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Development of a Multi-Tier Collaborative Optimization Model for Semiconductor Supply Chain Management

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ABSTRACT

With the continuous advancement of global information technology, the semiconductor industry has become a cornerstone of the world economy. The complexity and high interdependence of the semiconductor supply chain make its management and optimization a challenging task, particularly in achieving collaborative decision-making across different tiers of suppliers. Traditional research in supply chain management has largely focused on optimizing single-tier suppliers or partial segments of the supply chain, lacking a comprehensive analysis and optimization of multi-tier supplier collaboration. To address this challenge, this study proposes an optimization model based on a three-tier management and collaborative decision-making framework within the semiconductor supply chain. The model captures the intricate collaborative relationships among upstream raw material suppliers, midstream manufacturers, and downstream distributors, aiming to enhance the overall efficiency and responsiveness of the supply chain through coordinated multi-tier decision-making. Existing studies on semiconductor supply chains predominantly emphasize static or localized optimization, often neglecting the dynamic nature of supply chains and lacking systematic research on information sharing and coordination mechanisms. Moreover, these approaches frequently suffer from excessive simplification, inadequate adaptability to dynamic changes, and poor real-world applicability. To overcome these limitations, this paper develops and solves a collaborative optimization model covering three key supply chain tiers and introduces a dynamic framework for adjusting decisions across all tiers of suppliers. The results demonstrate that the proposed model significantly improves overall supply chain coordination, reduces the impact of uncertainties, and enhances both economic performance and market competitiveness.

1. INTRODUCTION

With the rapid development of information technology and the advancement of globalization, the semiconductor industry, as an important support for modern technology, has gradually become an indispensable part of the global economy [1, 2]. The complexity and high dependency of the semiconductor industry chain make its supply chain management a highly challenging field [3-6]. Under the background of global competition and market demand fluctuations, how to effectively manage and optimize the supply links in the semiconductor supply chain [7, 8], especially the collaborative cooperation among multi-tier suppliers, has become a hot topic of concern in both academia and industry. In order to respond to the constantly changing market demand, improve supply chain efficiency, and reduce costs, the management of multi-tier supply links and collaborative decision optimization in the semiconductor supply chain is particularly important.

In the field of semiconductor supply chain management, researchers have proposed a variety of management and optimization strategies [9-11], aiming to improve the flexibility, response speed, and cost-effectiveness of the supply chain. However, existing research mainly focuses on the optimization of single suppliers or only considers the collaborative effects of partial segments in the supply chain, lacking a comprehensive analysis of the collaborative relationships among supply links in the entire multi-tier supply chain [12, 13]. Therefore, exploring a multi-tier supply link management and collaborative decision optimization model suitable for the semiconductor industry can provide more operational solutions for practical supply chain management, which has important academic significance and application value.

At present, research methods in supply chain management mostly focus on static optimization or local optimization, lacking effective response mechanisms for dynamic changes [14-17]. For example, Meshalkin and Rakitina [18] and Sawik [19] solve supply chain management problems through traditional linear programming or integer programming methods. Although these methods are theoretically effective, they often ignore the complex interaction relationships among supply chain members as well as the real-time and flexibility of supply chain response in practical operation. In addition, Mahmoudi and Fazlollahtabar [20] ignore the role of information sharing and coordination mechanisms, resulting in unsatisfactory practical application effects. Therefore, existing research methods have limitations such as excessive model simplification, insufficient dynamics, and poor practical applicability in solving the optimization problem of collaborative decision-making among multi-tier suppliers.

This paper mainly focuses on the management and collaborative optimization of multi-tier supply links in the semiconductor supply chain, and proposes an optimization model based on three-tier supply link management and collaborative decision-making. Firstly, this paper constructs a multi-tier supply chain management framework covering upstream raw material suppliers, midstream manufacturers, and downstream distributors, and optimizes the behavior of suppliers at all tiers through a collaborative decision-making model. Secondly, this paper uses advanced optimization algorithms to solve the model, aiming to improve decision-making efficiency, reduce costs, and enhance the overall response ability and stability of the supply chain in practical supply chain management. The research results not only provide theoretical basis and practical guidance for supply chain management in the semiconductor industry, but also offer new ideas and methods for supply chain optimization in related fields, with high research value and practical application prospects.

