Advances in Consumer Research
https://acr-journal.com/
Volume-2 | Issue-6 | Dec: 2025

Original Researcher Article

Optimization of Supply Chain Operations Using Integer and Convex Programming Approaches

Dr. Devendra Singh[1], Raviteja Meda[2], Sreedevi[3], Dr Vipin Kumar[4]
[1] Professor, Mechanical Engineering, Ajay Kumar Garg Engineering College, Ghaziabad, Uttar Pradesh,
Email ID : deven.office.akg@gmail.c
[2]Lead Incentive Compensation Developer,
Email ID : rvtjmeda@gmail.com , ORCID ID: 0009-0009-1578-3865
[3]Ap/cse, VSB college of Engineering technical campus,
Email ID : sreedevivsb22121@gmail.com
[4]Associate Professor, Department of Mathematics, Faculty of Engineering, Teerthanker Mahaveer University, Moradabad, UP, India,
Email ID : drvipink.engineering@tmu.ac.in

ABSTRACT

Efficient supply chain operations are central to cost minimization, service level improvement, and resilience in modern competitive markets. This study investigates the application of integer programming and convex optimization techniques to address key decision-making problems in supply chain design and operations. A hybrid optimization framework is proposed to integrate strategic decisions such as facility location and capacity planning with tactical and operational decisions including inventory control and transportation allocation. Integer programming is employed to capture discrete choices such as warehouse activation and supplier selection, while convex programming is used to model continuous decisions involving production quantities, inventory levels, and transportation flows under cost and capacity constraints. The proposed framework is evaluated using a multi-echelon supply chain case scenario representing manufacturers, distribution centers, and retail outlets. Results demonstrate significant reductions in total operational cost, improved resource utilization, and enhanced demand fulfillment compared to traditional heuristic-based approaches. The findings confirm that combining integer and convex programming offers a robust, scalable, and analytically sound approach for optimizing complex supply chain systems in uncertain and resource-constrained environments. In addition, the proposed framework demonstrates strong computational stability and scalability, making it suitable for practical implementation in medium to large-scale supply chain networks. The integrated approach provides decision-makers with clear insights into cost–service trade-offs, supporting data-driven strategic planning and efficient operational execution across interconnected supply chain stages.

Keywords : Supply chain optimization, Integer programming, Convex optimization, Logistics management, Operations research.

1. INTRODUCTION:

Modern supply chains operate in an environment characterized by globalization, volatile demand patterns, shortened product life cycles, and increasing pressure to minimize costs while maintaining high service levels. As supply networks expand across multiple geographical regions and involve numerous stakeholders, decision-making becomes inherently complex, involving trade-offs between cost efficiency, responsiveness, and robustness. Traditional managerial approaches based on intuition, rules of thumb, or isolated optimization at individual stages of the supply chain often fail to capture system-wide interactions, leading to inefficiencies such as excess inventory, suboptimal facility utilization, and inflated logistics costs. In response to these challenges, mathematical optimization has emerged as a critical tool for structuring, analyzing, and improving supply chain operations. Optimization models provide a systematic framework to evaluate multiple decisions simultaneously under constraints, enabling organizations to identify globally optimal or near-optimal solutions that would otherwise be difficult to achieve through heuristic reasoning alone [1], [2]. Among the wide range of optimization techniques available, integer programming and convex programming have proven particularly effective in addressing the discrete and continuous decision components inherent in supply chain systems.

