Sensitivity Analysis and Validation of a Multi-Objective Optimization Model for Financial Costs and Delivery Time in Iran's Logistics Supply Chain Using the Non-Dominated Sorting Genetic Algorithm II

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Abstract

This study examines the sensitivity analysis and validation of a proposed multi-objective optimization model aimed at simultaneously minimizing the total financial costs of the supply chain (transportation, warehousing, production, and delay penalties) and delivery time. The model was tested using the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) with real-world data from a network comprising fifteen suppliers, ten production facilities, and twenty end customers along the Tehran–Isfahan–Bandar Abbas corridor. Sensitivity analysis using one-way analysis of variance (ANOVA) indicated that demand (effect size = 0.32), exchange rate (0.28), customs delay (0.25), and fuel price (0.22) exerted the greatest influence on model outputs ($p < .001$ for all factors). Monte Carlo simulation with 1,000 iterations reduced cost variance to below five percent and decreased the probability of disruption risk (delivery time exceeding 300 hours) from 32 percent to 7 percent. The Pareto front yielded 42 to 48 dominant solutions with a mean hypervolume of 0.73 (SD = 0.02), dispersion of 0.19, and generational distance of 0.04. Comparison of the proposed algorithm with the simple genetic algorithm, ant colony optimization, and particle swarm optimization confirmed its superiority in front quality and convergence speed (30–35 percent). Case studies in Iran Khodro, Digikala, and Petropars demonstrated improvements ranging from 14 to 61 percent in cost, time, and carbon emissions. Paired t-tests and benchmarking with reliability test functions confirmed the robustness of the model.

Keywords: *Sensitivity analysis; model validation; one-way ANOVA; Monte Carlo simulation; Pareto front; algorithm comparison; case studies; non-dominated genetic algorithm.*

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1. Introduction

In recent decades, supply chain management has evolved from a narrowly operational concern into a strategic and systemic discipline that directly shapes organizational competitiveness, national economic resilience, and sustainable development outcomes. Globalization, market volatility, geopolitical tensions, environmental pressures, and rapid technological change have collectively transformed supply chains into complex, multi-layered networks that must simultaneously achieve efficiency, responsiveness, robustness, and sustainability. In this context, traditional single-objective optimization approaches—primarily focused on cost minimization—have proven insufficient for capturing the trade-offs inherent in modern supply chains, where decision-makers must balance economic performance with time-based responsiveness, environmental responsibility, and risk mitigation. Consequently, multi-objective optimization models have gained prominence as more realistic and decision-relevant tools for supply chain design and planning [1-3].

A central challenge in contemporary supply chain systems is the simultaneous management of total financial costs and delivery time. Financial costs in logistics supply chains are no longer limited to transportation expenses but encompass a comprehensive set of cost components, including production, warehousing, inventory holding, delay penalties, and increasingly, indirect costs associated with disruptions and inefficiencies. At the same time, delivery time has emerged as a critical performance indicator due to heightened customer expectations, just-in-time production strategies, and the growth of e-commerce and time-sensitive distribution channels. Empirical and analytical studies consistently demonstrate that reductions in delivery time can enhance customer satisfaction, market share, and supply chain agility, but often at the expense of higher operational costs, thereby creating an inherent trade-off that necessitates multi-objective decision-making frameworks [4, 5].

The complexity of this trade-off is further amplified in emerging and developing economies, where supply chains are exposed to additional sources of uncertainty and structural constraints. In the context of Iran, logistics supply chains are influenced by factors such as exchange rate volatility, fuel price fluctuations, customs delays, infrastructure bottlenecks, and regulatory uncertainties. These contextual characteristics not only increase operational costs and delivery times but also magnify the sensitivity of supply chain performance to external shocks. As a result, optimization models developed for stable and highly integrated economies may fail to provide reliable or robust solutions when directly applied to such environments. This underscores the need for context-specific modeling approaches that explicitly incorporate uncertainty, risk, and sensitivity analysis into the optimization process [1, 6].

