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A multi-objective model for integrated supplier order allocation and supply chain network transportation planning decision-making

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A B S T R A C T

Effective supplier order allocation (SOA) and transportation planning (TP) are critical for the smooth operation of supply chains, especially in dynamic markets with evolving customer demands. While previous research has made significant strides in addressing these areas individually, studies that integrate both aspects while considering a comprehensive set of objectives are limited. This study introduces an innovative multi-objective model that concurrently addresses total operational costs, supplier defect rates, sustainability performance, and supply chain network disruption risks. The model applies an augmented max–min approach of fuzzy multiple objective linear programming (AMM-FMOLP), which enhances overall utility while ensuring balanced performance across all objectives. The inclusion of all five objectives in the model is essential for a holistic evaluation of supply chain performance. The model's effectiveness and practicality are validated through a case study involving a computer numerical control (CNC) machine tool assembly company, under various scenarios. Additionally, sensitivity analysis reveals how adjustments in supply chain structure can further improve performance. Moreover, the execution process of this study does not require expert intervention, making it a unique data-driven decision model particularly suitable for intelligent supply chain management and decision-support systems. This approach enhances the flexibility and resilience of supply chains, enabling them to effectively respond to unforeseen events and minimize their impact on business operations, especially in volatile global markets.

1. Introduction

In an increasingly complex and uncertain environment, the task of supply chain management (SCM) has become more crucial

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[12,13]. The resilience planning and control of supply chains have a direct impact on ensuring their stable operation [25,26]. To implement adaptive management principles, real-time coordination of the supply chain system is necessary, encompassing procurement management, delivery planning, logistics control, and so on. The control parameters of the system should be considered to minimize costs, minimize risks, maximize service levels, and pursue other quantifiable, structured, and uncertainty-related objectives [16,44,33,34,45].

Amidst heightened complexities, supply chains are susceptible to disturbances and inefficiencies stemming from operational lapses and misalignment of information. Prominent examples of such disruptive events encompass the bullwhip and ripple effects [6]. The ripple effect, in particular, unfolds when a disruption spreads beyond its initial point in the supply chain, triggering a domino effect that impairs the performance across the entire supply chain network (SCN)[42,34,41]. These phenomena pose substantial challenges for supply chain managers as they lead to cycles of overproduction and underproduction, culminating in excessive inventory, potential shortages, and compromised network efficiency. These issues can be exacerbated when the supply chain's structural and operational frailties are intertwined[23].

Transportation planning (TP) within a supply chain refers to the strategic coordination of transportation activities to ensure timely and efficient delivery of goods from suppliers to customers. This process is dynamic, continuously shaped by fluctuations in customer demand and the strategic allocation of orders from suppliers [11,31]. Supplier order allocation (SOA) involves distributing orders among multiple suppliers to optimize critical performance objectives such as cost, delivery time, and sustainability [29]. This process is particularly vital because, in many industries, approximately 60 % to 80 % of a company's manufacturing costs stem from procurement activities. The quality of the initial materials or components sourced from suppliers fundamentally determines the quality level of the final product. Therefore, decisions made during SOA have profound implications for a company's overall operational efficiency, cost structure, and product quality[24]. For instance, in scenarios where there is an unexpected surge in demand for a particular product, the supply chain must rapidly adjust its transportation plan to ensure that products are delivered on time and in full to customers[40]. Conversely, a drop in demand can result in underutilized transportation resources, leading to inefficiencies and increased costs.

Moreover, the lead time and reliability of deliveries from suppliers are critical factors that influence the overarching transportation strategy within a supply chain[19,24,47]. Consistent and timely deliveries from suppliers help maintain lean inventory levels, reducing costs associated with holding excess inventory. However, unpredictability in supplier deliveries can force companies to hold additional inventory as a buffer against potential stockouts, directly impacting transportation needs and costs[15].

The integration of SOA and TP is crucial because these two elements are intrinsically linked and mutually reinforcing. Effective SOA can significantly enhance transportation efficiency by minimizing lead times and ensuring reliable delivery schedules, which in turn supports the company's ability to meet customer demands promptly and cost-effectively. This integration is essential not only for optimizing supply chain performance but also for ensuring that the quality of the final product meets the expected standards [3]. However, the challenge lies in balancing multiple, often conflicting objectives such as cost, speed, quality, and sustainability. Achieving this balance requires a strategic approach, as optimizing one objective can impact others. This complexity underscores the importance of developing a cohesive strategy that aligns SOA with TP, thereby ensuring that both cost and quality objectives are met across the entire supply chain[4].

Although past studies have contributed substantially to addressing supply chain network issues, there still exist notable research gaps: (i) there are only a few studies that simultaneously discuss SOA and TP, particularly lacking applications in the context of "contract manufacturing assembly enterprises." It is essential to integrate these two issues and discuss them together, rather than seeking separate optimal solutions for each, as individual optimization may not yield the best overall outcome. (ii) current research often does not comprehensively include considerations of procurement costs, defect rates, and sustainability performance of suppliers, along with the delivery costs and supply interruption risks of the overall supply chain. An SCN model must address these multiple objectives simultaneously to enable companies to balance and enhance various aspects of their competitive advantage effectively. (iii) there is a relative scarcity of studies that offer comparative analysis across multiple scenarios. Planning across various scenarios allows decision-makers to select the most suitable strategies.

In response to the identified gaps in SCN research, this study introduces an innovative multiple objective decision-making (MODM) model for SCNs, specifically tailored to the unique characteristics of contract manufacturing assembly. This model uniquely integrates SOA with TP within the SCN, a critical step for advancing intelligent supply chain management systems that rely on comprehensive data analysis for decision-making. Additionally, the data used in this model is sourced directly from the company's management systems, ensuring real-time, accurate insights for dynamic decision-support. This integration enhances both short-term operational effectiveness and long-term strategic flexibility, making the model highly applicable for intelligent, data-driven supply chain management systems. The proposed model's objective function addresses key aspects such as operational costs (including procurement and delivery costs), supplier defect rates, sustainability performance, and SCN disruption risks. Moreover, the model incorporates several critical practical constraints that are especially relevant to contract manufacturing assembly environments. These include fulfilling customer demand, adhering to capacity limitations, maintaining equilibrium in assembly and delivery processes, and ensuring the non-negativity of variables. By integrating traditional objectives like cost and defect rate with sustainability and disruption risk measures, the study not only incentivizes high-performing suppliers through increased order allocations but also mitigates overall disruption risks within the SCN.

This comprehensive approach provides a more holistic evaluation of supply chain dynamics, balancing operational efficiency with strategic risk management. Demonstrating its practical applicability, this research applies the model to a four-level SCN (comprising suppliers, assemblers, warehouses, and customers), reflective of real-world contract manufacturing assembly enterprises. Utilizing data from comprehensive field surveys, the study employs an augmented max–min approach of fuzzy multiple objective linear programming (AMM-FMOLP) to derive an optimal solution. In addition to solving the problem using the AMM-FMOLP model, this study also conducted a comparison of several other models, including the vector maximum model, utility function model, global criterion model, max–min model, and arithmetical average model. The analysis results indicate that AMM-FMOLP is the most suitable method for converting multiple objectives into a single objective in this particular case. It improves the overall utility while also maintaining a more even distribution of performance across all objectives. This balanced strategy is essential for optimizing supply chain outcomes, as it prevents the compromise of any individual objective's effectiveness in favor of others. By achieving this equilibrium, the model ensures that no single aspect of the supply chain is disproportionately affected, leading to a more robust and efficient overall system.

Moreover, the practicality and feasibility of the proposed SCN model are further illustrated through its application in various scenarios. This approach not only underscores the model's versatility but also enhances its value as a tool for effective decision-making in complex supply chain environments, contributing to the development of intelligent supply chain management and decision-support systems. The main features and contributions of this study are summarized as follows:

(i) This paper introduces a comprehensive assessment model that simultaneously addresses the issues of SOA and supply chain network TP.
(ii) The proposed SCN model considers multiple objectives, including minimizing total operational costs, reducing the overall defect rate of suppliers, maximizing the sustainability performance of suppliers, and minimizing SCN disruption risks.
(iii) This study compares various scenarios to demonstrate the importance of measuring supplier sustainability performance and assessing SCN disruption risks.
(iv) Practical case scenarios that consider the reduction of warehouse establishment are explored, providing appropriate decision-making and managerial implications.
(v) The implementation of this research does not rely on expert intervention, making it a unique data-driven decision model for supply chain management and a valuable contribution to intelligent supply chain management systems.

The structure of the remainder of this study is organized as follows. Section 2 reviews the literature related to SCN. Section 3 introduces the proposed SCN model, including a detailed explanation of the symbols, objective functions, and constraints. Section 4 provides a comprehensive explanation of the research methodology, detailing the steps involved in solving the model. Section 4 illustrates the application of the model to a real case study, covering the problem description, data introduction, theoretical underpinnings, and analysis results. Section 6 discusses the findings, offering a comparison of scenarios, sensitivity analysis, and a comparison of MODM models. Finally, Section 7 presents the conclusions and suggests directions for future research.

2. Literature review

The research on TP within SCN has continually expanded in the past, with an increasing number of objectives being considered. For example, Yaghin and Darvishi [43] discussed an order allocation and procurement transport planning problem in the apparel supply chain. They considered the objectives of maximizing the total value of purchasing, minimizing logistics costs (including purchasing and transportation), and minimizing late deliveries of procured items. Lo et al. [24] explored a sustainable supplier evaluation and TP problem. Their objectives included minimizing the total cost of operation, maximizing reliability, and maximizing sustainable performance. Santos et al. [36] focused on a collaborative TP problem. The objectives were minimizing the total cost of the routing plan and maximizing the total profits collected with all routes. Sun et al. [38] examined a disaster response planning problem with the objectives of minimizing the total cost and minimizing the sum of injury severity scores. Peng et al. [31] tackled a TP problem for a sustainable supply chain network (SCN), with the objective of maximizing total revenue.

