresses sustainability risks in supplier selection through a structured two-phase methodology:

Phase 1: Supplier Sustainability Risk Assessment: The model begins with a sustainability risk assessment of potential suppliers. This involves evaluating suppliers based on economic, environmental, and social criteria to determine their sustainability risk levels. Each supplier is assigned a Supplier Sustainability Risk Score (SSRS), which quantifies the sustainability risks associated with each supplier.

Phase 2: Multi-objective Mixed Integer Linear Programming (MILP) Model: The SSRS calculated in Phase 1 is integrated into the MILP model as one of the objectives to minimize supplier sustainability risk. The model allows for the identification of backup suppliers, which serves as a risk mitigation mechanism against supply disruptions. This is crucial for maintaining supply chain resilience in the face of sustainability risks.

3.3 Mathematical model integrating sustainability

Order cycle time for a single order = $\frac{Q}{d}$ ...1

Quantity divided by demand gives us order cycle time.

Order cycle time (t_{ij}) = $\Sigma J_i \times \frac{Q}{d}$ ...2

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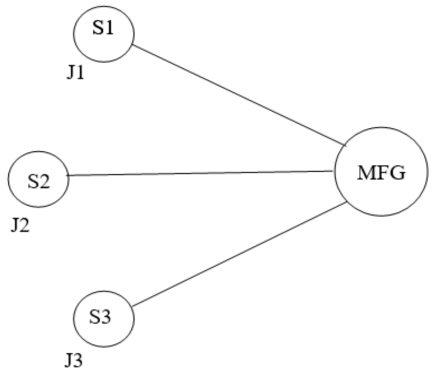
The number of orders multiplied by order cycle time for a single order gives us total order cycle time. The supply network structure as shown in Figure 4 demonstrates how suppliers are interconnected in our case study.

Figure 4: Supply Network (Source: Compiled by Authors)



Setup Cost = $\frac{\Sigma J_{ij}K_{ij}}{\Sigma J_{ij}\times\frac{Q}{d}}$ ...3

Set up cost is the product of set up cost per order and number of orders multiplied by total order cycle time.

$= \frac{d}{Q}\frac{\Sigma J_{ij}K_{ij}}{\Sigma J_{ij}}$ ...4

Carrying Cost = $\frac{Q}{2} \times a \times \frac{\Sigma J_{ij}P_{ij}}{\Sigma J_{ij}}$ ...5

Carrying cost per unit time for an order cycle is the product of average price from all the suppliers, inventory holding rate (%) per unit time (*a*) and average inventory (*Q*/2).

$\frac{aQ}{2} \times \frac{\Sigma J_{ij}P_{ij}}{\Sigma J_{ij}}$ ...6

Unit cost of production = $\frac{\Sigma Q\times J_{ij}\times P_{ij}}{\Sigma J_{ij}\times\frac{Q}{d}}$ ...7

Product of quantity, number of orders and unit price of product divided by total order cycle time gives unit cost of production.

$= d\,\frac{\Sigma J_{ij}\times P_{ij}}{\Sigma J_{ij}}$ ...8

Inventory cost = setup cost + carrying cost + unit cost ...9

Now we are adding one more element, i.e. sustainability cost to the inventory cost to develop the new model.

Sustainability cost

Fuel consumption = $\frac{distance}{mileage} = \frac{km}{\frac{km}{l}} = l$ ...10

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$C0_2$ emission per order cycle = Fuel consumption/trip × FEF × Number of trips ...11

$$\Sigma \frac{distance_{ij}}{mileage} \times FEF \times J_{ij} \quad ...12$$

$$C0_2\text{/unit time (in tonnes)} = \frac{\Sigma \frac{distance_{ij}}{mileage} \times FEF \times J_{ij}}{\frac{Q\Sigma J_{ij}}{d}} \quad ...13$$

$C0_2$ emission per order cycle divided by total order cycle time gives $C0_2$ per unit time.

$$= \frac{d \times FEF}{Q \times mileage}\left(\Sigma \frac{distance_{ij} \times J_{ij}}{\Sigma J_{ij}}\right) \quad ...14$$

Sustainability cost (in rupees) = sustainability cost × CP × exchange rate ...15

$C0_2$ emission = fuel consumption × FEF (in tonnes) ...16

According to the European Energy Exchange (EEX, 2014), the cost of one emission permit (GC) is 6.19 € or 8.85 USD. According to the new model,

