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An Integrated Multi-Objective Mathematical Model for Optimizing the Open-Loop Supply Chain in the Mazandaran Wood and Paper Industry

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Abstract

The wood and paper industry are considered one of the key and strategic industries in the country's economy. Mazandaran, as one of the important provinces in the production and supply of raw materials for this industry, plays a significant role in meeting domestic and export needs. However, this industry faces numerous challenges, including sustainable supply of resources, cost management, maintaining product quality, and compliance with environmental requirements. In this regard, the use of mathematical models can help identify and solve complex problems that exist in this chain. The main goal of this model is to simultaneously optimize several objectives in the open supply chain of the Mazandaran wood and paper industry. These objectives include reducing costs, improving the importance of distributors, and environmental impacts. In this regard, supply chain optimization is proposed as an effective solution to increase efficiency and reduce costs. This research has examined optimizing the open-loop supply chain in the Mazandaran wood and paper industry using an integrated multi-objective mathematical model. Given the specific challenges of this industry, including the supply of sustainable raw materials and the need to reduce costs, this model has been able to simultaneously pay attention to various criteria, including price, environmental sustainability, and the importance of suppliers. To solve the model, a heuristic method based on AUGMECON2 is used to determine Pareto solutions. The results of this research show that by using advanced optimization methods, appropriate choices can be made in terms of vehicles, and transport routes, and the volume of products moved between chain components and supply chain performance can be improved. In addition, this model can serve as an effective decision-making tool for managers of the wood and paper industry in Mazandaran and contribute to the sustainable development of this industry. The model allows managers to make better decisions and improve overall supply chain performance by using real-world data and simulating different scenarios. Ultimately, this model can contribute to sustainable development in the wood and paper industry and increase its competitiveness in domestic and international markets.

Keywords: Supply chain, open loop, sustainability, environment, wood and paper

Paper Type: Original Research

1. Introduction

In modern times, organizational and corporate leaders have experienced significant transformations in commerce and industry. Key drivers of this evolution include trade globalization, market expansion, technological advancements, increased consumer access to product details worldwide, and shifts in business dynamics (Ghasemi et al., 2025). A supply chain encompasses the entire network of distribution channels and entities—such as suppliers, producers, warehouses, and retailers—that facilitate the movement of raw materials to finished goods, ultimately fulfilling consumer demands (Rahmanzadeh et al., 2022). Contemporary supply chains function as interconnected systems of products, services, and associated processes (Yan et al., 2022). Increasingly, these systems operate as structured, cyclical frameworks that manage both forward and reverse flows (Stekelorum et al., 2021). This collaborative network, known as a closed-loop supply chain, emphasizes sustainability and efficiency (Iyigun, 2022). The strategic value of these systems is widely recognized. An optimized network design can significantly enhance profitability for producers while delivering benefits to consumers through improved service and reliability (Al-Matarneh et al., 2022). As a long-term strategic choice, supply chain design critically influences operational effectiveness and competitive edge (Hassan et al., 2021). Supply chain network design shapes both immediate and long-term operational choices. Effective supply chain management involves strategic

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planning, execution, and oversight of all activities from sourcing to end-user delivery. However, supply chains encounter multiple challenges due to their pivotal role in business success. A major obstacle is creating an integrated model that addresses pricing, logistics, data flow, and market strategies. With the rise of global trade and heightened competition, there is a growing demand for adaptable, customer-responsive supply chain solutions (Iraj et al., 2024). The open-loop supply chain model prioritizes cooperation, transparency, and knowledge exchange among its participants. By working together, members share data, expertise, and resources, fostering enhanced efficiency and cost reduction. A defining characteristic of this model is transparency (Berlin et al., 2022), which strengthens trust and minimizes operational errors. Greater integration among members leads to better coordination in decision-making, boosting service quality and responsiveness. Additionally, open-loop systems offer adaptability to shifting market demands and external conditions, improving resilience and sustainability. The free flow of ideas and innovations within the network also fosters a competitive edge (Padoulah et al., 2022). Ultimately, organizations leveraging this approach benefit from improved collaboration, cost savings, and higher product and service standards. Selecting the right suppliers is critical for maintaining a sustainable and high-performing supply chain. Key considerations include (Asadi & Abolghasemian, 2018):

- Quality and Reliability: Suppliers must meet strict quality, safety, and sustainability benchmarks (Chen, 2024).
- Risk Mitigation: Over-reliance on a single supplier poses risks; diversifying sources enhances stability.
- Financial Stability: Suppliers should have robust financial health to prevent disruptions.
- Environmental Responsibility: Eco-friendly practices contribute to long-term sustainability.

A well-chosen supplier enhances supply chain efficiency while ensuring resource availability and sustainability (Jahangiri et al., 2023).

According above mentioned this study aims to develop a multi-objective mathematical model for sustainable supplier selection in an open-loop supply chain, specifically for the Mazandaran wood and paper industry. The model seeks to:

- Optimize performance and cost efficiency
- Enhance product quality and supply chain flexibility
- Streamline procurement, production, and distribution processes
- Improve sustainability and reliability while minimizing sourcing risks

By implementing this model, companies in the industry can achieve greater operational efficiency, sustainability, and overall productivity.