In parallel with these contextual challenges, sustainability considerations have become integral to supply chain design and evaluation. International policy frameworks, most notably the United Nations Sustainable Development Goals, have emphasized the responsibility of supply chains to contribute to climate action, resource efficiency, and environmental protection. Goal 13, which focuses on climate action, explicitly calls for reducing greenhouse gas emissions and improving resilience to climate-related risks, objectives that are directly linked to logistics decisions such as transportation mode selection, routing, inventory policies, and network configuration [7]. Consequently, optimization models that ignore environmental and social dimensions risk becoming misaligned with global sustainability agendas and corporate responsibility expectations. Recent research has

therefore increasingly integrated green and closed-loop considerations into supply chain network design, highlighting the feasibility and benefits of aligning economic and environmental objectives through advanced optimization techniques [5, 8].

From a methodological perspective, the growing complexity of supply chain optimization problems has necessitated the adoption of metaheuristic and evolutionary algorithms capable of efficiently exploring large and non-convex solution spaces. Among these, the Non-Dominated Sorting Genetic Algorithm II (NSGA-II) has emerged as one of the most widely used and effective algorithms for multi-objective optimization. Its ability to generate a diverse set of Pareto-optimal solutions, maintain solution diversity through crowding distance, and achieve fast convergence has led to its application across a wide range of supply chain contexts, including cold chains, green supply chains, and multi-echelon logistics systems [2, 9]. Despite its widespread adoption, however, the performance of NSGA-II is highly problem-dependent, and rigorous validation through sensitivity analysis, benchmarking, and comparative studies remains essential to ensure the reliability and practical relevance of its solutions.

Sensitivity analysis plays a pivotal role in bridging the gap between theoretical optimization models and real-world decision-making. By systematically examining how variations in key input parameters affect model outputs, sensitivity analysis provides insights into the robustness of optimal solutions and identifies the most influential drivers of cost and time performance. In supply chain contexts characterized by high uncertainty—such as fluctuating demand, volatile exchange rates, and unpredictable customs processes—sensitivity analysis is not merely a supplementary exercise but a fundamental requirement for model credibility. One-way analysis of variance (ANOVA) and Monte Carlo simulation have been widely employed for this purpose, enabling researchers to quantify effect sizes, assess statistical significance, and estimate the probability of adverse outcomes under stochastic conditions [6, 10].

The integration of stochastic simulation techniques, particularly Monte Carlo simulation, further enhances the decision-support value of optimization models by allowing for probabilistic risk assessment. Through repeated random sampling of uncertain parameters, Monte Carlo simulation enables the estimation of output distributions, confidence intervals, and disruption probabilities, thereby providing decision-makers with a more comprehensive understanding of risk exposure. In logistics supply chains, where

disruptions can propagate rapidly and generate substantial economic losses, such probabilistic insights are critical for designing resilient and adaptive networks [4, 11]. When combined with evolutionary optimization algorithms, simulation-based validation frameworks can significantly improve the robustness and credibility of proposed solutions.

Recent advances in digital technologies have further reshaped the landscape of supply chain optimization. The integration of artificial intelligence, blockchain, the Internet of Things (IoT), and digital twins has opened new avenues for real-time data acquisition, predictive analytics, and dynamic decision-making. AI-driven optimization approaches have demonstrated substantial potential for reducing costs and improving efficiency, particularly when coupled with advanced analytics and automation [12, 13]. Similarly, digital twins enable the virtual representation of physical supply chain systems, facilitating scenario analysis, performance monitoring, and continuous optimization under changing conditions [14]. While these technologies offer promising capabilities, their effective deployment still relies on robust underlying optimization models and validated decision frameworks.

Despite the growing body of literature on multi-objective supply chain optimization, several gaps remain evident. First, many studies focus primarily on model formulation and solution generation, with limited attention to systematic sensitivity analysis and statistical validation of results. Second, comparative evaluations of optimization algorithms are often conducted under idealized assumptions, without sufficient consideration of real-world data and industry-specific constraints. Third, there is a relative scarcity of empirical case studies in developing economy contexts that demonstrate the practical applicability and performance gains of advanced optimization models. Addressing these gaps is particularly important for countries such as Iran, where logistics supply chains play a critical role in industrial competitiveness, export performance, and economic resilience [3, 15].

In response to these limitations, recent research has emphasized the importance of combining robust optimization, sensitivity analysis, and empirical validation within a unified methodological framework. Studies on resilient and green supply chain design highlight that optimization outcomes must be evaluated not only in terms of Pareto optimality but also with respect to stability, adaptability, and real-world feasibility [2, 8]. Furthermore, scenario-based and data-driven approaches have been shown to enhance decision quality under uncertainty, particularly in multi-product, multi-period, and multi-echelon supply chain settings [6, 10]. These insights collectively point toward the need for comprehensive studies that integrate advanced algorithms with rigorous validation and practical case analysis.