Inventory cost = setup cost + carrying cost + unit cost of product + sustainability cost ...17

Our objective is to minimize this cost,

$$Z_{min} = \frac{d}{Q}\frac{\Sigma J_{ij}K_{ij}}{\Sigma J_{ij}} + \frac{aQ}{2}\left(\frac{\Sigma J_{ij}P_{ij}}{\Sigma J_{ij}}\right) + d\left(\frac{\Sigma J_{ij} \times P_{ij}}{\Sigma J_{ij}}\right) + \frac{d}{Q} \times \frac{FEF}{mileage}\left(\Sigma \frac{distance_{ij} \times J_{ij}}{\Sigma J_{ij}}\right) \quad ...18$$

Where in Z_{min}, the first term is setup cost; the second term is carrying cost; the third term is unit cost of production, and the fourth term is sustainability cost.

Table 1: GHG Emission Factors for Fuel Types

Fuel Type	**CO_2 emissions**	
	kgCO2e/kg	kgCO2e/l
Diesel	3.9	3.24
Jet kerosene	3.88	3.1
Heavy Fuel Oil (HFO)	3.41	3.31

3.4 Applying the model to a real-life case study

The mathematical model is validated using a real-life case study of an Indian electric appliance company.

Table 2: Inputs for Design of Experiments (DOE) (Source: Compiled by Authors)

Variables	**Supplier 1**	**Supplier 2**	**Supplier 3**
Demand	80000		
Carrying Cost	120	110	112
Ordering Cost	5000	6000	7000
Distance	1000	1300	1200
Cost	400	410	406

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The model is applied to this case study to determine optimal order quantities and supplier allocations, minimizing both inventory and sustainability costs. The goal is to validate the model's effectiveness in optimizing supply network costs while minimizing environmental impact. The mathematical relationships in this system are defined by above equations with key parameters summarized in Table 1 (GHG emission factors) and Table 2 (DOE input variables). The above inputs are used for the case analysis:

3.5 Sensitivity analysis using design of experiments (DOE)

The next step focuses on conducting a sensitivity analysis using Design of Experiments (DOE) to evaluate the impact of five key variables- demand, distance, ordering cost, carrying cost, and unit price, on both inventory cost and sustainability cost. Each variable is examined at three levels: the real-case scenario of a supplier, and two alternative scenarios representing ±10% deviations from the base values.

In this study, the dependent variable is the total supply network cost, which includes both inventory costs and sustainability costs. Design of Experiments (DOE) is used to identify which variables have the most significant impact on supply network costs, determine how these variables interact with each other and to optimize the supply network by focusing on the most influential variables.

The DOE is carried out using LINGO software, a powerful optimization tool, to design and analyse the experiments. The outcomes from the DOE were further analysed using Minitab, a statistical software, to determine the significance of each variable and their interactions. The results highlight the relative importance of each factor in optimizing inventory costs and sustainability costs, offering actionable insights for supply chain decision-making.

3.6 Optimization of the overall supply network cost

The insights gained from the Sensitivity Analysis are used to optimize the overall supply network cost. The goal is to minimize both inventory costs and sustainability costs while ensuring that the supply chain operates efficiently and aligns with global sustainability goals.
Incorporating sustainability metrics into supply chain management is essential for modern businesses aiming to balance economic performance with environmental and social responsibility. In this study, sustainability metrics such as CO_2 emissions and fuel consumption are integrated into the mathematical model to optimize supply network costs while minimizing environmental impact.

4.0 Results and Discussions

The study explores not only the linear effects of these variables but also their two-way interactions, providing a comprehensive understanding of how these factors collectively influence supply chain performance.

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4.1 Optimization of supply network costs

The primary objective of the study is to minimize total supply network costs, which include inventory costs and sustainability costs. The study demonstrates that centralized sourcing reduces inventory costs by approximately 1.69% compared to decentralized sourcing. This is achieved by coordinating supplier selection and order quantity allocation across multiple tiers of the supply chain. It also simplifies relationships with fewer suppliers, reduces redundancy, and improves overall supply chain efficiency. It also fosters long-term relationships with suppliers, encouraging them to participate in sustainability programs.