Rest of paper organized as: in section 2 presented literature review. In section 3 presented research method. In section 4 presented findings and finally in section 5 prepared overall conclusion and suggestion for further study.

2. Literature Review

Hejazi and Khorshidvand (2024) presented a robust optimization approach to overcome uncertainty in the closed loop supply chain. As a contribution that targets growing the chain's market, products are supplied with specific modules to meet customer demands and create product families. The proposed model is developed under mixed-integer linear programming (MILP). The multi-objective model is converted to a single-objective model through the ε-constraint method and is solved using the GAMS software package. Xia et al. (2024) developed a multi-objective mixed integer nonlinear programming model to manage uncertainty in reverse logistics design, introducing a genetic algorithm for facility selection and recycling volume distribution, validated through a case study on end-of-life vehicles in Changchun, China. Izadian et al. (2024) studied a multi-level, multi-product, and multi-period closed-loop supply chain with environmental considerations, presenting a bi-objective mixed integer linear programming model aimed at minimizing costs and maximizing supplier reliability. They introduced a novel method for modeling supplier availability, accounting for catastrophic failures, and proposed a two-stage scenario-based stochastic programming approach to address uncertainties in demand and CO_2 emissions. Daryanian et al. (2023) created a fuzzy robust stochastic model to tackle logistics challenges in pharmaceuticals, focusing on stability and flexibility through multi-objective programming. Their model identifies optimal locations for field hospitals and routes for transporting pharmaceutical products, validated through a case study in Iran. Heidari et al. (2023) proposed a bi-objective mathematical programming model for a two-level closed-open location routing problem, aiming to minimize costs and CO_2 emissions while optimizing routes, vehicle numbers, and facility locations, using meta-heuristic algorithms to manage complexity. Rajak et al. (2022) formulated a mathematical model to transform a traditional linear supply chain into a closed-loop system in India, integrating remanufacturing with reverse logistics for sustainability. They used a multi-objective mixed integer linear programming approach to optimize production, recycling, repair, and disposal, confirmed by sensitivity analysis. Khorshidvand et al. (2021) proposed a new hybrid method, in which supply chain coordination decisions and closed loop supply chain network design objectives are simultaneously involved. First, this approach makes price, greenness, and advertisement decisions, and then it aims at maximizing profit and minimizing CO2 emission. A new nonlinear programming (NLP) model is developed based on the sensitivity of the return rate to green quality and the customers' maximum tolerance, while the demands are uncertain. In order to overcome the uncertain demands, a robust optimization (RO) model is used. Soleimani et al. (2021) explored closed-loop supply chain design, focusing on cost and sustainability under demand uncertainty, applying the epsilon constraint method and robust optimization for effective green supply chain solutions. Khorshidvand et al. (2021) presented a two-stage approach to model and solve a sustainable closed loop supply chain, taking into account pricing, green quality, and advertising. In the first stage, optimal decisions on pricing, greening, and advertising are made, while in the second stage, a fuzzy multi-objective Mixed Integer Linear Programming (MILP) model is used to maximize the total profit, reduce CO2 emissions, and improve social impacts. Suitable solution methods are introduced according to the scale of the problem. For small-scale instances, an augmented ϵ-constraint method is used to solve the problem. For large-scale instances, approximations are required, and a Lagragian relaxation algorithm solves the problem in polynomial time. Khorshidvand et al., (2021) addressed a novel two-stage model for a Sustainable Closed-Loop Supply Chain (SCLSC). This model, as a contribution, provides a balance among economic aims, environmental concerns, and social responsibilities based on price, green quality, and advertising level. Çalık et al. (2020) aimed to design a multilayer, multi-period, and multi-objective open-loop supply chain network, focusing on reducing total and environmental costs while maximizing supplier importance. They developed a fuzzy approach to assess supplier performance based on sustainable quality criteria and validated their model with a numerical example. Guo et al. (2018) addressed a routing-inventory-location problem in a closed-loop supply chain, formulating it as a nonlinear integer programming model and introducing a heuristic approach that combined simulated refrigeration with an adaptive genetic algorithm for optimization. Kannan (2018) created a decision support system for sustainable supplier selection in the Indian textile industry, emphasizing social concerns over environmental issues in supplier rankings. According to the studies mentioned above, each of them is classified in Table 1 according to their purpose and nature.