Additionally, Hashemi-Amiri et al. [15] investigated an integrated supplier selection, scheduling, and routing problem for a perishable product supply chain. They aimed to minimize the total cost and maximize the overall reliability of selected suppliers in the perishable food supply chain (PFSC) network. Giri et al. [12] addressed a TP problem for an electric sustainable supply chain network. Their objectives were minimizing the overall cost of the electric network, minimizing de-resiliency, maximizing job opportunities and economic growth, and minimizing lost days. Mohammed et al. [28] explored the design of a sustainable and resilient supply chain network. The study focused on minimizing the total supply chain network design cost, minimizing environmental impact, maximizing sustainable design, and maximizing resilient design in re-engineering the two-tier supply chain network (2TSCN). Abushaega et al. [1] discussed an efficient restoration planning for transportation networks and a distribution planning for downstream SCNs. The objectives were to minimize the time required to distribute the total flows and to minimize total penalty costs.

Table 1 summarizes the key focus areas of recent research related to Supply Chain Networks (SCNs). The literature highlights three major objectives: cost reduction, which is addressed by studies such as Feng et al. [9], Lacomme et al. [20], and Lo et al. [24]; environmental and social sustainability, which is emphasized in the works of Guo et al. [14], Li et al. [22], and Nayeri et al. [30]; and efficiency and profitability, as explored by Darayi et al. [8], Santos et al. [36], and Karuppiah et al. [17]. To tackle these objectives, a variety of solution methods have been employed, reflecting the complexity and diversity of SCN challenges. These include heuristic approaches (e.g., [9,5], optimization algorithms (e.g., [39], and simulation tools (e.g., [19]. Furthermore, some studies, such as those by Lo et al. [24] and Ghasemy Yaghin and Sarlak [11], have adopted advanced methods like fuzzy multiple objective optimization and goal programming to address the multi-faceted nature of SCN issues.

Table 1
Compilation of recent researches on SCN.

Author (year)	Objective	Issue / Application	Solution method
Feng et al. [9]	• Minimizing production set-up cost • Minimizing marginal production cost	A coordinated production and TP problem	A decomposition-based heuristic (DBH) and a heuristic is based on Lagrangian relaxation (called LRBH)
Lacomme et al. [20]	• Minimizing the makespan	An extension of the integrated production and transportation scheduling problem (PTSP)	A greedy randomised adaptive search procedure (GRASP) with an evolutionary local search (ELS)
Li et al. [22]	• Maximizing revenue • Minimizing costs • Minimizing time for discharge, loading, and travel • Minimizing emissions	A multi-depot green vehicle routing problem	An improved ant colony optimization (IACO) algorithm
Darayi et al. [8]	• Maximizing the progress in reducing economic loss	An adaptive capacity planning problem in a freight transportation network	An optimization software LINGO (version 15)
Kelle et al. [19]	• Maximizing the environmental goals and other performance measures	A multimodal freight TP problem	A simulation tool for intermodal freight transportation
Guo et al. [14]	• Minimizing the sum of procurement, production, transportation, and operating costs • Minimizing the sum of total CO2 emissions and water consumption	A sustainable supply chain network design problem	A mixed integer linear programming (MILP) and an efficient distributed approximation approach (DAA)
Tirkolaee et al. [39]	• Minimizing total network cost in all periods • Maximizing customer satisfaction	A pollution-routing problem with cross-dock selection problem	A multi-objective simulated-annealing algorithm (MOSA) and a non-dominated sorting genetic algorithm II (NSGA-II)
Gao and Cao [10]	• Minimizing the weighted unmet demand proportion • Minimizing the transportation time	A multi-commodity rebalancing and TP problem	An epsilon-constraint method
Nayeri et al. [30]	• Minimizing the total cost, reduce and control the total carbon emissions • Maximizes the social impacts	A sustainable closed-loop supply chain network design problem	A multi-objective fuzzy robust optimization approach
Ghasemy Yaghin and Sarlak [11]	• Maximizing the total profits and the social value of purchasing • Minimizing delivery lead-time, air and water pollution, and energy consumption	A joint order allocation and TP	A multi-choice goal programming
Yaghin and Darvishi [43]	• Maximizing the total value of purchasing • Minimizing logistics costs, including purchasing and transportation • Minimizing the late deliveries of procured items	An order allocation and procurement transport planning in apparel supply chain	A utility-based possibilistic-flexible programming approach
Lo et al. [24]	• Minimizing the total cost of operation • Maximizing the reliability • Maximizing the sustainable performance	A sustainable supplier evaluation and TP problem	A modified indifference threshold-based attribute ratio analysis (ITARA), A performance calculation technique of the integrated multiple multi-attribute decision-making (PCIM-MADM), and FMOLP
Santos et al. [36]	• Minimizing the total cost of the routing plan • Maximizing the total profits collected with all routes	A collaborative TP problem	An equivalent single-level mixed integer linear program
Sun et al. [38]	• Minimizing the total cost • Minimizing the sum of injury severity scores	A disaster response planning problem	A $\varepsilon-$constraint method
Peng et al. [31]	• Maximizing total revenue	A TP for sustainable SCN	A linear programming
Hashemi-Amiri et al. [15]	• Minimizing the total cost • Maximizing the overall reliability of selected suppliers in the PFSC network	An integrated supplier selection, scheduling, and routing problem for perishable product supply chain	A weighted goal programming approach
Giri et al. [12]	• Minimizing the overall cost of the electric network • Minimizing the de-resiliency • Maximizing the job opportunities and economical growth • Minimizing the objective of lost days	A TP for electric sustainable supply chain network	A multi-choice conic goal programming with utility function (MCCGP-UF)
Mohammed et al. [28]	• Minimizing of total supply chain network design cost • Minimizing of environmental impact throughout the two-tier supply chain network design (2TSCN)	A design of sustainable and resilient supply chain network	A fuzzy four-objective optimization model (FFOOM) and a hybrid AHP-OCRA method

(continued on next page)

Table 1 (*continued*)

Author (year)	Objective	Issue / Application	Solution method
Abushaega et al. [1]	• Maximizing of sustainable design in re-engineering the 2TSCN • Maximizing of resilient design in re-engineering the 2TSCN • Minimizing the time that takes to distribute the total flows • Minimizing the total penalty costs	An efficient restoration planning for the transportation network and a distribution planning for downstream SCN	A novel multi-objective non-linear mixed-integer programming (NMIP) model

3. The proposed SCN model

3.1. Explanation of symbols

In this study, constructing a SCN model stands as a pivotal component. The model introduced here is a deterministic SCN framework, centering on SOA and TP of SCN. It is structured around four primary objectives: minimizing total operational costs, minimizing the overall defect rate of suppliers, maximizing the sustainability performance of suppliers, and minimizing SCN disruption risks. The model developed in this study integrates constraints crucial for fulfilling customer demand, adhering to capacity limitations, maintaining equilibrium in assembly and delivery, and ensuring the non-negativity of variables. This construction of the SCN model is aimed at optimizing decision-making processes in supply chain management. Distinctive features of the model include its comprehensive integration of order allocation, the inclusion of diverse objectives, and the incorporation of an array of constraints, all of which collectively ensure operational feasibility and efficiency.

Table 2 provides an overview of the parameters and symbols used in the model. Here, $F(e, i)$ denotes the i^{th} supplier of component e, $i = 1, 2, \ldots, I_e$, where I_e is the number of suppliers of component e, $e = 1, 2, \ldots, E$. It is assumed that each supplier specializes in providing a specific type of component.

3.2. Objective functions

The proposed SCN model selects four objective functions—minimizing total operational costs, reducing the overall defect rate of suppliers, maximizing the sustainability performance of suppliers, and minimizing SCN disruption risks—as the core of its analysis, based on their critical importance in enhancing overall supply chain efficiency. First and foremost, one of the central goals of supply chain management is to reduce operational costs, which directly impacts a company's profitability and competitiveness. Additionally, the quality of supplier products is vital for maintaining high levels of customer satisfaction. Minimizing defect rates helps companies

Table 2
The symbols used in the SCN model.

Indices	**Description**
e	The e^{th} component, $e = 1, 2, \ldots, E$
$F(e, i)$	The i^{th} supplier in "component e," $i = 1, 2, \ldots, I_e$
j	The j^{th} assembler, $j = 1, 2, \ldots, J$
v	The v^{th} warehouse, $v = 1, 2, \ldots, V$
h	The h^{th} customer, $h = 1, 2, \ldots, H$
Variables	**Description**
FA_{eij}	Quantity of component e shipped from supplier $F(e, i)$ to assembler j
AL_{jv}	Quantity of goods shipped from assembler j to warehouse v
LM_{vh}	Quantity of goods shipped from warehouse v to customer h
Parameters	**Description**
$tcfa_{eij}$	Unit delivery cost of component e from supplier $F(e, i)$ to assembler j
$tcal_{jv}$	Unit delivery cost of goods from assembler j to warehouse v
$tclm_{vh}$	Unit delivery cost of goods from warehouse v to customer h
$drfa_{eij}$	Unit delivery defective rate of component e from supplier $F(e, i)$ to assembler j
cf_{ei}	Unit purchase cost of component e provided by supplier $F(e, i)$
ca_j	Unit assembly cost of goods assembled by assembler j
cl_v	Unit holding cost of goods in warehouse v
τ_e	Quantity of component e required for a goods is typically obtained from the bill of materials
w_{ei}	Unit purchase performance of component e provided by supplier $F(e, i)$
dm_h	Demand of customer h
rfa_{eij}	Unit delivery risks of disruption of component e from supplier $F(e, i)$ to assembler j
ral_{jv}	Unit delivery risks of disruption of goods from assembler j to warehouse v
rlm_{vh}	Unit delivery risks of disruption of goods from warehouse v to customer h
$capf_{ei}$	Capacity of the supply of component e from supplier $F(e, i)$
$\otimes capa_j$	Fuzzy capacity of the production of assembler j
$capl_v$	Capacity of the storage of warehouse v
γ	Threshold of the delivery risks

reduce waste and returns, thereby improving the overall efficiency of the supply chain.