2. CONSTRUCTION OF THE THREE-TIER MANAGEMENT AND COLLABORATIVE DECISION OPTIMIZATION MODEL FOR SUPPLY LINKS IN THE SEMICONDUCTOR SUPPLY CHAIN

In the semiconductor supply chain, the structure of the supply links usually presents a multi-tier and highly complex characteristic, involving multiple key links and different types of suppliers. Overall, the supply links in the semiconductor supply chain include raw material suppliers and manufacturers. Suppliers are mainly responsible for providing the basic raw materials required for semiconductor manufacturing, such as silicon wafers, chemicals, photoresists, etc. The quality and supply stability of these raw materials directly affect the manufacturing process and final quality of semiconductor products. Manufacturers include wafer fabs and packaging and testing plants, which undertake the core production tasks of semiconductor products, including chip design, wafer manufacturing, packaging, and testing processes. The complexity of the manufacturing link requires high-precision equipment and technical support, and it also has strict requirements on production cycle and inventory management. In the semiconductor supply chain, the relationship between suppliers and manufacturers is extremely close and clearly hierarchical. Suppliers at different tiers not only need to share information during the production process, but also need to respond collaboratively in the face of demand fluctuations and supply uncertainties. The delivery timeliness and quality assurance of upstream suppliers directly affect the production scheduling and manufacturing progress of midstream manufacturers; manufacturers, in turn, strive to shorten the production cycle and improve production efficiency by optimizing production scheduling and inventory management. In the semiconductor industry, all supply links in the supply chain may be affected by market demand fluctuations, technological innovations, or policy changes. Therefore, coordination and cooperation between suppliers, manufacturers, and consumers are particularly important. The collaborative decision optimization among various links can not only improve the overall efficiency of the supply chain but also reduce the risk of supply chain disruption caused by decision-making errors in a single link.

This paper constructs a three-tier management and collaborative decision optimization model of supply links in the semiconductor supply chain around three key objectives: customer satisfaction, manufacturer profit of the supply link, and supplier profit of the supply link. Among them, customer satisfaction is one of the core objectives of semiconductor supply chain optimization, which is directly related to the market competitiveness of end products and customer loyalty. Since semiconductor products usually have a high level of technical content and complex production processes, customers have very strict requirements on product quality, delivery time, and technical support. Therefore, in the three-tier management and collaborative decision model, customer satisfaction needs to be improved by optimizing factors such as response speed, delivery timeliness, and product quality of each link in the supply chain. The profit optimization of manufacturers and suppliers is another important decision-making objective in the three-tier management model. Manufacturers in the semiconductor supply chain usually need to face multiple challenges in the production process, such as raw material price fluctuations, production capacity constraints, and technical requirements. In order to maximize manufacturer profit, the model needs to optimize production planning, inventory management, and cost control under the premise of ensuring product quality and delivery time. Meanwhile, as a key link in the supply chain, suppliers also need to consider their own profit optimization strategies in the multi-tier decision-making process. Supplier profit is not only affected by the cost of raw materials, but also influenced by production efficiency, delivery cycle, and long-term cooperative relationships with manufacturers. Assume that the first, second, and third-tier decision-makers in the model control decision variables a_1, a_2, and $a3$, respectively. Customer satisfaction is denoted by D_1, manufacturer profit is denoted by D_2, and supplier profit is denoted by D_3. The model expression is:

$$\begin{aligned} &\max D_1 = D_1(a_1,a_2,a_3)\, s.t.\, h_1(a_1,a_2,a_3) \le 0, a_1,a_2,a_3 \ge 0 \\ &\max D_2 = D_2(a_1,a_2,a_3)\, s.t.\, h_2(a_1,a_2,a_3) \le 0, a_1,a_2,a_3 \ge 0 \\ &\max D_3 = D_3(a_1,a_2,a_3)\, s.t.\, h_3(a_1,a_2,a_3) \le 0, a_1,a_2,a_3 \ge 0 \end{aligned} \tag{1}$$