Table 1. Literature review categorization

Author's name	Year	Chain type		Objective Function		TIME FRAME		Logic		Methodology
		Open	Close	Single-objective	Multi-objective	Single.	Multiple	Exact	Non-deterministic.	
Xia et al.	2024		*	-	*	*	-	*	-	Meta-heuristic
Izadian et al	2024		*	-	*	-	*	*	-	Meta-heuristic
Daryanian et al	2023		*	*	-	-	*	*	-	heuristic
Heidari et al	2023		*	*	-	*	-	*	-	heuristic
Rajak et al.	2022		*	-	*	*	-	*	-	Exact and meta-heuristic
Soleimani et al.	2022		*	*	-	*	-	*	-	heuristic
Çalık et al.	2020	*		*	-	*	-	-	*	Benders analysis
Guo et al.	2018		*	-	*	*	-	-	-	-
Kannan	2018		*	-	*	*	-	-	-	heuristic
This research	2025	*	-	-	*	-	*	*	-	Epsilon constraint

Despite significant advances in supply chain modeling and the consideration of sustainability in supplier selection, there are still significant gaps in the integration of fuzzy and multi-objective methods in the context of open-loop supply chains. Especially in the Mazandaran wood and paper industry, there is a need for an integrated model that can simultaneously address different sustainability criteria, cost, quality, and delivery time. Also, the lack of accurate and reliable data on local suppliers and the specific challenges of this industry, especially in the field of environmental and social impacts, hinders the development of efficient optimization models. Therefore, research in this field can help identify and fill these gaps and lead to improved decision-making in the selection of sustainable suppliers in the Mazandaran wood and paper industry.

3. Research Methodology

The open-loop supply chain model examined in this research is illustrated in Figure 1. The forward logistics network includes four tiers: Suppliers (i), Manufacturers (j), Distributors (k), and end Consumers (l). On the other hand, the reverse logistics system comprises five stages: Collection Hubs (m), Recycling Facilities (r), Remanufacturing Plants (q), Secondary Markets (s), and Waste Disposal. In the forward flow, suppliers provide raw materials periodically, which manufacturers then transform into final goods. These products are distributed to consumers via logistics centers to fulfill steady demand. However, the product lifecycle continues after delivery. In the reverse flow, consumers return used items at a specified rate after usage. These products are gathered at collection hubs, where they undergo inspection and are sorted for recycling, refurbishing, or disposal. Refurbished items in good condition may be resold at lower prices in secondary markets. The overall framework of this open-loop supply chain is depicted in Figure 1.

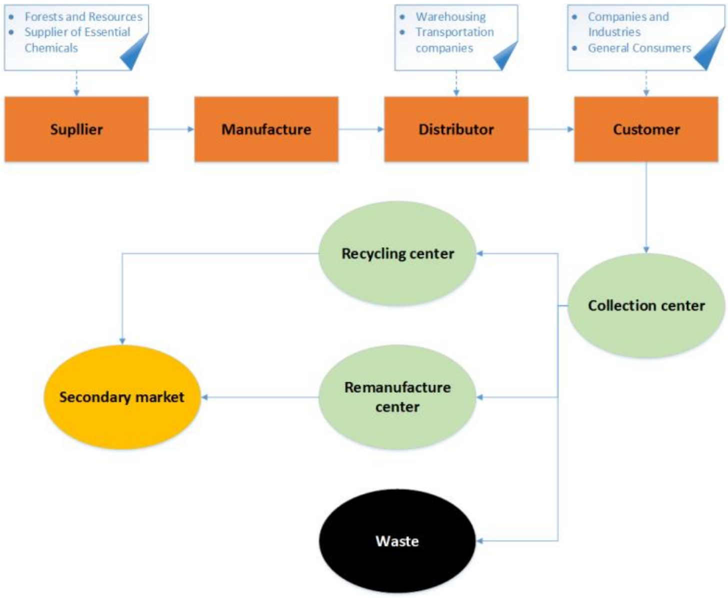

Figure 1. Supply chain structure

3.1 Mathematical modeling

This research examines an open-loop supply chain structured as a nine-tier network: suppliers, production plants, distribution hubs, end-users, collection points, recycling facilities, remanufacturing units, secondary markets, and waste disposal sites. The following section defines the notation, including sets, parameters, and decision variables used in the model.

Sets:

i set of suppliers $i = 1, \dots, I$

j set of manufactures $j = 1, \dots, J$

k set of distributors $k = 1, \dots, K$

l set of customers $l = 1, \dots, L$

m collection centers $m = 1, \dots, M$

r set of recycling center $r = 1, \dots, R$

q set of remanufacturing center $q = 1, \dots, Q$

s set of secondary market $s = 1, \dots, S$

v set of vehicle $v = 1, \dots, V$

t set of time frame $t = 1, \dots, T$

Parameters:

$samt_i; Um_j; top_{im}; grm_r; yum_q;\ dc$: Amount of purchases from suppliers, amount of production, and amount of collection, recycling, remanufacturing, and disposal cost (currency per ton)

$tasgr_r; tasyu_q$: Unit cost savings in recycling and remanufacturing facilities (unit of money per ton)

smf_τ: Fixed cost of facilities (Monetary unit)

c_{co2}: Cost of CO2 emission unit (monetary unit per gram)