In today's environment, where sustainability is increasingly emphasized, supply chains must not only consider economic benefits but also their environmental and social impacts. By maximizing the sustainability performance of suppliers, companies can reduce their environmental footprint, meet regulatory requirements, and enhance brand reputation. Furthermore, various risks within the supply chain pose threats to its stability, making it essential to maintain continuity and reliability. These four objectives collectively address the key pillars of supply chain management—cost, quality, sustainability, and risk—ensuring the resilience and long-term sustainability of the supply chain. Here is an introduction to the four objective functions.

(a) f_1: Minimizing total operational costs

Operational costs are a critical and indispensable component of the SCN model. In today's highly competitive global market, firms are driven to identify and leverage cost-effective solutions[21]. Supplier costs can vary significantly, encompassing both production and delivery expenses[37]. Within the SCN framework, each delivery route incurs distinct costs. Additionally, assembly manufacturers impose fees for their services, and warehouses generate costs associated with inventory management. The first objective function, represented by **Eq. (1)**, is designed to minimize the total operational expenses across the SCN. These costs are composed of six key elements: the procurement cost from suppliers, the cost of assembling components, warehouse management costs, and the costs associated with three main supply chain routes—supplier to assembly plant, assembly plant to warehouse, and warehouse to customer. Here, the assembly cost for components is calculated based on time. Since the production process has achieved line balancing, the assembly cost for each component is the same. For example, if producing a goods requires two units of a certain component, the parameter τ_e is used to adjust the cost proportion accordingly.

$$\begin{aligned} \min f_1 = & \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(cf_{ei}FA_{eij}\right) + \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(\frac{1}{\tau_e}ca_jFA_{eij}\right) + \sum_{j=1}^{J}\sum_{v=1}^{V}\left(cl_vAL_{jv}\right) + \\ & \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(tcfa_{eij}FA_{eij}\right) + \sum_{j=1}^{J}\sum_{v=1}^{V}\left(tcal_{jv}AL_{jv}\right) + \sum_{v=1}^{V}\sum_{h=1}^{H}\left(tclm_{vh}LM_{vh}\right) \end{aligned} \tag{1}$$

(b) f_2: Minimizing the overall defect rate of suppliers

Minimizing the defect rate among suppliers is key to ensuring the quality of components delivered to assembly plants, consequently decreasing the likelihood of damage or the need for rework[2]. This focus on supplier defect rates underscores the importance of maintaining high standards of product quality from the very beginning of the supply chain. By addressing defects at the supplier level, the model aims to prevent quality issues from propagating through subsequent stages of production. A reduction in defects across the delivery process not only optimizes operational workflows but also curtails waste and bolsters the overall efficiency of production activities. The emphasis on minimizing defects among suppliers specifically ensures that the quality of incoming materials meets the required standards, thereby enhancing the reliability and performance of the final product. The objective function, designed to lower the defect rate and encompassing the delivery pathway of suppliers, is formulated in **Eq. (2)**.

$$\min f_2 = \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(drfa_{eij}FA_{eij}\right) \tag{2}$$

(c) f_3: Maximizing the sustainability performance of suppliers

The sustainability performance of suppliers is derived from the company's supplier procurement evaluation system, which assesses key performance indicators (KPIs) across economic, environmental, social, and institutional dimensions. This framework aligns with the one proposed by Chang et al. [7]. The factor rating method is employed as a systematic approach to evaluate the sustainability performance index of suppliers. This assessment considers both the volume of purchases from each supplier and their respective performance indices, allowing for a comprehensive evaluation of sustainability performance[46]. The aggregate sustainability performance is calculated by summing these individual scores, providing an overall sustainability level across all suppliers. The objective function, as detailed in **Eq. (3)**, plays a crucial role in this process. It supports strategic decision-making by prioritizing the selection of suppliers with higher sustainability scores, thereby optimizing sustainable performance within the SCN. This approach not only emphasizes sustainability outcomes more effectively than existing models but also integrates ethical procurement practices into the SCN, ensuring that the company's supply chain strategy is aligned with broader sustainability objectives.

$$\max f_3 = \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(w_{ei}FA_{eij}\right) \tag{3}$$

(d) f_4: Minimizing the SCN disruption risks

The fourth objective of this study is focused on minimizing the risk of interruptions along the delivery paths within the SCN. This objective considers two critical factors: the interruption rate of the delivery routes and the delivery accuracy and timeliness. The latter includes ensuring that the correct products and quantities are delivered precisely at the specified times, without delays or premature arrivals. These two factors are integrated into a composite metric, ranging from 0 to 1, which is provided by the company's logistics management department. Delivery disruptions can cause significant challenges, including production delays, inventory shortages, complications in order fulfillment, and negative impacts on company reputation and customer satisfaction[37,48,49]. By reducing these disruptions, the model enhances both the precision of deliveries and the adherence to strict delivery schedules[27]. The objective function dedicated to mitigating the risk of delivery interruptions is detailed in **Eq. (4)**, playing a crucial role in ensuring smoother operations and increasing the overall reliability of supply chain processes.

$$\min f_4 = \sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(rfa_{eij}FA_{eij}\right) + \sum_{j=1}^{J}\sum_{v=1}^{V}\left(ral_{jv}AL_{jv}\right) + \sum_{v=1}^{V}\sum_{h=1}^{H}\left(rlm_{vh}LM_{vh}\right) \tag{4}$$

3.3. Constraints

The construction of the four types of constraints in the SCN model is as follows.

(a) Fulfilling customer demand

The primary objective in designing an SCN is to fulfill customer demand. Consequently, it is necessary to ensure that the quantities shipped from the warehouses to each customer are equal to the number of goods requested by customer h. This requirement for precise demand fulfillment is showed in **Equation (5)**.

$$\sum_{v=1}^{V} LM_{vh} = dm_h, \forall h = 1, 2, \ldots, H \tag{5}$$

(b) Adhering to capacity limitations

It is essential to respect the supply capabilities of each supplier $F(e, i)$, for every component e they provide. This means that the supply from these suppliers must not exceed their inherent production capacities. To encapsulate this principle, **Eq. (6)** is formulated, representing the constraints imposed by the capacity load of each supplier.

$$\sum_{j=1}^{J} FA_{eij} \leq capf_{ei}, \forall e = 1, 2, \ldots, E; i = 1, 2, \ldots, I_e \tag{6}$$

The assemblers in the SCN model are responsible for assembling the components received from the suppliers. It is assumed that each assembler has a designated production capacity. The production capacity of an assembler can be adjusted by increasing or decreasing the number of shifts. Therefore, **Eq. (7)** represents the fuzzy assembly capacity constraints of assembler j.

$$AL_{jv} \in \otimes capa_j \Rightarrow capa_j^L \leq \sum_{v=1}^{V} AL_{jv} \leq capa_j^U, \forall j = 1, 2, \ldots, J \tag{7}$$

Here, $capa_j^L$ and $capa_j^U$ respectively denote the lower and upper bounds of the capacity of assembler j.

The assemblers will transport the assembled goods to the warehouses. When designing an SCN, it is essential to consider the storage capacity constraints. This relationship is represented by **Eq. (8)**.

$$\sum_{j=1}^{J} AL_{jv} \leq capl_v, \forall v = 1, 2, \ldots, V \tag{8}$$

Next, this study aims to ensure that the overall delivery path interruption risk is below the threshold of the delivery risk, as shown in **Eq. (9)**.

$$\begin{aligned}&\sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J}\left(rfa_{eij}FA_{eij}\right) + \sum_{j=1}^{J}\sum_{v=1}^{V}\left(ral_{jv}AL_{jv}\right) + \sum_{v=1}^{V}\sum_{h=1}^{H}\left(rlm_{vh}LM_{vh}\right)\\ &\quad\leq \gamma\left(\sum_{e=1}^{E}\sum_{i=1}^{I_e}\sum_{j=1}^{J} FA_{eij} + \sum_{j=1}^{J}\sum_{v=1}^{V} AL_{jv} + \sum_{v=1}^{V}\sum_{h=1}^{H} LM_{vh}\right)\end{aligned} \tag{9}$$

(c) Maintaining equilibrium in assembly and delivery

It is assumed that the goods are assembled using multiple components. The bill of material (BOM) specifies the quantity of each component required to produce a finished goods. In addition, to avoid excess inventory, it is crucial to ensure a balanced supply of all components. The quantity of delivery paths for each station should be equal, as represented by **Eqs. (10–12)**.

$$\frac{1}{\gamma_1}\sum_{i=1}^{I_1} FA_{1ij} = \frac{1}{\gamma_2}\sum_{i=1}^{I_2} FA_{2ij} = \ldots = \frac{1}{\gamma_E}\sum_{i=1}^{I_E} FA_{Eij}, \forall j = 1, 2, \ldots, J \tag{10}$$

$$\sum_{i=1}^{I_e} FA_{eij} = \sum_{v=1}^{V} AL_{jv}, \forall e = 1, 2, \ldots, E; j = 1, 2, \ldots, J \tag{11}$$

$$\sum_{j=1}^{J} AL_{jv} = \sum_{h=1}^{H} LM_{vh}, \forall v = 1, 2, \ldots, V \tag{12}$$

(d) Ensuring the non-negativity of variables

All variables are non-negative.

4. Methodology

In this study, the multi-objective optimization process is driven by the integration of diverse data sources, which are essential for effective decision-making within the SCN. The intelligent system processes data in real-time, dynamically adjusting decisions to meet the objectives of SOA and TP. The proposed model retrieves data from both supply chain management (SCM) and enterprise resource planning (ERP) systems, which provide crucial information such as unit delivery costs, supplier defect rates, purchase costs, assembly costs, and holding costs. Additionally, specific data related to customer demand, supplier capacity, production capacity, and storage capacity are gathered from the bill of materials and other operational databases. Furthermore, critical data points like unit delivery risks from suppliers to assemblers, from assemblers to warehouses, and from warehouses to customers are included to account for potential disruptions. The model also incorporates fuzzy capacities for assemblers, offering a more flexible evaluation of production capabilities under varying conditions. These data inputs are processed using the Augmented Max-Min Fuzzy Multiple Objective Linear Programming (AMM-FMOLP) technique, which ensures balanced optimization across all objectives. The required data, as outlined in Table 2, can be collected based on the parameters listed. By solving the multi-objective optimization, it is possible to determine the order allocation for all suppliers as well as the transportation volumes across all SCN pathways. The actual data analysis procedure is detailed in Section 5.