Integer programming plays a vital role in modeling strategic and tactical supply chain decisions that involve indivisible choices, such as whether to open or close a distribution center, select a supplier, or assign a transportation route. These binary or integer decisions are central to supply chain network design and long-term capacity planning [3], [4]. Conversely, many operational decisions within supply chains, including production quantities, inventory levels, shipment sizes, and resource allocation, are naturally continuous and often exhibit convex cost structures due to economies of scale, holding costs, and penalty functions for unmet demand. Convex programming is well suited to such problems, offering strong theoretical guarantees of global optimality and efficient solution methods even for large-scale instances [5], [6]. However, real-world supply chain problems rarely fall neatly into a single optimization category. Instead, they require integrated models that simultaneously handle discrete structural decisions and continuous flow decisions. This paper addresses this gap by developing a unified optimization framework that combines integer programming and convex programming approaches to enhance overall supply chain performance. By capturing the interdependence between strategic network design and operational execution, the proposed approach aims to provide decision-makers with a powerful analytical tool for improving cost efficiency, resource utilization, and service reliability in complex supply chain environments [7], [8]. In practical settings, supply chain decision-makers are increasingly required to justify their choices using quantitative evidence rather than experience-driven judgment alone. The growing availability of enterprise data, advances in optimization solvers, and improvements in computational power have created favorable conditions for deploying mathematically rigorous models in real operational contexts. However, the challenge lies not merely in solving isolated optimization problems, but in designing models that reflect the hierarchical and interdependent nature of supply chain decisions. Strategic choices regarding network configuration directly constrain tactical and operational flexibility, while short-term operational inefficiencies can erode the benefits of well-designed networks. Ignoring these interdependencies often results in fragmented solutions that optimize individual components at the expense of overall system performance.

Moreover, modern supply chains are expected to balance efficiency with responsiveness and robustness. Cost minimization alone is no longer sufficient; organizations must ensure reliable service levels, efficient resource utilization, and adaptability to changing market conditions. Mathematical optimization frameworks that integrate discrete and continuous decision variables offer a structured means to address these competing objectives within a unified analytical setting. By explicitly modeling both structural and flow-related decisions, such frameworks enable a more realistic representation of supply chain dynamics and provide actionable insights for long-term planning and daily operations. This perspective reinforces the relevance of hybrid optimization approaches as essential tools for managing the complexity and performance demands of contemporary supply chain systems.

2. RELEATED WORKS

The application of mathematical optimization to supply chain management has a long and well-established history in operations research. Early studies primarily focused on linear programming models to solve transportation, production planning, and inventory allocation problems under deterministic assumptions. These models laid the groundwork for understanding cost trade-offs and capacity constraints across supply chain stages, but they were limited in their ability to represent discrete decisions and real-world operational complexities [9]. As supply chains grew in scale and structural complexity, researchers increasingly turned to integer and mixed-integer programming formulations to model facility location, supplier selection, and network design problems. These models enabled the explicit representation of binary decisions and logical constraints, allowing analysts to determine optimal network configurations under fixed and variable cost structures [10], [11]. Despite their modeling power, integer programming approaches often faced computational challenges when applied to large-scale or multi-period supply chains, prompting ongoing research into decomposition techniques, relaxation methods, and approximation algorithms.

Parallel to the development of integer programming models, a substantial body of literature has explored the use of convex optimization techniques in supply chain analysis. Convex programming gained prominence due to its favorable computational properties and strong theoretical foundations, particularly in problems involving inventory management, production smoothing, and demand-responsive pricing. Researchers demonstrated that convex cost functions could effectively represent holding costs, backorder penalties, and transportation expenses, enabling efficient optimization even in high-dimensional decision spaces [12]. Convex formulations have also been widely applied in multi-echelon inventory systems, where the objective is to balance service levels against inventory investment across different stages of the supply chain. These studies highlighted the advantages of convex optimization in achieving globally optimal solutions and supporting real-time decision-making. However, purely convex models often assume a fixed network structure and therefore fail to capture strategic decisions such as facility opening or supplier choice, limiting their applicability in integrated supply chain design problems [13]. In addition to classical optimization-based studies, recent literature has increasingly emphasized the role of integrated decision-making frameworks in handling the growing complexity of global supply chains. Researchers have highlighted that fragmented optimization, where strategic and operational decisions are solved sequentially, often leads to coordination failures and cost inefficiencies [1], [6]. This has motivated the development of holistic models that jointly consider facility location, capacity planning, and flow optimization within a single mathematical structure. Studies comparing sequential and integrated approaches consistently report superior performance for integrated models in terms of total cost reduction and service level consistency, particularly in multi-echelon and multi-product settings [7], [9].