$\pi; \alpha; \beta; \theta; \lambda$: Percentage of products collected by centers (percentage)

c_v: Cost of transporting a unit by vehicle v (monetary unit per ton-kilometer)

u_v: Maximum vehicle capacity v (tons)

cet_v: CO2 emissions from producing one ton of product in factory j (grams per ton)
w_i: Weighted importance level of supplier i for the production of products.
cep_j: CO2 emissions from producing one ton of product in factory j (grams per ton).
tal_{lt}: Demand of customer l in period t (tons)
$cap_{\vartheta t}$: Capacity of facilities ϑ in period t $\vartheta \in \{i,j,k,l,m,r,q,s\}$ (tons).
$d_{\mu\sigma}$: Distance of origin μ to destination σ $\mu, \sigma \in \{i,j,k,l,m,r,q,s\}$ (Kilometers).
Variables:

The variables of this research are of two types: continuous and binary. These variables are:

X_{ijvt}; Y_{jkvt}; Z_{klvt}; U_{lmvt}; B_{mrvt}; C_{mqvt}; D_{mvt}; F_{rsvt}; G_{qsvt}: Number of products between pairs of nodes by vehicle v in period t.

XX_{ijvt}; YY_{jkvt}; ZZ_{klvt}; UU_{lmvt}; BB_{mrvt}; CC_{mqvt}; DD_{mvt}; FF_{rsvt}; GG_{qsvt}: It is equal to one if the products between the pair of nodes are transported by the vehicle at time t, otherwise it is zero.

$INTX_{ijvt}$; $INTY_{jkvt}$; $INTZ_{klvt}$; $INTU_{lmvt}$; $INTB_{mrvt}$; $INTC_{mqvt}$; $INTD_{mvt}$; $INTF_{rsvt}$; $INTG_{qsvt}$: The number of paths between pairs of nodes by a vehicle in a time period$t$.

OP_j; OC_m; $Oger_r$; Oyu_q: If the facility is used within the period, it is equal to one, otherwise it is zero.

Objective function

Based on these factors, a deterministic linear programming model has been formulated to mathematically represent the problem, as expressed in the following equations.

$$A = \sum_{i}^{I}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} d_{ij}X_{ijvt} + \sum_{k}^{K}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} d_{jk}Y_{jkvt} + \sum_{k}^{K}\sum_{l}^{L}\sum_{v}^{V}\sum_{t}^{T} d_{kl}Z_{klvt} + \sum_{l}^{L}\sum_{m}^{M}\sum_{v}^{V}\sum_{t}^{T} d_{lm}U_{lmvt} + \sum_{m}^{M}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} d_{mr}B_{mrvt} + \sum_{m}^{M}\sum_{q}^{Q}\sum_{v}^{V}\sum_{t}^{T} d_{mq}C_{mqvt} + \sum_{r}^{R}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} d_{rs}F_{rsvt} + \sum_{q}^{Q}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} d_{qs}G_{qsvt} \quad (1)$$

$$B = \sum_{i}^{I}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} samt_i X_{ijvt} + \sum_{k}^{K}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} um_j Y_{jkvt} + \sum_{l}^{L}\sum_{m}^{M}\sum_{v}^{V}\sum_{t}^{T} top_{lm}U_{lmvt} + \sum_{m}^{M}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} gr_{mr}B_{mrvt} + \sum_{m}^{M}\sum_{q}^{Q}\sum_{v}^{V}\sum_{t}^{T} yum_{mq}C_{mqvt} + \sum_{r}^{R}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} dc.D_{mvt} - \sum_{r}^{R}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} tasgr_r.G_{qsvt} \quad (2)$$

$$C = \sum_{j}^{J} smf_j.OP_j + \sum_{m}^{M} smto_m.OC_m + \sum_{r}^{R} smgr_r.OGER_r + \sum_{q}^{Q} smu_q.OYU_q \quad (3)$$

The first objective function has three components, shown in Equations 1 to 3. The cost of transportation between facilities is shown in the first component. The costs of purchasing, producing, collecting, disposing of, and saving the cost of remanufactured products are shown in the component. The fixed cost of establishing the facility is shown in the third component. Therefore; the first objective function of the problem is considered as$Min\ z_1 = A + B + C$. This function considers the economic aspect of sustainability. The second objective function in equation (4) minimizes the environmental impact of the open-loop supply chain. The costs of CO2 emissions generated from transportation and manufacturing are calculated accordingly.

$$\min z_2 = C_{co2}[cet_v.\sum_{i}^{I}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} d_{ij}X_{ijvt}$$
$$+\sum_{k}^{K}\sum_{j}^{J}\sum_{v}^{V}\sum_{t}^{T} d_{jk}Y_{jkvt}$$
$$+\sum_{k}^{K}\sum_{l}^{L}\sum_{v}^{V}\sum_{t}^{T} d_{kl}Z_{klvt} + \sum_{l}^{L}\sum_{m}^{M}\sum_{v}^{V}\sum_{t}^{T} d_{lm}U_{lmvt} + \sum_{m}^{M}\sum_{r}^{R}\sum_{v}^{V}\sum_{t}^{T} d_{mr}B_{mrvt}$$
$$+\sum_{m}^{M}\sum_{q}^{Q}\sum_{v}^{V}\sum_{t}^{T} d_{mq}C_{mqvt} + \sum_{r}^{R}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} d_{rs}F_{rsvt} + \sum_{q}^{Q}\sum_{s}^{S}\sum_{v}^{V}\sum_{t}^{T} d_{qs}G_{qsvt}$$
$$+\sum_{j}^{J}\sum_{k}^{K}\sum_{v}^{V}\sum_{t}^{T} cep_jY_{jkvt}$$