Here, we explain the computational concept of AMM-FMOLP. The AMM-FMOLP is a methodology designed to consolidate multiple objective functions into a singular objective function. This is achieved by employing a utility function to quantify the attainment levels of each individual objective function. A higher utility function value signifies greater satisfaction of the associated objective function. One of the key advantages of AMM-FMOLP is its capability to pinpoint a singular optimal compromise solution, thus resolving the common dilemma of selecting from multiple solutions, a challenge often faced with other heuristic algorithms. Moreover, the augmented max–min technique considers the utilities of multiple objectives concurrently, ensuring that the utility of no single objective function is compromised in the process. This feature enhances the method's ability to deliver a balanced and holistic solution to complex multiple objective problems. The implementation process of AMM-FMOLP follows the steps outlined below.

Step 1. Constructing the SCN model.

The constructed SCN falls under the category of a fuzzy multiple objective model. Consequently, it can be classified into several types of functions and constraints: minimization functions Z_g (**Eq. (13)**), maximization functions Z_q (**Eq. (14)**), fuzzy constraints $\otimes y_t(r)$ (**Eq. (15)**), general constraints $y_n(r)$ (**Eq. (16)**), and non-negativity constraints (**Eq. (17)**). This classification enables a comprehensive and nuanced approach to modeling, addressing the diverse and often conflicting objectives inherent in supply chain management.

$$Z_g, g = 1, 2, \ldots, G \; (forminimizationfunctions) \tag{13}$$

$$Z_q, q = 1, 2, \ldots, Q \; (formaximizationfunctions) \tag{14}$$

s.t.

$$\otimes y_t(r) \leq \otimes k_t, \; t = 1, 2, \ldots, T \; (forfuzzyconstraints) \tag{15}$$

$$y_n(r) \leq k_n, \; n = 1, 2, \ldots, N \; (fordeterministicconstraints) \tag{16}$$

$$r \geq 0, \; r = 1, 2, \ldots, R \; (fornon-negativityconstraints) \tag{17}$$

In the FMOLP formulation, the variables G and Q represent the number of minimization and maximization functions. The variables T, N, and R represent the number of fuzzy, deterministic, and non-negativity constraints, respectively. The fuzzy value $\otimes k_t$ is decomposed into lower, middle, and upper values, namely $\otimes k_t = (\underline{k}_t, k_t, \overline{k}_t)$. The variable r represents all the variables in the SCN model, and they must satisfy the condition of being greater than or equal to 0.

Step 2. Obtaining the membership functions.

To effectively consolidate multiple objectives into a single objective function, it is crucial to first determine the optimal positive and negative solutions (Z^+ and Z^-) for each objective function, as outlined in Table 3 [24]. In the FMOLP approach, where all objective functions are assumed to be linear, we can define the membership functions through linear transformations. These transformations enable the conversion of objective values into fuzzy membership values, providing a unified framework for integrating and optimizing the objectives.

Specifically, for minimization functions, the linear membership function ($\omega_{zg}(Z_g(r))$) is determined based on **Eq. (18)**. These include total operational costs, the overall defect rate of suppliers, and the SCN disruption risks. Similarly, for maximization functions, the linear membership function ($\omega_{zq}(Z_q(r))$) is defined according to **Eq. (19)**. This includes the sustainability performance of suppliers. These membership functions help us quantify the degree of satisfaction or achievement for each objective and facilitate the fuzzy-based analysis and decision-making process. Moreover, the fuzzy constraints are characterized by the linear membership function $\omega_{yt}(r)$, which is defined based on the value of $\otimes k_t = (\underline{k}_t, k_t, \overline{k}_t) = (k_t - l_t, k_t, k_t + u_t)$. **Eq. (20)** represents the mathematical expression of the membership function for the fuzzy constraint formula.

This step allows us to determine the range of values for each objective under a single-objective scenario. With this information, the next step can integrate these objectives for maximization.

$$\omega_{zg}(Z_g(r)) = \begin{cases} 1, Z_g(r) \le Z_g^+ \\ \dfrac{\left(Z_g^- - Z_g(r)\right)}{\left(Z_g^- - Z_g^+\right)}, Z_g^+ \le Z_g(r) \le Z_g^-, g = 1,\ 2,\ \ldots,\ G\ (forminimizationfunctions) \\ 0, Z_g(r) \ge Z_g^- \end{cases} \tag{18}$$

$$\omega_{zq}(Z_q(r)) = \begin{cases} 1, Z_q(r) \ge Z_q^+ \\ \dfrac{\left(Z_q(r) - Z_q^-\right)}{\left(Z_q^+ - Z_q^-\right)}, Z_q^- \le Z_q(r) \le Z_q^+, q = 1,\ 2,\ \ldots,\ Q\ (formaximizationfunctions) \\ 0, Z_q(r) \le Z_q^- \end{cases} \tag{19}$$

$$\omega_{yt}(r) = \begin{cases} 0, y_t(r) \le k_t - l_t \\ \dfrac{k_t - y_t(r)}{l_t}, k_t - l_t \le y_t(r) \le k_t \\ \dfrac{y_t(r) - k_t}{u_t}, k_t \le y_t(r) \le k_t + u_t \\ 0, y_t(r) \ge k_t + u_t \end{cases}, t = 1, 2, \ldots, T\ \ (forfuzzyconstraints) \tag{20}$$

Step 3. Obtaining an optimal compromise solution

In this step, all the transformed membership functions are integrated, with the requirement that each function must exceed a baseline utility value (λ), as presented in **Eq. (21)**. After converting the objective functions into membership functions ($\omega_{zg}(Z_g(r))$ and $\omega_{zq}(Z_q(r))$), not only must they surpass the baseline utility function, but there is also an expectation for them to achieve a balanced performance across all objectives. In this technique, the membership functions of the objectives, after linear transformation, are treated as constraints, as indicated by **Eqs. (22) and (23)**. These constraint equations are designed to maximize objectives λ_g and λ_q as much as possible.

Additionally, we incorporate other constraints as outlined in **Eqs. (24)-(28)**. These original constraints simulate the practical limitations and conditions of the real-world scenario. By solving this transformed FMOLP model, we can obtain an optimal compromise solution that balances all objectives while adhering to the practical constraints of the problem.

$$\max \lambda + \frac{\left\{\sum_{g=1}^{G} \lambda_g + \sum_{q=1}^{Q} \lambda_q + \sum_{t=1}^{T} \lambda_t\right\}}{(G + Q + T)} \tag{21}$$

s.t.

$$\lambda_g \le \omega_{zg}(Z_g(r)), g = 1, 2, \ldots, G, \tag{22}$$

Table 3
The payoff table of determining the maximum and minimum values for functions.

	Z_g (Minimization)	Z_q (Maximization)
Z^+	$Z_g^+ = \min Z_g$	$Z_q^+ = \max Z_q$
Z^-	$Z_g^- = \max Z_g$	$Z_q^- = \min Z_q$

$$\lambda_q \le \omega_{zq}(Z_q(r)), q = 1, 2, ..., Q, \tag{23}$$

$$\lambda_t \le \omega_{kt}(r), t = 1, 2, ..., T, (for \text{ fuzzy constraints}) \tag{24}$$

$$y_n(r) \le k_n, n = 1, 2, ..., N, (for \text{ deterministic constraints}) \tag{25}$$

$$\lambda_g, \lambda_q, \lambda_t \ge \lambda. \tag{26}$$

$$\lambda, \lambda_g, \lambda_q, \lambda_t \in [0, 1]. \tag{27}$$

$$r \ge 0, \ r = 1, 2, ..., R \tag{28}$$

5. Illustration of a real case study

5.1. Problem description and data introduction

This study demonstrates the effectiveness and practicality of the SCN model through a real case study. The case study involved close collaboration with a decision-making team from the case company, which played a crucial role in investigating and collecting the necessary data. The motivation behind this study stemmed from the case company's commitment to sustainable development and the need to enhance the competitiveness of their SCN in the face of market competition. To address these challenges, the case company decided to implement a SOA and supply chain network TP strategy.

The case company specializes in assembling CNC machine tools, and the data utilized in this study was derived from their flagship products. The data collection process was thorough and systematic, involving detailed interactions with the decision-making team to ensure accuracy and relevance. The sample size for this study included 6 critical components, with data collected from 15 suppliers, 2 assemblers, 3 warehouses, and 6 customers within the supply chain network. The data source primarily consisted of the company's internal databases, which provided comprehensive records of past orders, supplier performance metrics, transportation schedules, and inventory levels.

Prior to analysis, the data underwent a series of pre-processing steps to ensure its suitability for the SCN model. These steps included data cleaning to remove any inconsistencies or outliers, normalization to standardize the data for comparison across different entities, and aggregation to consolidate information relevant to the four-level SCN structure. Here, it is important to emphasize that the units for money and quantity must be consistent. The resulting data was then used to populate the SCN model, providing a robust foundation for analyzing the supply chain dynamics within the company. The SCN model implemented by the case company features a four-level

Table 4
The data used in this study is from the SCN model.