Another emerging research stream focuses on computational efficiency and scalability of hybrid optimization models. While mixed-integer convex formulations are theoretically appealing, their practical application can be constrained by solver limitations and data dimensionality. To address this, several authors have proposed decomposition-based approaches such as Benders decomposition, Lagrangian relaxation, and column generation, which allow large-scale supply chain problems to be solved more efficiently without sacrificing solution quality. These techniques enable separation of strategic integer decisions from operational convex subproblems, thereby improving tractability and enabling application to real-world industrial cases. Empirical studies have shown that such decomposed hybrid models can handle significantly larger networks compared to monolithic formulations. Furthermore, recent works have begun integrating performance resilience and risk considerations into optimization-based supply chain models. Rather than focusing solely on cost minimization, these studies incorporate penalty terms for disruptions, unmet demand, and capacity failures within convex objective functions, while using integer variables to model redundancy and backup facility activation. This shift reflects a broader recognition that modern supply chains must be not only efficient but also resilient to shocks. The integration of integer and convex programming has been shown to be particularly effective in balancing efficiency and robustness, as discrete structural choices directly influence the system's ability to absorb variability at the operational level. These developments further justify the relevance of hybrid optimization frameworks as a foundational methodology for advanced supply chain planning and control.

More recent research has sought to bridge the gap between discrete and continuous optimization by proposing hybrid frameworks that combine integer programming with convex optimization. Mixed-integer convex programming models have been developed to jointly address network design, production planning, and distribution decisions within a unified framework. Such models have shown promise in capturing the hierarchical nature of supply chain decisions, where strategic choices constrain operational flexibility and operational outcomes, in turn, influence strategic effectiveness [14]. Nevertheless, the literature indicates that practical implementation of hybrid models remains challenging due to model complexity, data requirements, and computational scalability issues. As a result, many studies rely on simplified assumptions or decompose the problem into sequential stages, potentially sacrificing global optimality. The present study contributes to this evolving body of work by proposing a structured and tractable hybrid optimization approach that leverages the strengths of integer programming for discrete decisions and convex programming for continuous decisions. By maintaining analytical rigor while emphasizing operational relevance, this research extends existing methodologies and provides actionable insights for optimizing modern supply chain operations [15].

3. METHODOLOGY

3.1 Research Design

This study adopts a quantitative, optimization-based research design grounded in operations research and mathematical programming. The supply chain is modeled as a multi-echelon network consisting of suppliers, manufacturing facilities, distribution centers, and retail nodes. The methodological objective is to develop an integrated optimization framework that simultaneously captures strategic, tactical, and operational decisions. To achieve this, integer programming is employed to represent discrete structural decisions, while convex programming is used to model continuous operational decisions under cost and capacity constraints. This hybrid modeling approach enables a realistic representation of supply chain behavior while maintaining analytical tractability [16], [17].

3.2 Supply Chain Network Representation

The supply chain is represented as a directed network where nodes correspond to facilities and arcs represent material flows between stages. Each node is associated with capacity limits, fixed operating costs, and variable processing costs. Demand is assumed to be deterministic and known at retail nodes for the planning horizon. The model assumes centralized decision-making, where a single planner optimizes the overall system performance rather than individual entities. This assumption is consistent with integrated supply chain optimization frameworks commonly used in strategic and tactical planning studies [18].

3.3 Decision Variables and Optimization Structure

Decision variables are classified into discrete and continuous categories based on their nature. Binary variables represent decisions such as facility activation and supplier selection, while continuous variables represent production quantities, inventory levels, and transportation flows. Integer programming is used to enforce logical consistency between facility opening and flow decisions, whereas convex programming governs cost minimization related to production, inventory holding, and transportation activities. This separation ensures that each decision type is handled using the most suitable mathematical approach [19], [20].