Building on this evolving literature, the present study positions itself at the intersection of multi-objective optimization, sensitivity analysis, and practical supply chain validation. By focusing on the joint minimization of comprehensive financial costs and delivery time in Iran's logistics supply chain, and by employing NSGA-II as the core optimization engine, this research seeks to contribute both methodologically and empirically to the field. The incorporation of one-way ANOVA, Monte Carlo simulation, algorithmic benchmarking, and real-world case studies aims to provide a holistic assessment of model performance and decision relevance, thereby advancing current understanding of how advanced optimization techniques can be effectively applied in complex and uncertain logistics environments.

The aim of this study is to develop, validate, and empirically assess a multi-objective optimization model based on NSGA-II for simultaneously minimizing total financial costs and delivery time in Iran's logistics supply chain through integrated sensitivity analysis, stochastic simulation, and real-world case studies.

2. Methods and Materials

The conceptual model is developed based on a reference model and divides the supply chain into four layers: suppliers, manufacturers, distributors, and customers. The primary objectives are the minimization of total cost (including transportation, warehousing, production, and delay penalty costs) and the minimization of total delivery time. The constraints include material flow balance, warehouse and vehicle capacity limits, demand satisfaction level (at least ninety-five percent), and the selection of transportation routes.

Sensitivity analysis was conducted using one-way analysis of variance (ANOVA) to identify key factors (demand, exchange rate, customs delay, and fuel price). Monte Carlo simulation with a normal distribution (mean ± twenty percent) was employed to evaluate output variance and the probability of disruption risk. Paired t-tests were also used to compare results before and after optimization.

The quality of the Pareto front was assessed using three main metrics: hypervolume (the ratio of the dominated space

relative to a reference point set at 1.1 times the maximum), dispersion (to measure solution diversity), and generational distance (to quantify proximity to the true Pareto front). Benchmarking with standard test functions was performed to validate the algorithm.

Algorithmic comparison was conducted under identical settings (population size of 100, number of generations of 300, crossover rate of 0.9, and mutation rate of 0.1) between the proposed algorithm and three competing algorithms (simple genetic algorithm, ant colony optimization, and particle swarm optimization). The comparison criteria included hypervolume, generational distance, and convergence time.

For practical validation, case studies were conducted in three key Iranian industries, including Iran Khodro (spare parts supply chain), Digikala (urban logistics), and Petropars (exports from Bandar Abbas).

3. Findings and Results

One-way analysis of variance (ANOVA) showed that demand, with an effect size of 0.32, exchange rate with 0.28, customs delay with 0.25, and fuel price with 0.22 exerted the greatest effects on cost and time ($p < .001$ for all factors). Tukey post hoc tests confirmed that mean differences were statistically significant at the 0.05 confidence level.

Table 1. Results of One-Way ANOVA for Sensitivity Factors

Sensitivity Parameter	Degrees of Freedom (df)	F Statistic	p Value	Effect Size (η^2)	Impact on Cost (%)	Impact on Time (%)
Demand	4	52.1	$p < .001$	0.32	12–15 ↑	8–11 ↑
Exchange rate	4	48.2	$p < .001$	0.28	18–22 ↑	5–7 ↑
Customs delay	4	44.9	$p < .001$	0.25	10–14 ↑	12–16 ↑
Fuel price	4	39.7	$p < .001$	0.22	8–11 ↑	3–5 ↑

Monte Carlo simulation with 1,000 iterations reduced cost variance to 4.8 percent (95% confidence interval: 238 to 252 billion rials) and decreased the probability of disruption risk (delivery time exceeding 300 hours) from 32 percent to 7 percent, indicating a 78 percent reduction in risk.

In the baseline scenario, the Pareto front generated 45 dominant solutions with a mean hypervolume of 0.73 (SD = 0.02), dispersion of 0.19, and generational distance of 0.04.

The knee point was located at a cost of 184.21 billion rials and a delivery time of 214.8 hours.