Supplier $F(e, i)$	$capf_{ei}$	cf_{ei}	w_{ei}
F (1, 1–3)	(200, 270, 320)	(3600, 3550, 3650)	(0.528, 0.513, 0.620)
F (2, 1–2)	(350, 390)	(3000, 3050)	(0.555, 0.608)
F (3, 1–2)	(395, 400)	(3250, 3300)	(0.638, 0.702)
F (4, 1–3)	(280, 250, 300)	(2650, 2350, 2800)	(0.500, 0.451, 0.515)
F (5, 1–3)	(155, 245, 235)	(2350, 2450, 2150)	(0.623, 0.694, 0.426)
F (6, 1–2)	(420, 405)	(2600, 2550)	(0.530, 0.490)
Assembler j	$\otimes \boldsymbol{capa_j}$	$\boldsymbol{ca_j}$	
1, 2	[190–280], [150–210]	7650, 7650	
Warehouse v	$\boldsymbol{capl_v}$	$\boldsymbol{cl_v}$	
1, 2, 3	(145, 170, 180)	(300, 250, 280)	
Customer h	$\boldsymbol{dm_h}$		
1, 2, 3, 4, 5, 6	(95, 41, 69, 30, 95, 60)		
Delivery routes	**Delivery cost**	**Defect rate**	**Interruption risk**
Supplier to assembler	$\boldsymbol{tcfa_{eij}}$	$\boldsymbol{drfa_{eij}}$	$\boldsymbol{rfa_{eij}}$
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(210, 210, 110, 190, 160, 170, 120, 255, 190, 105, 175, 150, 230, 110, 100)	(0.07, 0.10, 0.08, 0.08, 0.07, 0.08, 0.05, 0.09, 0.09, 0.07, 0.09, 0.07, 0.10, 0.07, 0.07)	(0.058, 0.078, 0.080, 0.080, 0.087, 0.073, 0.091, 0.059, 0.096, 0.077, 0.084, 0.088, 0.083, 0.065, 0.080)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(160, 150, 105, 230, 105, 185, 120, 260, 250, 185, 180, 150, 260, 220, 175)	(0.10, 0.09, 0.07, 0.07, 0.10, 0.08, 0.07, 0.09, 0.08, 0.08, 0.08, 0.09, 0.07, 0.07, 0.10)	(0.071, 0.026, 0.085, 0.087, 0.074, 0.078, 0.080, 0.075, 0.093, 0.048, 0.075, 0.085, 0.079, 0.065, 0.072)
Assembler to warehouse	$\boldsymbol{tcal_{jv}}$		$\boldsymbol{ral_{jv}}$
AL_{11}, AL_{12}, AL_{13}	(550, 650, 780)		(0.025, 0.027, 0.035)
AL_{21}, AL_{22}, AL_{23}	(785, 615, 570)		(0.028, 0.020, 0.028)
Warehouse to customer	$\boldsymbol{tclm_{vh}}$		$\boldsymbol{rlm_{vh}}$
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(195, 140, 205, 140, 170, 195)		(0.019, 0.029, 0.017, 0.026, 0.009, 0.010)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(210, 180, 140, 110, 160, 170)		(0.017, 0.038, 0.016, 0.026, 0.019, 0.018)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(165, 120, 135, 180, 210, 160)		(0.015, 0.039, 0.028, 0.015, 0.018, 0.017)

structure, showcasing the intricate and multi-faceted nature of their supply chain. Table 4 presents a comprehensive overview of all the relevant data in the SCN model, illustrating the complex interplay between various supply chain entities essential to the production and distribution of their CNC machine tools.

5.2. Theoretical underpinnings and assumptions

To ensure the robustness and practicality of the proposed four-level SCN model, several theoretical underpinnings and assumptions are established:

(i) Fixed supply chain sequence:

The model assumes a fixed sequence in the supply chain process across the four levels, prohibiting any reordering of the sequence. This reflects the structured and hierarchical nature of supply chain operations where each level has a defined role.

(ii) Known customer demand:

The model operates under the assumption that customer demand is known and serves as the primary driver for initiating SOA and overall TP. This assumption allows the model to focus on optimizing the supply chain's response to demand rather than predicting or estimating demand itself.

(iii) Transparent supply chain information:

It is assumed that the entire supply chain operates with full transparency, meaning that all relevant information is accessible and shared across the supply chain partners. As a result, the model does not consider scenarios involving inventory management or stockouts, focusing instead on the coordination and optimization of supply chain activities.

(iv) Sufficient capacity across suppliers and facilities:

The model assumes that all suppliers have adequate supply quantities, assemblers possess sufficient production capacity, and warehouses have enough storage capacity to meet customer demand. This assumption simplifies the model by eliminating the need to account for capacity constraints or shortages, allowing for a more direct focus on order allocation and TP.

5.3. Analysis results

All data presented in Table 4 serve as the input for the proposed SCN model. A set of optimal solutions can be obtained through solving the model with the augmented max–min approach of FMOLP. By utilizing **Eqs. (13)–(17)**, we solve each individual objective problem to derive the positive and negative optimal solutions for the four objectives, as demonstrated in Table 5. In this study, there are two assemblers with different capacity limitations represented by fuzzy numbers ($\otimes capa_j$). The first assembler has a capacity limitation ranging from 190 to 280, while the second assembler has a limitation ranging from 150 to 210. These capacity limitations are applied in **Eq. (15)**. Next, this study proposes four linear objective functions that can be transformed using **Eqs. (18)–(19)**. Additionally, fuzzy constraints can be converted into linear membership degrees using **Eq. (20)**. Finally, based on **Eqs. (21)-(28)**, an optimal solution for all decision variables can be obtained.

Table 6 displays the results of solving with FMOLP, revealing the individual utilities of the four objective functions as 0.6667, 0.6820, 0.6747, and 0.6667, respectively. Furthermore, the results are as follows: minimizing total operational costs results in 26,585,670, minimizing the overall defect rate of suppliers yields 209.57, maximizing the sustainability performance of suppliers achieves 1,546.148, and minimizing the SCN disruption risks amounts to 214.223. This indicates that through the FMOLP solution process, a compromise solution is obtained by considering the overall trade-offs among multiple objectives. The allocation of orders to suppliers can also be discerned from Table 6, where F (2, 2), F (4, 2), and F (4, 3) are identified as suppliers at full capacity. From this data, we can clearly determine the selected delivery routes and quantities throughout the entire Supply Chain Network (SCN), which reveal an average defect rate of 0.078 and an average interruption risk of 0.052.

Further analysis results are visualized for enhanced clarity. The outcomes of SOA and TP of SCN can be effectively illustrated in Fig. 1. Here, the selected suppliers are F (1, 2), F (1, 3), F (2, 2), F (3, 2), F (4, 1), F (4, 2), F (4, 3), F (5, 1), F (5, 2), and F (6, 1). The components they produce are distributed to Assemblers 1 and 2. The overall SCN delivery status and quantities are balanced, with a

Table 5
The positive and negative optimal solutions (Z^+ and Z^-) of each objective function.

	f_1 (Minimization)	f_2 (Minimization)	f_3 (Maximization)	f_4 (Minimization)
Z^+	26,501,100	193.8	1,598.03	197.38
Z^-	26,754,810	243.4	1,438.54	247.91
Z^+- Z^-	−253,710	−49.6	159.49	−50.53

Table 6
The results of the analysis (Our proposed approach).

Objective function	**Utility of objective function**	**Compromise solution**
λ_1	0.6667	26,585,670 (Unit: Thousand)
λ_2	0.6820	209.57
λ_3	0.6747	1,546.148
λ_4	0.6667	214.223

Supplier $F(e, i)$	**Supply quantity**
$F(1, 1)$, $F(1, 2)$, $F(1, 3)$	(0, 170, 220)
$F(2, 1)$, $F(2, 2)$	(0, 390)
$F(3, 1)$, $F(3, 2)$	(0, 390)
$F(4, 1)$, $F(4, 2)$, $F(4, 3)$	(230, 250, 300)
$F(5, 1)$, $F(5, 2)$, $F(5, 3)$	(0, 211, 179)
$F(6, 1)$, $F(6, 2)$	(390, 0)

	Component 1				**Component 2**				**Component 3**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (1, 1)	–	–	0/200 (0%)	Supplier (2, 1)	–	–	0/350 (0%)	Supplier (3, 1)	–	–	0/395 (0%)
Supplier (1, 2)	–	170	170/270 (62%)	Supplier (2, 2)	**220**	**170**	390/390 (100%)	Supplier (3, 2)	220	170	390/400 (97%)
Supplier (1, 3)	220	–	220/320 (68%)	Sum	390			Sum	390		
Sum	390										

	Component 4				**Component 5**				**Component 6**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (4, 1)	230	–	230/280 (82%)	Supplier (5, 1)	–	–	0/155 (0%)	Supplier (6, 1)	220	170	390/420 (92%)
Supplier (4, 2)	**195**	**55**	250/250 (100%)	Supplier (5, 2)	211	–	211/245 (86%)	Supplier (6, 2)	–	–	0/405 (0%)
Supplier (4, 3)	**15**	**285**	300/300 (100%)	Supplier (5, 3)	9	170	179/235 (76%)	Sum	390		
Sum	780			Sum	390						

Delivery routes	**Supply quantity and route selection**
Supplier to assembler	
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(0, 0, 220, 0, 220, 0, 220, 230, 195, 15, 0, 211, 9, 220, 0)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(0, 170, 0, 0, 170, 0, 170, 0, 55, 285, 0, 0, 170, 170, 0)
Assembler to warehouse	
AL_{11}, AL_{12}, AL_{13}	(145, 75, 0)
AL_{21}, AL_{22}, AL_{23}	(0, 24, 146)
Warehouse to customer	
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(0, 41, 0, 0, 95, 9)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(0, 0, 69, 30, 0, 0)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(95, 0, 0, 0, 0, 51)
Average defect rate	0.078
Average interruption risk	0.052

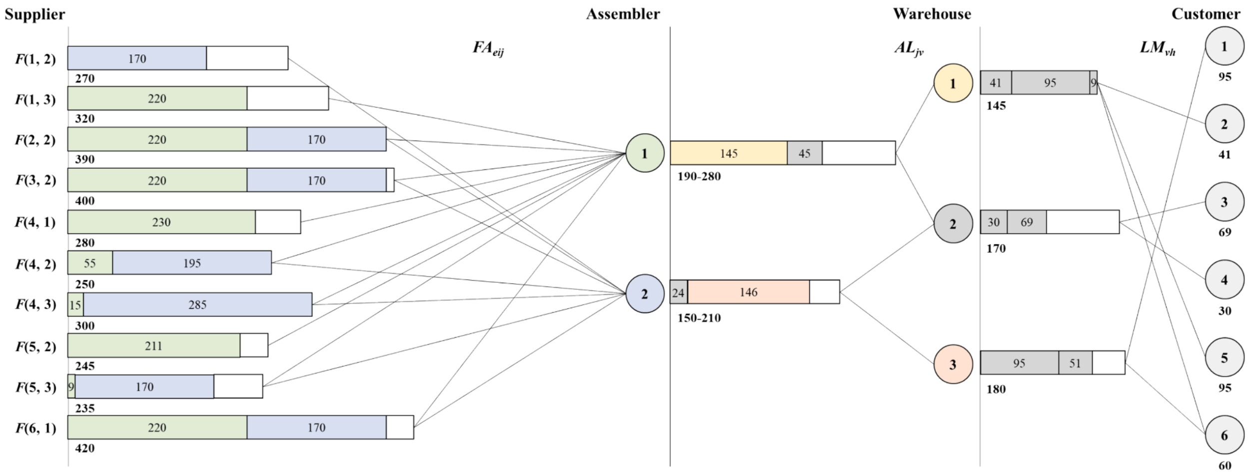

Fig. 1. The schematic diagram of results of the analysis.

requirement of zero stockouts and inventories.