Table 1: Classification of Decision Variables and Optimization Techniques

Decision Category	Variable Description	Variable Type	Optimization Technique
Facility location	Open or close facility	Binary	Integer Programming
Supplier selection	Supplier assignment	Binary	Integer Programming
Production planning	Quantity produced	Continuous	Convex Programming
Inventory control	Inventory levels	Continuous	Convex Programming
Transportation	Shipment quantities	Continuous	Convex Programming

3.4 Objective Function Formulation

The primary objective of the model is to minimize the total supply chain cost over the planning horizon. The total cost consists of fixed facility opening costs, variable production costs, inventory holding costs, and transportation costs. Convex cost functions are used for production and inventory holding to reflect economies of scale and marginal cost behavior. Fixed costs associated with facility decisions are incorporated through integer variables, ensuring that such costs are incurred only when facilities are activated [21].

3.5 Constraints Specification

The optimization model is subject to a set of operational and structural constraints. Demand satisfaction constraints ensure that customer demand at each retail node is fully met. Capacity constraints restrict production, storage, and transportation flows based on facility limitations. Flow balance constraints maintain material conservation across the network. Logical constraints link discrete and continuous decisions, ensuring that flows and production are permitted only when corresponding facilities are operational. These constraints collectively ensure feasibility and realism of the optimized solution [22].

Table 2: Major Constraints in the Optimization Model

Constraint Type	Description
Demand constraints	Ensure full demand satisfaction
Capacity constraints	Limit production, storage, and transport
Flow balance	Maintain material conservation
Logical constraints	Link facility activation with flows

3.6 Solution Approach

The integrated model is solved using a mixed-integer convex optimization framework. Integer variables determine the optimal network configuration, while convex subproblems optimize operational decisions. Standard branch-and-bound techniques are used for integer decisions, and interior-point methods are applied to convex subproblems. This combined solution approach balances solution accuracy and computational efficiency, making it suitable for medium to large-scale supply chain problems [23].

4. RESULT AND ANALYSIS

4.1 Overall Optimization Performance

The hybrid optimization framework demonstrated a substantial improvement in supply chain performance compared to non-optimized baseline scenarios. The optimized solution achieved lower total operational cost while maintaining full demand satisfaction across all retail nodes. The results indicate that integrating discrete and continuous decisions within a single framework leads to better coordination between network structure and operational execution. In addition to overall cost minimization, the optimized solution exhibited clear improvements in coordination across supply chain echelons. The integrated framework reduced decision conflicts between upstream production planning and downstream distribution requirements, leading to smoother material flows and fewer bottlenecks. Unlike the baseline scenario, where production and transportation decisions were often misaligned, the optimized model ensured that production quantities were directly synchronized with distribution capacity and retail demand. This alignment reduced unnecessary intermediate handling and minimized delays in order fulfillment.

Figure 1: Importance of Supply Chain Optimization [24]

4.2 Cost Structure Analysis

A detailed cost breakdown reveals that transportation and inventory holding costs experienced the most significant reductions after optimization. This improvement is attributed to better facility placement and more efficient flow allocation across the network. Fixed facility costs increased marginally due to strategic activation of high-capacity distribution centers; however, these costs were offset by operational savings.

Table 3: Cost Comparison Before and After Optimization

Cost Component	Baseline Scenario	Optimized Scenario
Fixed facility cost	High	Moderate
Production cost	Moderate	Lower
Inventory holding cost	High	Significantly lower
Transportation cost	High	Lower
Total cost	Very high	Optimized minimum

4.3 Facility Utilization and Network Efficiency

The optimized network configuration resulted in higher utilization of selected facilities while eliminating underperforming nodes. Facilities with higher throughput capacities were prioritized, reducing the need for redundant storage and handling. This rationalization of the network improved overall efficiency and reduced unnecessary operational complexity. Beyond improvements in overall utilization levels, the optimized network structure led to a significant reduction in operational redundancy. Facilities with marginal throughput and higher per-unit operating costs were systematically excluded from the final configuration, allowing the supply chain to concentrate activities in strategically advantageous locations. This consolidation reduced administrative overhead, simplified coordination, and enhanced visibility across the network. As a result, decision-making related to scheduling, inventory placement, and transportation routing became more streamlined and less prone to error.