The third objective function is shown in equation (5). The maximum level of importance of suppliers is ensured through it.

$$\min z_3 = \sum_i^I \sum_j^J \sum_v^V \sum_t^T w_i X_{ijvt} \quad (5)$$

Constraints:

$$\sum_l^L \sum_v^V U_{lmvt} \le Kapto_{mt}.OC_m \quad \forall m,t \quad (6)$$

$$\sum_m^M \sum_v^V B_{mrvt} \le Capgr_{rt}.OGR_r \quad \forall r,t \quad (7)$$

$$\sum_m^M \sum_v^V C_{mqvt} \le Capyu_{qt}.OYU_q \quad \forall q,t \quad (8)$$

$$\sum_m^M \sum_v^V C_{mqrt} \le Capyu_{qt}.OYU_q \quad \forall q,t \quad (9)$$

$$\sum_k^M \sum_v^V Z_{klvt} \le Tal_{lt} \quad \forall l,t \quad (10)$$

$$\sum_i^I \sum_v^V X_{ijvt} - \sum_k^K \sum_v^V Y_{jkvt} = 0 \quad \forall j,t \quad (11)$$

$$\sum_j^J \sum_v^V Y_{jkvt} - \sum_l^L \sum_v^V Z_{klvt} = 0 \quad \forall k,t \quad (12)$$

$$\beta \sum_l^L \sum_v^V U_{lmvt} - \sum_r^R B_{mrvt} = 0 \quad \forall m,t \quad (13)$$

$$\theta \sum_l^L \sum_v^V U_{lmvt} - \sum_q^Q \sum_v^V C_{mqvt} = 0 \quad \forall m,t \quad (14)$$

$$\lambda \sum_l^L \sum_v^V U_{lmvt} - \sum_v^V D_{mvt} = 0 \quad \forall m,t \quad (15)$$

$$\sum_m^M \sum_v^V B_{mrvt} - \sum_s^S \sum_v^V F_{rsvt} = 0 \quad \forall r,t \quad (16)$$

$$\sum_m^M \sum_v^V C_{mqvt} - \sum_s^S \sum_v^V G_{qsvt} = 0 \quad \forall q,t \quad (17)$$

Constraints (6) to (9) are capacity constraints on the facility, which require that the total quantity of products shipped from the facility to other facilities must be equal to or less than the facility capacity in each period. Constraint (10) guarantees customer demand. Constraints (11) to (17) are equilibrium equations for the facility.

3.2 Solution approach

This study employs AUGMECON2, an enhanced constraint transformation technique, to address a multi-objective optimization problem in loop modeling. The algorithm is executed within GAMS using its native programming language. Table 2 outlines the notation used in this approach. AUGMECON2 treats one objective function as the primary optimization target while converting the remaining objectives into constraints with specified upper bounds. Compared to conventional methods, this technique offers notable computational efficiency, particularly for problems involving numerous integer variables or non-convex formulations. The algorithm is particularly effective for multi-objective integer programming problems with finite, enumerable Pareto optimal solutions. By fine-tuning parameters and avoiding suboptimal solutions, it ensures the generation of a high-quality Pareto frontier. Additionally, built-in mechanisms in AUGMECON2 enhance optimization speed while maintaining precision in identifying optimal solutions.

Table 2. Signature proposed solution approach

Parameters	Description
s_k	The lag variable (surplus) related to the $k-th$ objective function of the problem
r_k	Range of changes of the $k-th$ objective function of the problem
$step_k$	Step of changes of the $k-th$ objective function of the problem
LB_k	The lower bound of the $k-th$ objective function of the problem
n_p	Number of Pareto optimal solutions

The AUGMECON2 method consists of the following steps:

Initial Phase:

The optimization process begins by designating one objective as the primary function to maximize, while converting remaining objectives ($k = 2,3,\dots p$) into constraint conditions. Subsequently, a payoff matrix is generated through individual optimization of each objective function. The difference between maximum and minimum achievable values for each objective defines its performance spectrum or operational range.

Implementation Process:

The procedure continues by discretizing the $k-th$ objective function into qk uniform segments. This discretization determines the total computational iterations needed, calculated as$\prod_{k=2}^{p}(q_k+1)$. Subsequently, the algorithm systematically adjusts the constraint bound for the k-th objective through parametric variation. For each epsilon increment, the modified constraint formulation is solved iteratively. This cyclic process continues until the entire Pareto frontier is successfully generated.