While the case study clearly demonstrates the effectiveness of the proposed SCN model within the CNC machine assembly industry, it is important to consider its generalizability to other industries and regions. The model's structure, which focuses on minimizing operational costs, defect rates, sustainability performance, and disruption risks, is broadly applicable across various supply chain contexts. Industries that prioritize cost efficiency, quality control, and sustainability, such as automotive, electronics, and consumer goods, could potentially benefit from implementing this model.

However, there are certain limitations to be aware of when applying the model beyond the CNC machine assembly industry. The specific parameters and constraints, such as supplier capacity and customer demand, are tailored to the particular case study and may require significant adjustments when applied to different industries or geographical regions. For instance, industries with highly volatile demand patterns or regions with differing regulatory and logistical challenges may need to modify the model's inputs and assumptions to better reflect their unique conditions. Moreover, while the model successfully integrates multiple objectives, the trade-offs between these objectives might vary significantly across different sectors. For example, in industries where sustainability is less of a priority compared to cost or quality, the weighting of the objective functions may need to be adjusted. Additionally, the model's reliance on full transparency and known demand might not be feasible in all industries, particularly those facing high levels of uncertainty or incomplete information.

Therefore, while the SCN model provides a robust framework for optimizing supply chain operations in the CNC machine assembly industry, its practical deployment as an intelligent system requires detailed consideration of how the optimization results can be integrated into real-time decision-making. In our case study, this is achieved by embedding the model into the company's existing SCM and ERP systems, enabling automated data collection, real-time processing, and continuous adjustment of supplier order allocations and transportation planning. The optimization results, once generated, are used to guide operational decisions such as selecting suppliers, managing inventories, and scheduling deliveries, ensuring that the model's recommendations can be directly implemented within the company's daily operations. This integration creates a feedback loop where the system continuously updates based on real-time data, enhancing its precision and adaptability to changing market conditions. The same deployment approach can be adapted for other industries, with modifications to account for specific industry requirements and operational dynamics.

6. Discussions

Although this study overcomes the research gap of addressing both SOA and TP concurrently, it also necessitates the execution of comparative analyses across multiple scenarios to demonstrate the effectiveness and comprehensiveness of the proposed model.

6.1. Comparison of scenarios

6.1.1. Analysis of scenario 1: Only considering the function of total operational costs

By prioritizing cost as the sole objective, potential cost savings and improved financial performance can be achieved by optimizing existing cost-saving opportunities. However, the optimal solution presented in Table 7 reports that although the utility value for cost approaches 1, the total cost in our SCN model is higher compared to a cost-focused model (26,585,670—26,502,480 = 83,190), with a variation rate of less than 1 % (83,190 / 26,585,670). Nonetheless, this approach may overlook important factors related to quality, supplier performance, and risk management, which are critical for ensuring a robust and resilient supply chain. Neglecting these objectives can potentially result in additional cost implications.

Table 7
The optimal solution considering a single objective − cost.

Objective function	Utility of objective function	Compromise solution
λ_1	0.9945	26,502,480 (Unit: Thousand)
λ_2	0.2812	229.45
λ_3	0.2476	1,478.045
λ_4	0.4742	223.947
Supplier *F*(*e*, *i*)	**Supply quantity**	
F(1, 1), *F*(1, 2), *F*(1, 3)	(0, 170, 220)	
F(2, 1), *F*(2, 2)	(220, 170)	
F(3, 1), *F*(3, 2)	(220, 170)	
F(4, 1), *F*(4, 2), *F*(4, 3)	(280, 250, 250)	
F(5, 1), *F*(5, 2), *F*(5, 3)	(155, 0, 235)	
F(6, 1), *F*(6, 2)	(0, 390)	

	Component 1				**Component 2**				**Component 3**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (1, 1)	–	–	0/200 (0%)	Supplier (2, 1)	220	–	220/350 (62%)	Supplier (3, 1)	220	–	220/395 (55%)
Supplier (1, 2)	–	170	170/270 (62%)	Supplier (2, 2)	–	170	170/390 (43%)	Supplier (3, 2)	–	170	170/400 (42%)
Supplier (1, 3)	220	–	220/320 (68%)	Sum	390			Sum	390		
Sum	390										

	Component 4				**Component 5**				**Component 6**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (4, 1)	–	**280**	280/280 (100%)	Supplier (5, 1)	–	**155**	155/155 (100%)	Supplier (6, 1)	–	–	0/420 (0%)
Supplier (4, 2)	**190**	**60**	250/250 (100%)	Supplier (5, 2)	–	–	0/245 (0%)	Supplier (6, 2)	220	170	390/405 (96%)
Supplier (4, 3)	250	–	250/300 (83%)	Supplier (5, 3)	**220**	**15**	235/235 (100%)	Sum	390		
Sum	780			Sum	390						

Delivery routes	Supply quantity and route selection
Supplier to assembler	
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(0, 0, 220, 220, 0, 220, 0, 0, 190, 250, 0, 0, 220, 0, 220)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(0, 170, 0, 0, 170, 0, 170, 280, 60, 0, 155, 0, 15, 0, 170)
Assembler to warehouse	
AL_{11}, AL_{12}, AL_{13}	(145, 75, 0)
AL_{21}, AL_{22}, AL_{23}	(0, 75, 170)
Warehouse to customer	
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(9, 41, 0, 0, 95, 0)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(0, 0, 45, 30, 0, 0)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(86, 0, 24, 0, 0, 60)
Average defect rate	0.083
Average interruption risk	0.053

6.1.2. Analysis of scenario 2: Considering the functions of total operational costs and overall defect rate of suppliers

Considering only cost and defect rate as the two main objectives offers significant advantages such as the potential for cost savings, improved financial performance and customer satisfaction. Based on the optimal solution presented in Table 8, it can be observed that the utility values for cost and defect rate are notably higher compared to our proposed SCN model, with values of 0.7151 and 0.9284, respectively. However, the actual cost difference is (26,585,670——26,573,380 = 12,290), representing a change rate of less than 1 % (12,290 / 26,585,670). Similarly, the defect rate difference is (209.57 – 197.35 = 12.22), with a change rate of less than 1 % (12.22 / 209.57). Despite these results, this approach may overlook supplier performance and neglect route interruption risk, which can lead to issues such as compromised goods or service quality, production disruptions, or supply chain interruptions, ultimately causing delays in the overall production process.

6.1.3. Analysis of scenario 3: Considering the functions of total operational costs, overall defect rate, and sustainability performance of suppliers

In recent years, common TP objectives have included considerations of cost, defect rate, and performance. Integrating factors such as cost, defect rate, and performance into TP objectives can help organizations improve the efficiency and effectiveness of their transportation systems, reduce costs, provide high-quality goods, and enhance customer satisfaction. Optimal solution presented in Table 9 presents that, apart from the cost utility value being higher than our proposed SCN model, there is little difference in the utility values of defect rate and performance. The overall actual data differences are as follows: cost (26,585,670——26,585,670 = 0), with a change rate of less than 1 % (0 / 26,585,670); defect rate (209.57——204.48 = 5.09), with a change rate of less than 1 % (5.09 / 209.57); and performance (1,546.148——1,584.26 = -38.112), with a change rate of less than 1 % (−38.112 / 1,546.148). However, neglecting the risk of supplier disruptions may result in production interruptions or supply chain disruptions. If critical suppliers encounter issues or disruptions, the organization may be unable to continue production or deliver goods on time, which can have a significant impact on business operations.

6.1.4. Analysis of scenario 4: Considering the functions of total operational costs, overall defect rate of suppliers, and SCN disruption risks

Considering cost, defect rate, and interruption risk as multiple objectives provides a more comprehensive view of TP. It assists decision-makers in formulating transportation strategies and improving the efficiency of route planning and management. The optimal solution presented in Table 10 reports that the utility values for cost, defect rate, and interruption risk are higher than those of our proposed SCN model. The overall differences in actual data are as follows: cost (26,585,670——26,585,660 = 10), with a change rate of less than 1 % (10 / 26,585,670); defect rate (209.57——208.51 = 1.06), with a change rate of less than 1 % (1.06 / 209.57); and interruption risk (1,546.148——1,486.309 = 59.839), with a change rate of less than 1 % (59.839 / 1,546.148). By neglecting supplier performance evaluation, organizations miss the opportunity to identify and cultivate long-term relationships with high-performing suppliers. Establishing strategic partnerships with consistently reliable suppliers that meet or exceed expectations can bring numerous benefits, including improved supply chain stability, faster response times, and access to innovative solutions or technologies.