4.2 Hypothesis testing

It is a critical component of the sensitivity analysis conducted in this study. It is used to determine the statistical significance of key variables and their impact on total supply network costs. The goal was to determine which variables have a statistically

significant impact on the total supply network cost and to understand how these variables interact with each other. The hypothesis testing process involved the formulation of null (H_0) and alternative (H_1) hypotheses, conducting statistical tests, and interpreting the results. The hypothesis testing results in Table 3 confirm that demand, carrying cost, and material cost have statistically significant effects ($p < 0.001$).

Table 3: Hypothesis Table (Source: Compiled by authors)

Variables	Null Hypothesis (H_0)	Alternate Hypothesis (H_1)	p value	Significance
Demand	Demand has no significant effect on the total supply network cost.	Demand has a significant effect on the total supply network cost.	0.000	Yes
Carrying Cost	Carrying cost has no significant effect on the total supply network cost.	Carrying cost has a significant effect on the total supply network cost.	0.000	Yes
Ordering Cost	Ordering cost has no significant effect on the total supply network cost.	Ordering cost has a significant effect on the total supply network cost.	0.266	No
Distance	Distance has no significant effect on the total supply network cost.	Distance has a significant effect on the total supply network cost.	0.398	No
Material Cost	Material cost has no significant effect on the total supply network cost.	Material cost has a significant effect on the total supply network cost.	0.000	Yes
Comparison Factor	There is no significant interaction effect between demand and material cost on the total supply network cost.	There is a significant interaction effect between demand and material cost on the total supply network cost.	0.000	Yes

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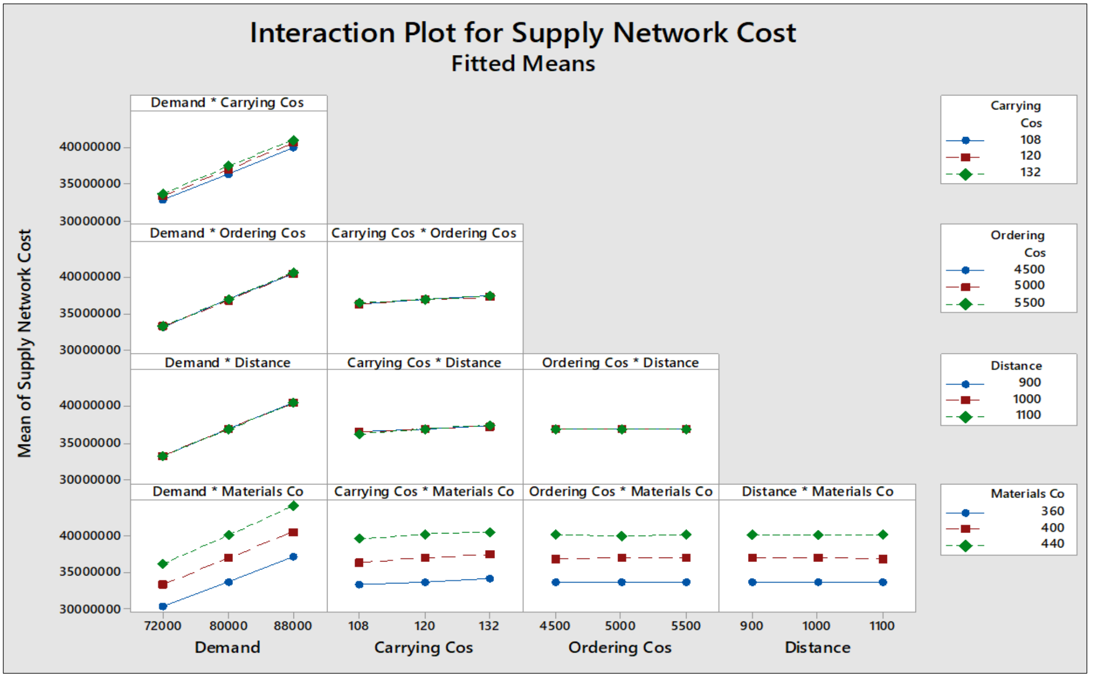
4.3 Visualization of results