$$maximize \quad Z_j(x) + eps * \sum_{k\neq j} \frac{s_k}{r_k} \tag{18}$$

$s.t.$

$$Z_k(x) + s_k = \varepsilon_k, \quad \forall k \neq j \tag{19}$$

$$x \in X, \quad s_k \in \mathbb{R}^+ \tag{20}$$

In the above equation, eps is a tuning parameter in the range [10−6, 10−3]. The AUGMECON2 algorithm uses a lexicographic optimization method to find Pareto optimal solutions. Based on the logic of the AUGMECON2 algorithm, the modified objective function for solving the multi-objective optimization model is defined as follows:

$$maximize \quad Z_1(x) + eps * (\frac{s_2}{r_2} + 10^{-1} * \frac{s_3}{r_3} + \dots + 10^{-(p-2)} * \frac{s_p}{r_p}) \tag{21}$$

The search step value for the $k-th$ objective function is defined as $step_k = \frac{r_k}{q_k}$. Accordingly, the right-hand side value for the $k-th$ objective function in the $i-th$ step of the algorithm is calculated as Equation 22.

$$\varepsilon_{kt} = LB_k + t * step_k \tag{22}$$

4. Findings

Using the predefined parameters from Table 3, we developed a scaled-down version of the problem to evaluate parameter control mechanisms. The model was coded and executed in GAMS software, utilizing the dataset values specified in Table 3. Through this implementation, we demonstrate the problem's feasibility by deriving a valid solution set from the model outputs.

Table 3. Sets defined for the problem in small dimensions

Sets	Value
Set of suppliers	$i_1; i_2$
Set of manufacturers	j_1
Periods	$t_1; t_2; t_3$
Set of distributors	$k_1; k_2$
Customers	$l_1; l_2; l_3$
Set of collection centers	l_1

Firstly, to assess the validity of a mathematical model, it is necessary and essential to examine two conditions during its execution on a random sample, as suggested by Abolghasemian et al. (2024). Firstly, the proposed model must be feasible, and secondly, it must be bounded. Under these conditions, a feasible solution can be obtained. If such a solution is derived, the developed model possesses the requisite validity, allowing its use in executing the main instances. The results for feasibility, bounded ness, and the objective function value are provided in Table 3. The value of the weighted aggregate objective function is calculated based on the weighted sum method for the problem, and the results are reported accordingly.

Table 4. Results of the Mathematical Model Solution

Model's status	Feasible zone	Best solution	Model execution time
Feasible	Bounded	0.985221674877	6 seconds

Based on the results obtained and presented in Table 4, the proposed mathematical model possesses the necessary validity. Then, given the size of the above-mentioned sets, the allocation of vehicles to each of the production, supply, distribution, customers, and collection centers in each time period is shown. According to the results obtained, we can identify the activity of the vehicle in each of the considered centers.

Table 5. Vehicle allocation per period

XX_{ij}	j_1			k_1			k_2			M_1			L_1			L_2			L_3		
	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3
i_1	1.00	0.00	1.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00	–	–	–	–	–	–	–	–	–
i_2	0.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	1.00	0.00	1.00	1.00	–	–	–	–	–	–	–	–	–
YY_{jk}																					
j_1	–	–	–	1.00	0.00	1.00	0.00	1.00	1.00	–	–	–	–	–	–	–	–	–	–	–	–
$ZZ_{kl}; UU_{lm}$																					
k_1	–	–	–	–	–	–	–	–	–	–	–	–	1.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00
k_2	–	–	–	–	–	–	–	–	–	–	–	–	0.00	1.00	0.00	1.00	0.00	1.00	0.00	0.00	0.00
L_1	–	–	–	–	–	–	–	–	–	1.00	0.00	1.00	–	–	–	–	–	–	–	–	–
L_2	–	–	–	–	–	–	–	–	–	0.00	1.00	0.00	–	–	–	–	–	–	–	–	–
L_3	–	–	–	–	–	–	–	–	–	1.00	1.00	0.00	–	–	–	–	–	–	–	–	–

Table 6 shows whether the collection facilities are active or inactive in each period.

Table 6. Facility status in each period

$OC_m; OP_j$	t_1	t_2	t_3
m_1	1.00	0.00	1.00
j_1	1.00	0.00	0.00

Finally, in Table 7, the volume of products moved in the considered open-loop network is shown.

4.1 Sensitivity analysis

In Figures 2 to 4, the non-dominant points obtained from the AUGMECON2 method for the multi-objective problem considered for a 10, 20, and 30 percent increase in the demand value are shown. With respect to the established boundary, the convergence of the answers is evident. In Figure 2, the answers are shown with a 10 percent increase. In this case, 15 non-dominant solutions are created for the problem. Also, in Figure 3, the answers are shown with a 20 percent increase. In this case, 19 non-dominant solutions are created for the problem. In addition, in Figure 4, the answers are shown with a 30 percent increase. In this case, 86 non-dominant solutions are created for the problem. The quality of the solutions provided in the case of a 30 percent increase in demand is more suitable than in the previous two cases. Figures 5, 6, and 7 show the non-dominant solutions for a 10, 20, and 30 percent decrease. Concerning each of the considered reductions, the number of non-dominant solutions is equal to 24, 27, and 35, in which case the obtained solutions have acceptable convergence.