In summary, considering cost, defect rate, performance, and interruption risk simultaneously in the SCN model offers multiple advantages in TP. Firstly, it enables organizations to adopt a comprehensive approach to transportation optimization by considering various dimensions of efficiency and effectiveness. Optimizing cost leads to significant savings and financial benefits. Addressing defect rates ensures goods quality and enhances customer satisfaction, thereby improving the organization's reputation. Incorporating performance evaluation allows for the identification and cultivation of long-term relationships with high-performing suppliers, leading to improved supply chain stability and access to innovative solutions. Lastly, considering interruption risk helps organizations proactively manage and mitigate potential disruptions, ensuring smooth goods flow and minimizing production delays. By considering these multiple objectives, organizations can achieve a well-balanced transportation strategy that maximizes cost savings, maintains high-quality standards, fosters supplier partnerships, and enhances overall supply chain resilience.

6.2. Sensitivity analysis

Due to strategic considerations by the management of the case company, there are plans to streamline the delivery routes to warehouses in the future. Assuming the overall customer demand remains constant, the case company adjusted the quantity of goods held in Warehouse 1 (capl1) from the initial 145 units, gradually increasing it in 5 % increments up to 210 units for sensitivity analysis. This aimed to evaluate the impact of different variables in the model on the utility values of the four objective functions (λ_1, λ_2, λ_3, and λ_4). Fig. 2 illustrates the outcomes of the sensitivity analysis. It indicates that after the increment in the holdings of warehouse 1, the utility values of the four objective functions λ_1, and λ_4 did not exhibit significant changes, while there was a slight increase in λ_2 and λ_3.

Fig. 3 illustrates the variations in inventory quantities across three warehouses, depicting the quantities of goods transported from Assemblers 1 and 2 to Warehouses 1–3. As Warehouse 1 expanded to 210 units, the capacity of Warehouse 2 decreased to 85 units, while Warehouse 3′s capacity decreased to 95 units. This phenomenon indicates that even when Warehouse 1 reaches a certain storage capacity, the other warehouses still maintain a certain level of goods holding capacity. Therefore, this outcome suggests that the case company still requires all three warehouses in transportation to achieve the optimal compromise solution for the four objective functions to the maximum extent.

6.3. Comparison of MODM models

In MODM, various models have been developed to convert multiple objectives into a single-objective model. The earliest of these is

Table 8
The optimal solution considering two objectives – cost and defect rate.

Objective function	Utility of objective function	Compromise solution
λ_1	0.7151	26,573,380 (Unit: Thousand)
λ_2	0.9284	197.35
λ_3	0.4676	1,513.12
λ_4	0.2071	237.442

Supplier *F*(*e*, *i*)	**Supply quantity**
$F(1, 1)$, $F(1, 2)$, $F(1, 3)$	(200, 0, 190)
$F(2, 1)$, $F(2, 2)$	(170, 220)
$F(3, 1)$, $F(3, 2)$	(0, 390)
$F(4, 1)$, $F(4, 2)$, $F(4, 3)$	(230, 250, 300)
$F(5, 1)$, $F(5, 2)$, $F(5, 3)$	(0, 155, 235)
$F(6, 1)$, $F(6, 2)$	(170, 220)

	Component 1				**Component 2**				**Component 3**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (1, 1)	**200**	–	200/200 (100%)	Supplier (2, 1)	–	170	170/350 (48%)	Supplier (3, 1)	–	–	0/395 (0%)
Supplier (1, 2)	–	–	0/270 (0%)	Supplier (2, 2)	220	–	220/390 (56%)	Supplier (3, 2)	220	170	390/400 (97%)
Supplier (1, 3)	20	170	210/320 (65%)	Sum	390			Sum	390		
Sum	390										

	Component 4				**Component 5**				**Component 6**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (4, 1)	–	230	230/280 (82%)	Supplier (5, 1)	–	–	0/155 (0%)	Supplier (6, 1)	–	170	170/420 (40%)
Supplier (4, 2)	**140**	**110**	250/250 (100%)	Supplier (5, 2)	155	–	155/245 (63%)	Supplier (6, 2)	220	–	220/405 (54%)
Supplier (4, 3)	**300**	–	300/300 (100%)	Supplier (5, 3)	**65**	**170**	235/235 (100%)	Sum	390		
Sum	780			Sum	390						

Delivery routes	**Supply quantity and route selection**
Supplier to assembler	
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(200, 0, 20, 0, 220, 0, 220, 0, 140, 300, 0, 155, 65, 0, 220)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(0, 0, 170, 170, 0, 0, 170, 230, 110, 0, 0, 0, 170, 170, 0)
Assembler to warehouse	
AL_{11}, AL_{12}, AL_{13}	(145, 75, 0)
AL_{21}, AL_{22}, AL_{23}	(0, 0, 170)
Warehouse to customer	
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(9, 41, 0, 0, 95, 0)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(0, 0, 45, 30, 0, 0)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(86, 0, 24, 0, 0, 60)
Average defect rate	0.074
Average interruption risk	0.057

Table 9
The optimal solution considering cost, defect rate, and sustainable performance.

Objective function	**Utility of objective function**	**Compromise solution**
λ_1	0.7151	26,573,380 (Unit: Thousand)
λ_2	0.9284	197.35
λ_3	0.4676	1,513.12
λ_4	0.2071	237.442

Supplier *F*(*e*, *i*)	**Supply quantity**
$F(1, 1)$, $F(1, 2)$, $F(1, 3)$	(200, 0, 190)
$F(2, 1)$, $F(2, 2)$	(170, 220)
$F(3, 1)$, $F(3, 2)$	(0, 390)
$F(4, 1)$, $F(4, 2)$, $F(4, 3)$	(230, 250, 300)
$F(5, 1)$, $F(5, 2)$, $F(5, 3)$	(0, 155, 235)
$F(6, 1)$, $F(6, 2)$	(170, 220)

	Component 1				**Component 2**				**Component 3**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (1, 1)	39	–	39/200 (19%)	Supplier (2, 1)	–	–	0/350 (0%)	Supplier (3, 1)	–	–	0/395 (0%)
Supplier (1, 2)	–	31	31/270 (11%)	Supplier (2, 2)	**220**	**170**	390/390 (100%)	Supplier (3, 2)	220	170	390/400 (97%)
Supplier (1, 3)	**181**	**139**	320/320 (100%)	Sum	390			Sum	390		
Sum	390										

	Component 4				**Component 5**				**Component 6**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (4, 1)	–	230	230/280 (82%)	Supplier (5, 1)	–	**155**	155/155 (100%)	Supplier (6, 1)	–	170	170/420 (40%)
Supplier (4, 2)	**140**	**110**	250/250 (100%)	Supplier (5, 2)	220	10	230/245 (93%)	Supplier (6, 2)	220	–	220/405 (54%)
Supplier (4, 3)	**300**	–	300/300 (100%)	Supplier (5, 3)	—	5	5/235 (2%)	Sum	390		
Sum	780			Sum	390						

Delivery routes	**Supply quantity and route selection**
Supplier to assembler	
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(200, 0, 20, 0, 220, 0, 220, 0, 140, 300, 0, 155, 65, 0, 220)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(0, 0, 170, 170, 0, 0, 170, 230, 110, 0, 0, 0, 170, 170, 0)
Assembler to warehouse	
AL_{11}, AL_{12}, AL_{13}	(145, 75, 0)
AL_{21}, AL_{22}, AL_{23}	(0, 0, 170)
Warehouse to customer	
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(9, 41, 0, 0, 95, 0)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(0, 0, 45, 30, 0, 0)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(86, 0, 24, 0, 0, 60)
Average defect rate	0.074
Average interruption risk	0.057

Table 10
The optimal solution considering cost, defect rate, and interruption risk.

Objective function	Utility of objective function	Compromise solution
λ_1	0.6667	26,585,660 (Unit: Thousand)
λ_2	0.7034	208.51
λ_3	0.2995	1,486.309
λ_4	0.7644	209.282

Supplier *F*(*e*, *i*)	**Supply quantity**
F(1, 1), *F*(1, 2), *F*(1, 3)	(200, 170, 20)
F(2, 1), *F*(2, 2)	(350, 40)
F(3, 1), *F*(3, 2)	(0, 390)
F(4, 1), *F*(4, 2), *F*(4, 3)	(230, 250, 300)
F(5, 1), *F*(5, 2), *F*(5, 3)	(111, 44, 235)
F(6, 1), *F*(6, 2)	(390, 0)

	Component 1				**Component 2**				**Component 3**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (1, 1)	**200**	–	200/200 (100%)	Supplier (2, 1)	**181**	**169**	350/350 (100%)	Supplier (3, 1)	–	–	0/395 (0%)
Supplier (1, 2)	–	170	170/270 (62%)	Supplier (2, 2)	39	1	40/390 (10%)	Supplier (3, 2)	220	170	390/400 (97%)
Supplier (1, 3)	20	–	20/320 (6%)	Sum	390			Sum	390		
Sum	390										

	Component 4				**Component 5**				**Component 6**		
	Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity		Assembler 1	Assembler 2	Sum/ Capacity
Supplier (4, 1)	230	–	230/280 (82%)	Supplier (5, 1)	111	–	111/155 (71%)	Supplier (6, 1)	220	170	390/420 (92%)
Supplier (4, 2)	**210**	**40**	250/250 (100%)	Supplier (5, 2)	44	–	44/245 (17%)	Supplier (6, 2)	–	–	0/405 (0%)
Supplier (4, 3)	—	**300**	300/300 (100%)	Supplier (5, 3)	**65**	**170**	235/235 (100%)	Sum	390		
Sum	780			Sum	390						