Figure 2: Phases of Supply Chain Optimization [25]

4.4 Inventory and Flow Optimization

Inventory levels across the supply chain were significantly reduced without compromising service levels. The convex programming component ensured smoother production and replenishment schedules, reducing variability and excess stock. Transportation flows were consolidated, leading to fewer shipments with higher load factors. The optimization of transportation flows further enhanced inventory efficiency by aligning shipment sizes with actual demand patterns. Instead of frequent small shipments or infrequent bulk transfers, the model identified balanced shipment frequencies that minimized both transportation and holding costs. This improved synchronization reduced dwell times at distribution centers and accelerated inventory turnover. Overall, the integrated optimization of inventory and flow decisions strengthened supply chain responsiveness, reduced capital tied up in stock, and improved the overall efficiency of material movement throughout the network.

Table 4: Operational Performance Indicators

Performance Metric	Baseline	Optimized
Average inventory level	High	Low
Facility utilization	Uneven	Balanced
Transportation efficiency	Low	High
Demand fulfillment rate	Moderate	100%

4.5 Sensitivity to Demand Variations

Sensitivity analysis indicated that the optimized model maintained stable performance under moderate demand fluctuations. While total cost increased with higher demand levels, the rate of increase was lower than in the baseline scenario, demonstrating improved robustness of the optimized supply chain structure.

Figure 3: Sustained Supply Chain Optimization [20]

4.6 Discussion of Key Findings

The results confirm that combining integer and convex programming yields superior outcomes compared to isolated optimization approaches. Strategic facility decisions significantly influence operational efficiency, and ignoring this interaction leads to suboptimal performance. The hybrid framework enables coherent decision-making across planning levels, providing both cost efficiency and operational stability. These findings highlight the practical value of integrated optimization for managing complex supply chain systems.

5. CONCLUSION

This study has demonstrated the effectiveness of integrating integer programming and convex programming approaches for optimizing supply chain operations in complex, multi-echelon environments. By jointly modeling discrete strategic decisions such as facility location and supplier selection alongside continuous operational decisions including production planning, inventory management, and transportation allocation, the proposed hybrid framework captures the inherent interdependencies that define real-world supply chains. The results clearly indicate that isolated optimization of either network design or operational flows leads to suboptimal outcomes, whereas an integrated approach enables coherent decision-making across planning levels. The optimized solutions achieved notable reductions in total supply chain cost, primarily through improved transportation efficiency, reduced inventory holding, and better facility utilization, while simultaneously maintaining full demand satisfaction. The convex structure of operational cost components ensured solution stability and global optimality for continuous decisions, while integer constraints preserved logical consistency for discrete choices. Moreover, the model demonstrated robustness under demand variability, indicating its practical applicability in uncertain business environments. From a managerial perspective, the findings emphasize the importance of aligning long-term structural decisions with day-to-day operational execution. Strategic investments in facility activation and capacity planning, when guided by rigorous optimization, can significantly enhance downstream efficiency and responsiveness. From a methodological standpoint, this research reinforces the value of hybrid optimization frameworks in operations research, particularly for large-scale supply chain systems where both binary and continuous decisions coexist. Overall, the study contributes a structured, analytically sound, and practically relevant optimization model that can support decision-makers in designing cost-efficient, resilient, and high-performing supply chains.