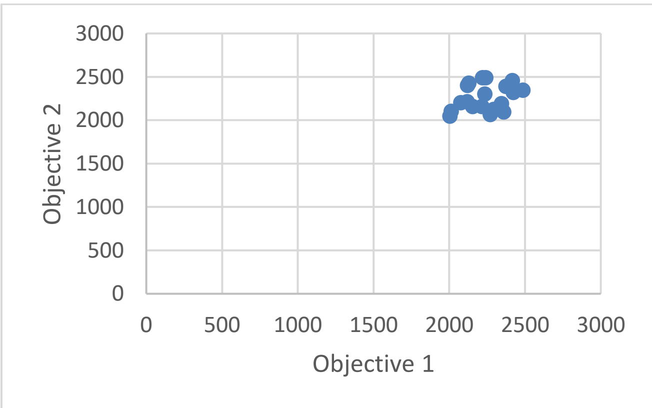

Figure 2. non-dominate points for a 10% increase in demand

Table 7. Amount of displacement products in the network

XX_{ij}	j_1			k_1			k_2			M_1			L_1			L_2			L_3		
	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3	t_1	t_2	t_3
i_1	11.236	1.256	10.478	11.368	10.114	0.00	0.00	11.368	10.114	0.00	11.236	1.256	10.478	11.368	10.114	0.00	0.00	11.368	10.114	0.00	0.00
i_2	1.025	0.347	11.268	10.114	10.114	0.00	0.00	10.114	0.00	0.00	10.114	0.00	1.025	0.347	11.268	10.114	10.114	0.00	0.00	10.114	0.00
YY_{jk}																					
j_1	0.00	2.033	0.349	11.236	0.00	2.033	0.349	11.236	0.00	0.00	0.00	0.00	2.033	0.349	11.236	0.00	2.033	0.349	11.236	0.00	0.00
$ZZ_{kl}; UU_{lm}$																					
k_1	0.00	2.033	0.349	0.00	0.00	2.033	0.349	1.256	0.00	0.00	0.00	2.033	0.349	0.00	1.256	0.00	0.00	0.00	2.033	0.349	0.00
k_2	0.00	2.033	0.349	11.236	1.256	2.033	10.678	11.247	2.033	0.00	0.00	2.033	0.349	11.236	11.247	2.033	0.00	1.256	2.033	10.678	1.256
L_1	11.236	1.256	10.678	0.00	2.033	1.256	11.268	0.00	1.256	0.00	11.236	1.256	10.678	0.00	0.00	1.256	0.00	2.033	1.256	11.268	2.033
L_2	1.025	0.347	11.268	0.00	2.033	0.347	10.114	1.256	0.347	1.256	1.025	0.347	11.268	0.00	1.256	0.347	1.256	2.033	0.347	10.114	2.033
L_3	10.678	11.268	10.114	0.00	0.00	0.268	0.268	0.00	0.00	0.00	10.678	11.268	10.114	0.00	0.00	0.00	0.00	0.00	0.268	0.268	0.00