Delivery routes	**Supply quantity and route selection**
Supplier to assembler	
FA_{111}, FA_{121}, FA_{131}, FA_{211}, FA_{221}, FA_{311}, FA_{321}, FA_{411}, FA_{421}, FA_{431}, FA_{511}, FA_{521}, FA_{531}, FA_{611}, FA_{621}	(200, 0, 20, 181, 39, 0, 220, 230, 210, 0, 111, 44, 65, 220, 0)
FA_{112}, FA_{122}, FA_{132}, FA_{212}, FA_{222}, FA_{312}, FA_{322}, FA_{412}, FA_{422}, FA_{432}, FA_{512}, FA_{522}, FA_{532}, FA_{612}, FA_{622}	(0, 170, 0, 169, 1, 0, 170, 0, 40, 300, 0, 0, 170, 170, 0)
Assembler to warehouse	
AL_{11}, AL_{12}, AL_{13}	(145, 75, 0)
AL_{21}, AL_{22}, AL_{23}	(0, 75, 95)
Warehouse to customer	
LM_{11}, LM_{12}, LM_{13}, LM_{14}, LM_{15}, LM_{16}	(0, 41, 0, 0, 95, 9)
LM_{21}, LM_{22}, LM_{23}, LM_{24}, LM_{25}, LM_{26}	(0, 0, 69, 30, 0, 51)
LM_{31}, LM_{32}, LM_{33}, LM_{34}, LM_{35}, LM_{36}	(95, 0, 0, 0, 0, 0)
Average defect rate	0.078
Average interruption risk	0.055

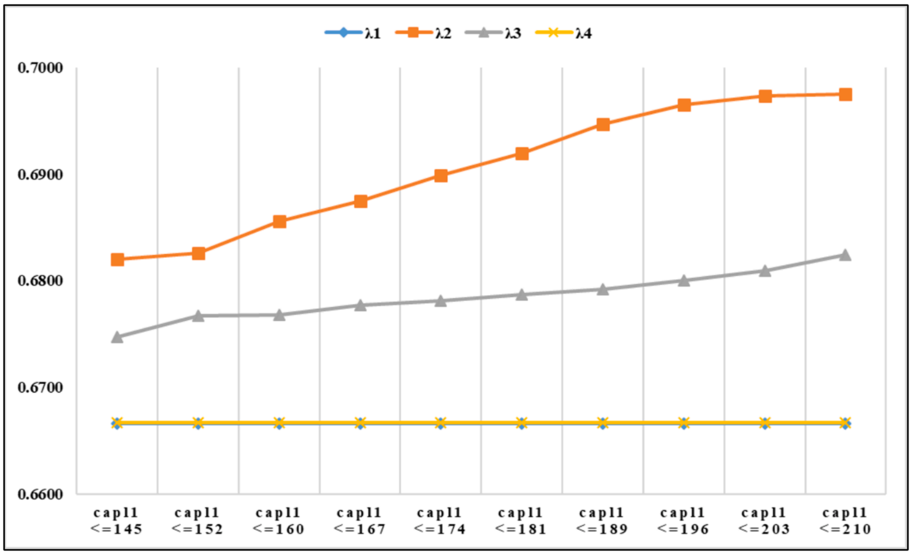

Fig. 2. The sensitivity analysis results for the utility values of the four objective functions.

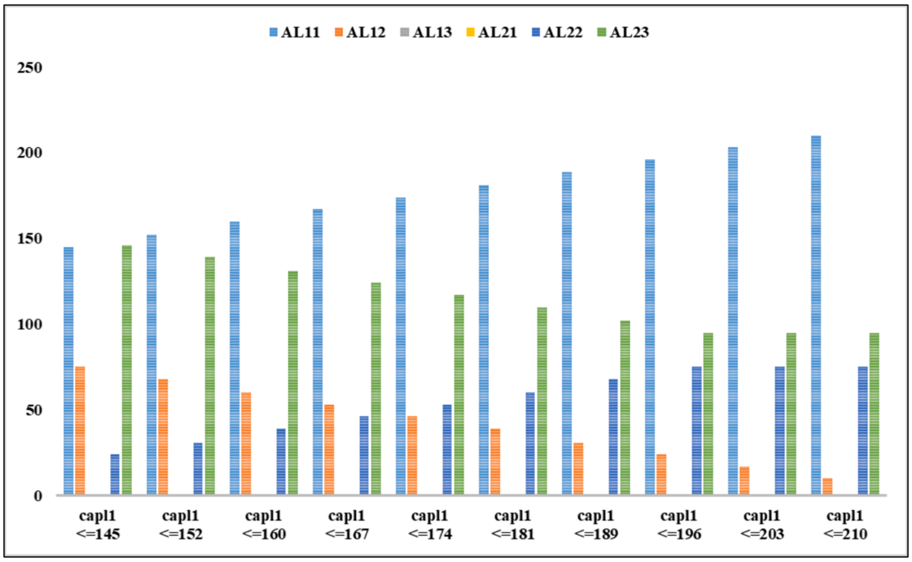

Fig. 3. The sensitivity analysis of inventory levels in three warehouses.

the vector maximum model. Over time, many scholars have proposed different methods to address the problem of finding optimal solutions, including the utility function model, global criterion model, max–min model, and arithmetical average model [32]. These approaches differ significantly from heuristic algorithms; they not only provide a single solution but also offer high computational efficiency [24].

This study employs several of these models to solve the proposed SCN model and compare their differences. The Model 1, the vector maximum model, sums all objective functions together to maximize the total objective function. The Model 2, the utility function model, assigns weight values to each objective function based on their importance (with weights of 0.2, 0.2, 0.3, and 0.3, respectively). The Model 3, the global criterion model, converts all objectives into "smaller-is-better" functions, aiming to minimize the total objective utility. The Model 4, the max–min model, sets a virtual parameter (λ) to maximize it. Each objective is first transformed using a utility function, and then they are required to be greater than the virtual parameter (λ). The Model 5, the arithmetical average model, is an extension of the max–min model, where multiple virtual parameters (λ_1 to λ_4) are set corresponding to each objective, aiming to maximize the average virtual parameter. The Model 6 is the AMM-FMOLP model used in this study. The model optimizes the arithmetical average model by not only setting a virtual parameter as a threshold value—requiring that each objective utility must exceed this threshold—but also ensuring that the utilities of each objective are as balanced as possible. The comparison of the models is presented in Table 11.

The comparative analysis of the models reveals several key insights. Models 1 and 2 yield identical solutions; however, the utility of each objective is notably imbalanced. Specifically, while one objective is fully satisfied, the utilities of the remaining objectives are significantly poor. Model 3 produces the least favorable outcome, with an average utility of only 0.3284. In contrast, Models 4, 5, and 6 show better performance, with average utilities of 0.6713, 0.7038, and 0.6725, respectively. Among these, Model 5 achieves the highest total utility of 2.8154. However, this comes at the cost of significant imbalance across individual objective utilities, which may compromise the performance of certain objectives.

In comparison, the AMM-FMOLP model employed in this study emerges as the most suitable approach. It not only enhances overall utility but also ensures a more balanced performance across all objectives. This balanced approach is crucial for optimizing supply chain performance without disproportionately sacrificing the effectiveness of any single objective.

7. Conclusions

This research addresses several critical gaps in the existing body of SCN studies. Firstly, it tackles the scarcity of research that simultaneously considers SOA and TP, especially within the specific context of contract manufacturing assembly enterprises. This dual focus is rare yet essential for a comprehensive understanding of SCNs. Secondly, our study enriches the field by incorporating a wide array of considerations into the decision-making model, including procurement and delivery costs, supplier defect rates, sustainability performance, and the risks of supply chain disruptions. Such a holistic approach ensures that both cost-efficiency and sustainability are balanced, filling a notable void in current research practices. The contributions of this study are significant and manifold:

(i) Innovative Integration

By uniquely integrating SOA with TP, our MODM model for SCNs offers a novel approach that enhances the strategic management of supply chains.

(ii) Comprehensive Objective Function

The model's objective function is comprehensive, covering operational costs, supplier defect rates, sustainability performance, and disruption risks. This broad scope ensures that our model not only focuses on economic efficiency but also on environmental and social sustainability, addressing a critical research gap.

(iii) Holistic Evaluation and Strategic Risk Management

We extend the evaluation of supply chain dynamics beyond traditional metrics, incorporating sustainability and disruption risks into our analysis. This approach not only rewards high-performing suppliers but also contributes to the reduction of overall disruption risks in the SCNs, thereby promoting a more resilient supply chain network.

(iv) Operational Efficiency and Sustainability

Our study underscores the importance of balancing operational efficiency with sustainability and risk management in SCNs. By doing so, it contributes to a more sustainable and efficient supply chain management practice, aligning with contemporary demands for corporate responsibility.

In summary, this paper provides a comprehensive model that addresses previously unexplored aspects of SCNs, offering practical insights for managing complex supply chain networks more effectively and sustainably.

Building upon the insights from our study, future research could delve into a variety of paths to further refine and expand the efficacy and comprehension of SCNs management. Potential avenues for exploration include the development of dynamic models. These models would be capable of adjusting to fluctuating market conditions, supplier capabilities, and customer demands in real-time, thereby enhancing the responsiveness and flexibility of SCNs. Additionally, the application of machine learning and artificial intelligence algorithms presents a promising opportunity to streamline SOA and TP, resulting in more streamlined and cost-effective supply chain operations. By exploring these and other future research directions, scholars and practitioners are positioned to advance the foundational efforts of our study, driving the field of supply chain management towards practices that are not only more efficient and robust but also more sustainable.

CRediT authorship contribution statement

Huai-Wei Lo: Writing – original draft, Software, Methodology, Investigation, Conceptualization. **Chun-Jui Pai:** Writing – original draft, Software, Data curation. **Muhammet Deveci:** Writing – review & editing, Visualization, Supervision, Investigation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to

Table 11
The comparative analysis of the multiple models.

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Utility of objective function 1 (λ_1)	1.0000	1.0000	0.4120	0.6713	0.5730	0.6667
Utility of objective function 2 (λ_2)	0.4284	0.4284	0.1653	0.6713	0.6673	0.6821
Utility of objective function 3 (λ_3)	0.3427	0.3427	0.5187	0.6713	0.9221	0.6747
Utility of objective function 4 (λ_4)	0.3653	0.3653	0.2177	0.6713	0.6529	0.6667
Average	0.5341	0.5341	0.3284	0.6713	0.7038	0.6725
Sum	2.1365	2.1365	1.3137	2.6852	2.8154	2.6901

influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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