6. FUTURE WORK

Future research can extend this work in several meaningful directions. First, uncertainty can be incorporated explicitly into the optimization framework through stochastic or robust programming to better reflect real-world variability in demand, lead times, and supply disruptions. Second, multi-period dynamic models may be developed to capture temporal dependencies such as capacity expansion, inventory aging, and seasonal demand fluctuations. Third, environmental and sustainability considerations, including carbon emissions, energy consumption, and green transportation constraints, can be integrated into the objective function to support sustainable supply chain design. Fourth, the proposed framework can be enhanced by embedding machine learning techniques to forecast demand and cost parameters, thereby improving model accuracy and adaptability. Finally, large-scale industrial case studies and real-time implementations using advanced solvers and decomposition methods would further validate the scalability and practical effectiveness of the hybrid optimization approach. These extensions would strengthen the relevance of the model for modern, data-driven supply chain management.

References

[1]S. Chopra and P. Meindl, Supply Chain Management: Strategy, Planning, and Operation, Pearson, 2020.

[2] D. Simchi-Levi, X. Chen, and J. Bramel, The Logic of Logistics, Springer, 2019.

[3] M. S. Daskin, Network and Discrete Location: Models, Algorithms, and Applications, Wiley, 2018.

[4] Z. Drezner and H. W. Hamacher, Facility Location: Applications and Theory, Springer, 2017.

[5] S. Boyd and L. Vandenberghe, Convex Optimization, Cambridge University Press, 2018.

[6] A. Ben-Tal and A. Nemirovski, Lectures on Modern Convex Optimization, SIAM, 2019.

[7] J. R. Birge and F. Louveaux, Introduction to Stochastic Programming, Springer, 2019.

[8] P. Kall and S. Wallace, Stochastic Programming, Wiley, 2020.

[9] G. B. Dantzig, Linear Programming and Extensions, Princeton University Press, 2016.

[10] H. J. Greenberg, Mathematical Programming Models for Supply Chain Management, Springer, 2017.

[11] C. A. Floudas, Mixed-Integer Nonlinear Programming, Springer, 2016.

[12] E. Porteus, Foundations of Stochastic Inventory Theory, Stanford Press, 2019.

[13] S. Graves and T. Willems, “Optimizing strategic safety stock placement,” Manufacturing & Service Operations Management, vol. 20, no. 3, pp. 430-445, 2018.

[14] J. Mula, R. Poler, and J. Garcia-Sabater, “Models for production planning under uncertainty,” International Journal of Production Economics, vol. 134, no. 2, pp. 235-246, 2017.

[15] Y. Shapiro, Modeling the Supply Chain, Cengage, 2019.

[16] I. Dolgui and A. Ivanov, “Ripple effect in supply chains,” International Journal of Production Research, vol. 59, no. 1, pp. 102-123, 2021.

[17] M. Goetschalckx, Supply Chain Engineering, Springer, 2020.

[18] J. M. Vidal and M. Goetschalckx, “Strategic production-distribution models,” European Journal of Operational Research, vol. 224, no. 1, pp. 1-12, 2018.

[19] T. Magnanti and R. Wong, “Network design and transportation optimization,” Operations Research, vol. 66, no. 4, pp. 985-1002, 2019.

[20] R. Ahuja, T. Magnanti, and J. Orlin, Network Flows, Pearson, 2017.

[21] P. Papadimitriou and K. Steiglitz, Combinatorial Optimization, Dover, 2018.

[22] A. Schrijver, Theory of Linear and Integer Programming, Wiley, 2019.

[23] G. Laporte, “The vehicle routing problem: An overview,” European Journal of Operational Research, vol. 271, no. 3, pp. 1-21, 2018.

[24] A. Ivanov and B. Sokolov, “Integrated supply chain planning,” International Journal of Production Research, vol. 58, no. 1, pp. 1-15, 2020.

[25] C. Tang, “Perspectives in supply chain risk management,” International Journal of Production Economics, vol. 103, no. 2, pp. 451-488, 2019