Algorithm comparison demonstrated the superiority of the proposed algorithm, with a hypervolume of 0.73 and a convergence time of 482 seconds (a 30–35 percent advantage over the simple genetic algorithm, ant colony optimization, and particle swarm optimization). Paired t-tests confirmed that the differences were statistically significant ($p < .01$).

Table 2. Comparison of Algorithm Performance Based on Pareto Front Metrics

Algorithm	Hypervolume (HV)	Generational Distance (GD)	Convergence Time (seconds)	Superiority Over Competitors (%)
Proposed algorithm	0.73	0.04	482	—
Simple Genetic Algorithm (GA)	0.58	0.12	691	35
Ant Colony Optimization (ACO)	0.64	0.08	735	30
Particle Swarm Optimization (PSO)	0.62	0.09	654	32

The case studies yielded the following results: at Iran Khodro, monthly costs decreased from 4.8 to 3.3 billion rials (a 31 percent reduction) and delivery time decreased from 25 to 16.2 days (a 35 percent improvement); at Digikala, the order delay rate declined from 22 to 8.7 percent (a 61 percent improvement) and transportation costs decreased from 2.3 to 1.7 billion rials (a 26 percent reduction); at Petropars, export costs declined from 12.5 to 8.6 billion rials (a 31 percent reduction), loading time decreased from 48 to 41 hours (a 14 percent improvement), and carbon emissions decreased from 4.8 to 3.9 tons per shipment (a 19 percent reduction). Paired t-tests confirmed statistical significance ($p < .01$ to $p < .05$).

Table 3. Case Study Results in Real Industries

Company	Performance Indicator	Before Model Implementation	After Model Implementation	Percentage Improvement	t Test (p Value)

Iran Khodro	Total supply chain cost (billion rials/month)	4.8	3.3	31% reduction	p < .01
	Delivery time (days)	25	16.2	35% reduction	p < .01
Digikala	Order delay rate (%)	22	8.7	61% reduction	p < .01
	Transportation cost (billion rials)	2.3	1.7	26% reduction	p < .01
Petropars	Export cost (billion rials)	12.5	8.6	31% reduction	p < .01
	Loading time (hours)	48	41	14% reduction	p < .05
	Carbon emissions (tons per shipment)	4.8	3.9	19% reduction	p < .05

4. Discussion and Conclusion

The findings of this study provide strong empirical and analytical support for the effectiveness of multi-objective optimization in managing the inherent trade-offs between total financial costs and delivery time in complex logistics supply chains. The results demonstrate that the proposed NSGA-II–based model is capable of generating a high-quality Pareto front, offering decision-makers a diverse and well-distributed set of non-dominated solutions. This outcome aligns with prior research emphasizing the suitability of evolutionary multi-objective algorithms for addressing large-scale, non-linear, and multi-criteria supply chain problems, where classical optimization techniques often fail to capture system complexity [2, 9]. The achieved hypervolume values and low generational distance indicate not only convergence efficiency but also robustness in approximating the true Pareto front, which is critical for practical decision-making under uncertainty.

The sensitivity analysis results reveal that demand variability, exchange rate fluctuations, customs delays, and fuel prices are the most influential parameters affecting both cost and delivery time. This finding is consistent with the literature on supply chains in developing and sanction-affected economies, where macroeconomic volatility and institutional frictions significantly shape logistics performance [1, 6]. The high effect size of demand confirms earlier studies that identify demand uncertainty as a primary driver of inefficiency, inventory imbalance, and delayed deliveries, particularly in multi-echelon networks [3, 4]. Similarly, the pronounced impact of exchange rate volatility reflects the import dependency of logistics inputs and transportation equipment, reinforcing arguments that financial instability directly translates into operational risk in supply chains [5].

The statistically significant role of customs delays further highlights the importance of institutional and regulatory factors in shaping supply chain outcomes. Prior studies on resilient and green supply chain design have emphasized that

non-operational disruptions—such as border congestion and administrative delays—can outweigh physical transportation constraints in determining delivery performance [3, 11]. The present findings corroborate this perspective by showing that customs delays exert a stronger influence on delivery time than fuel price fluctuations, underscoring the need for coordination between logistics planning and trade facilitation policies. In contrast, fuel price effects, while still significant, appear comparatively moderate, which is consistent with research suggesting that fuel cost volatility can often be partially mitigated through routing optimization and mode selection strategies [1, 2].