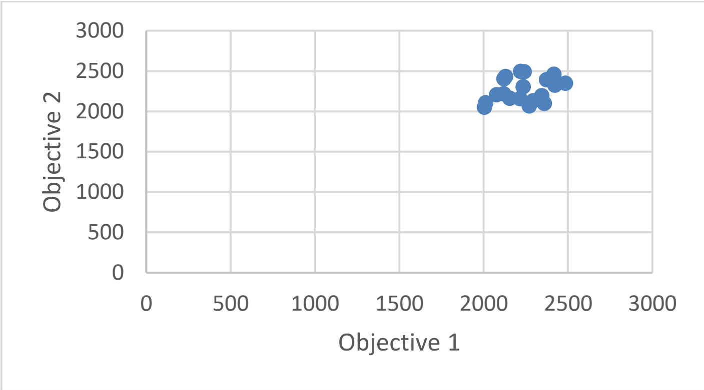

Figure 3. non-dominate points for a 20% increase in demand

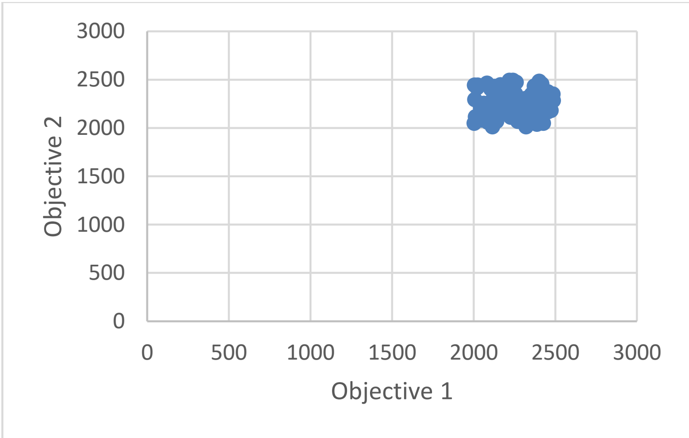

Figure 4. non-dominate Points for a 30% Increase in Demand

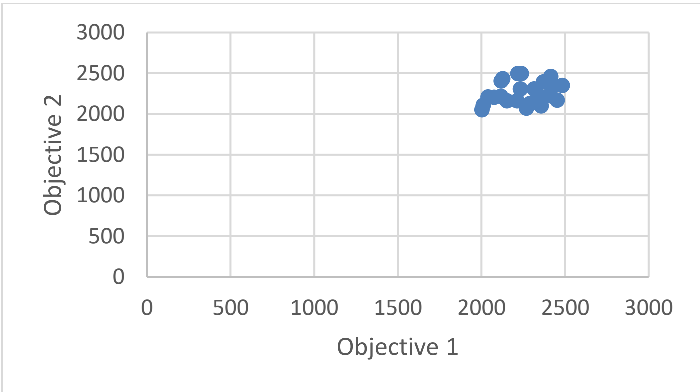

Figure 5. non-dominate points for a 10% decrease in demand quantity

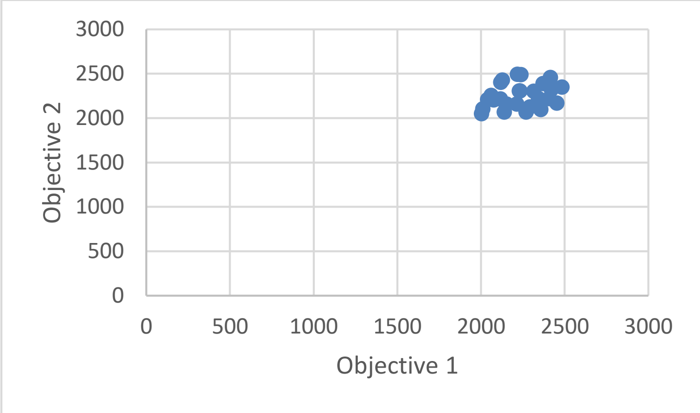

Figure 6. non-dominate points for a 20% decrease in demand quantity

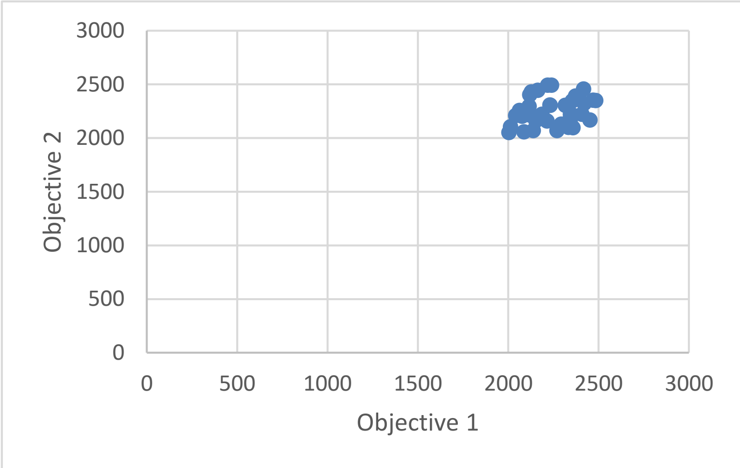

Figure 7. non-dominate points for a 30% reduction in demand

4.2. Managerial insights

Open-loop supply chain management in the Mazandaran wood and paper industry necessitates innovative and comprehensive approaches to optimize processes and minimize costs. An integrated, multi-objective mathematical model designed for supply chain optimization can help managers in this industry make more informed decisions. First, this model allows managers to simultaneously consider multiple goals, such as reducing costs, improving product quality, and increasing customer satisfaction. This multi-objective approach helps them strike a better balance between costs and quality, and as a result, improve the overall performance of the supply chain. Second, using this model can help identify weaknesses and strengths in the supply chain. By analyzing data and simulating different scenarios, managers will be able to make data-based decisions and optimize processes. Third, this model can help managers design better strategies for inventory management and product distribution. By forecasting demand and optimizing inventory, they can prevent resource waste and reduce operating costs. Finally, this model can serve as an effective decision-making tool to improve collaboration and communication in the supply chain. By sharing information and coordinating between different stakeholders, it is possible to achieve improved overall supply chain performance and contribute to sustainable development in the wood and paper industry.

5. Conclusion

This study uses an integrated multi-objective mathematical model to optimize the open-loop supply chain in the Mazandaran wood and paper industry. Given the specific challenges of this industry, including the supply of sustainable raw materials and the need to reduce costs, this model was able to simultaneously consider various criteria, including cost, environmental sustainability, and the importance of suppliers. The results obtained from this study indicate that by applying advanced optimization methods, it is possible to achieve the appropriate choice in terms of the appropriate vehicle, transportation routes, and volume of products moved between chain components and improve supply chain performance. Also, this model can act as an effective decision-making tool for managers of the Mazandaran wood and paper industry and contribute to the sustainable development of this industry. Finally, this study emphasizes the need to consider environmental and economic aspects in supply chain processes and suggests that future research should investigate the practical implementation of this model and evaluate its effects on supply chain performance using robust planning and meta-heuristic methods. Because if the degree of model difficulty increases, the mathematical model may not be able to solve the problem in large or very large dimensions. For this purpose, the use of meta-heuristic methods is proposed.

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