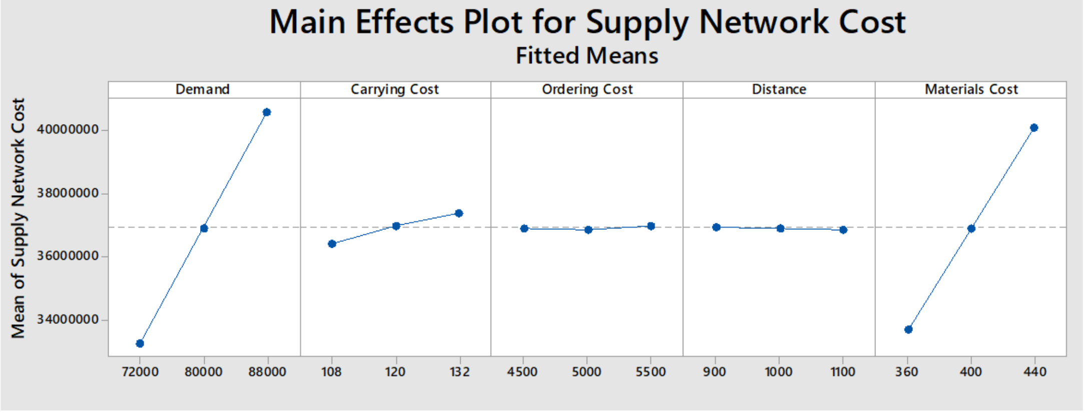
The results of the sensitivity analysis are visualized using interaction plots and main effects plots generated by Minitab.

Figure 5: Interaction Plot for Supply Network Cost



Source: Minitab

Figure 6: Main Effects Plot for Supply Network Cost



Source: Minitab

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The 'Interaction plot' as displayed in Figure 5 shows the combined effect of demand and unit price on total supply network costs. The plot reveals that higher demand levels amplify the impact of unit price on costs, while lower demand levels mitigate this impact. The 'Main effects' plot as shown in Figure 6 exhibits the individual effect of each variable (demand, carrying cost, unit price, ordering cost, and distance) on total supply network costs. The plot highlights that demand, carrying cost, and unit price have the most significant impact on costs.

5.0 Implications of the Research

5.1 Theoretical implications

There was no such model existing that integrated sustainability into construction supply network optimization and we have developed such a model. The paper contributes to the theoretical framework of sustainable supply chain management (SSCM) by integrating environmental costs like CO_2 emissions into traditional inventory optimization models. This bridges the gap between economic and environmental objectives in supply network design.

5.2 Practical implications

From a real-life perspective, these findings have significant implications for supply chain managers aiming to optimize inventory costs while addressing sustainability concerns. For example, reducing carrying costs through efficient inventory management practices can lead to lower overall supply network costs and improved sustainability by minimizing waste and excess storage. Similarly, understanding the interaction between demand and material costs can help businesses better forecast and plan for fluctuations, ensuring a more resilient and cost-effective supply chain. Our findings also support (Kumar *et al.*, 2015) argument for green logistics integration.

6.0 Conclusion

The study provides a general model for reducing supply network costs by considering sustainability aspects. Employing the Design of Experiments (DOE) and advanced analysis tools like LINGO and Minitab, the study was able to determine the most influential variables-demand, carrying cost, and material cost, whose impact has a significant bearing on both inventory and sustainability cost. The study highlights the use of a centralized sourcing policy for cost reduction and sustainability enhancement, particularly in multi-tier supply chains. The use of sustainability parameters like CO_2 emissions and fuel consumption in the supply chain model further highlights the importance of green logistics practices in the construction industry. The interrelation between demand and material cost is significant, which justifies the implementation of a comprehensive supply chain optimization policy where economic as well as environmental factors are given due importance.

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The developed model considers demand, distance, ordering cost, carrying cost, and unit price as parameters and does not account for other parameters such as the reliability of suppliers, geopolitical factors, and fluctuations in the market, which would affect supply chain performance. The model accounts for CO_2 emissions as a cost of sustainability, but other environmental and social aspects like water usage and labour practices are not accounted for, which are also some determinants of sustainability. While this research offers valuable insights into sustainable logistics management, there are some areas of research left open. Future research should address areas like social sustainability (Jørsfeldt *et al.*, 2016) and AI applications (Kanáliková *et al.*, 2019) to advance the triple bottom line (Lazar *et al.*, 2021). Future studies may include social cost impacts, such as labour practices and community well-being, to offer a better picture of the triple bottom line-economic, environmental, and social sustainability. Integration of new technologies such as blockchain, IoT, and AI may further enhance supply chain transparency and efficiency. Addressing these concerns, future studies can use the results of this research to create more sophisticated and integrated models for sustainable logistics management in the construction sector.

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