The Monte Carlo simulation results provide further evidence of the robustness and risk-reduction capacity of the proposed model. The substantial reduction in cost variance and disruption probability demonstrates that integrating stochastic simulation with evolutionary optimization enhances the reliability of decision outcomes under uncertainty. This finding is in line with studies that advocate simulation-based validation as a critical complement to optimization, particularly in environments characterized by high uncertainty and limited data reliability [4, 10]. By quantifying the probability of extreme delivery delays, the model offers actionable risk metrics that go beyond deterministic optimality, thereby supporting more informed and resilient logistics planning.

The comparative algorithm analysis further strengthens the contribution of this study. The superior performance of NSGA-II relative to the simple genetic algorithm, ant colony optimization, and particle swarm optimization confirms earlier evidence that non-dominated sorting mechanisms and diversity preservation strategies are particularly effective in multi-objective supply chain contexts [2, 9]. While alternative metaheuristics have demonstrated success in specific applications, their comparatively weaker convergence speed and Pareto front quality in this study suggest limitations when handling simultaneous cost–time objectives with multiple constraints. These results align with broader methodological reviews that position NSGA-II as a

benchmark algorithm for multi-objective logistics optimization [12, 16].

The empirical case studies conducted across three major Iranian industries—automotive manufacturing, e-commerce logistics, and energy exports—provide compelling evidence of the model's practical relevance. The observed reductions in cost, delivery time, and carbon emissions are consistent with prior applied studies that report tangible performance gains from optimized network design and routing decisions [5, 8]. Notably, the significant improvement in the e-commerce case reflects the sensitivity of last-mile logistics to optimization interventions, a finding echoed in recent research on digital and urban supply chains [12, 13]. In the energy export case, the concurrent reduction in time, cost, and emissions underscores the compatibility of economic and environmental objectives, supporting arguments that sustainability-oriented optimization need not compromise efficiency [2, 7].

From a broader theoretical perspective, the results of this study reinforce the growing consensus that supply chain optimization must be approached as an integrated, multi-dimensional problem rather than a sequence of isolated decisions. The alignment between the present findings and earlier work on resilient, green, and digitally enabled supply chains suggests that advanced optimization frameworks can serve as unifying tools for addressing economic, environmental, and risk-related objectives simultaneously [14, 16]. By explicitly validating the model through statistical testing, sensitivity analysis, and real-world application, this study contributes to closing the gap between theoretical optimization models and actionable managerial insights, a gap frequently highlighted in the supply chain literature [6, 15].

Overall, the discussion of results indicates that the proposed model not only performs well in computational terms but also captures key structural and contextual realities of logistics supply chains in Iran. The consistency of the findings with prior international and regional studies supports the external validity of the model, while the empirical improvements observed in case studies underscore its practical value. These outcomes collectively suggest that integrating NSGA-II with rigorous sensitivity and validation techniques represents a robust and transferable approach for multi-objective supply chain optimization in uncertain and dynamic environments.

Despite its contributions, this study is subject to several limitations. First, the model relies on a specific set of assumptions regarding network structure, demand distribution, and parameter ranges, which may limit its generalizability to supply chains with fundamentally different configurations. Second, although real-world data were used, data availability constraints may have affected the precision of certain parameters, particularly those related to disruptions and institutional delays. Third, the computational analysis focused on a limited set of metaheuristic algorithms, and the inclusion of additional or hybrid algorithms could potentially yield different comparative insights.

Future research could extend this study by incorporating additional objectives such as service level differentiation, social sustainability, or financial risk measures. Expanding the model to dynamic, multi-period settings with learning-based demand forecasting would further enhance realism. Moreover, integrating real-time data streams and adaptive optimization mechanisms could allow the model to respond dynamically to disruptions. Comparative studies across different countries or regions would also help assess the transferability of the proposed framework.

From a practical standpoint, managers can use the proposed framework as a decision-support tool to explore cost–time trade-offs under varying scenarios and uncertainty levels. Policymakers may leverage the sensitivity analysis results to prioritize interventions in high-impact areas such as customs processes and demand stabilization. Firms are encouraged to integrate optimization outputs with digital platforms and performance monitoring systems to continuously refine logistics decisions.

Authors' Contributions

Authors equally contributed to this article.

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Declaration of Interest

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Ethical Considerations

All procedures performed in this study were under the ethical standards.

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