(1) Collaborative Center

As the coordination and decision-making hub of the supply chain, the collaborative center is mainly responsible for integrating, coordinating, and making decisions based on the information from various links of the supply chain. Its core objective is to balance the interests of suppliers, manufacturers, and customers at different tiers from a global perspective, so as to realize the overall optimal operation of the supply chain. Specifically, the decision-making basis of the collaborative center includes key data such as demand forecasting, production capacity, delivery time, and inventory management of each link of the supply chain. In the semiconductor supply chain, due to large market demand fluctuations and frequent technology updates, the collaborative center needs to dynamically adjust production planning and resource allocation to cope with uncertainties. Suppose the delivery rate is denoted by PSFF, the defective rate is denoted by FE, and the weight of the defective rate in the customer satisfaction calculation formula is denoted by φ, the objective function is:

$$D_1 = (1-\phi) * PSFF - \phi * FE \tag{2}$$

(2) Manufacturer

In the semiconductor supply chain, manufacturers face great cost pressures, including raw material procurement costs, production equipment investment, labor costs, and R&D expenses. At the same time, semiconductor manufacturers must also cope with challenges such as short product life cycles and rapid technological updates. Therefore, the optimization objective of the manufacturer's profit is not only to ensure the maximization of production efficiency based on meeting market demand but also to reduce operating costs through refined production scheduling and inventory control. Let the quantity of products produced by the manufacturer be denoted by W, the product sales price by o_2, the unit production cost of the manufacturer by z_2, the unit cost required for the manufacturer to expand production by q_2, the unit cost for the manufacturer to conduct sampling inspection of components by ρ, the sampling proportion of components by j, the unit compensation to customers when defective products are found by customers by $\zeta 1$, and the penalty imposed by the manufacturer on the supplier when defective products are found by the manufacturer by $\zeta 2$, the objective function is:

$$\begin{aligned} D_2 = (o_2 - z_2) * W - \zeta_1 * (1-j) * \Phi * W \\ -\rho * j * w - o_3 * w + \zeta_2 * j * \Phi * w - q_2 * W \end{aligned} \tag{3}$$

(3) Supplier

In the semiconductor industry, the supplier's profit is affected by multiple factors, including the procurement cost of raw materials, the benefit of production scale, the stability of order volume, and long-term cooperation relationships with manufacturers. Since semiconductor manufacturing usually requires high-precision and high-quality raw materials, suppliers need to ensure timely and stable delivery and carry out effective coordination with manufacturers. In the supply chain collaborative optimization model, the profit objective of the supplier needs to consider its production and supply capacity, as well as the cooperation relationship with manufacturers and end customers. Assume the quantity of components produced by the supplier is denoted by w, the sales price of components is denoted by o_3, the unit production cost of the supplier is denoted by z_3, the cost required for the supplier to expand production is denoted by o, the capital investment used by the supplier to reduce the defective rate is denoted by g, the defective rate of the components produced by the supplier is denoted by Φ, the objective function is:

$$D_3 = (o_3 - z_3) * w - \zeta_2 * j * \Phi * w - g - o_3 * w \tag{4}$$

3. SOLUTION OF THE THREE-TIER MANAGEMENT AND COLLABORATIVE DECISION OPTIMIZATION MODEL IN THE SUPPLY SEGMENT OF THE SEMICONDUCTOR SUPPLY CHAIN

In the solution of the three-tier management and collaborative decision optimization model in the supply segment of the semiconductor supply chain, the fuzzy membership principle is first used to transform the multi-tier objectives into a single-objective programming problem for global optimization. Specifically, the objectives of customer satisfaction, manufacturer profit, and supplier profit involve certain fuzziness and uncertainty. Therefore, the fuzzy membership function is used to quantify the respective weights and influence degrees of these objectives. The introduction of fuzzy membership can effectively handle the conflicts and trade-offs between the objectives, so that each tier's objectives can be solved through a unified single-objective function. In this model, the three-tier decision-makers interact and coordinate continuously, adjusting their decision parameters, and use the max-min method to obtain an acceptable equilibrium solution. The core of the equilibrium solution is to balance customer demand, manufacturer and supplier profit, while ensuring that each tier of decision-maker can find a mutually acceptable decision result in a changing market environment. In the second step of the optimization process, with customer satisfaction as the top-priority decision objective, an appropriate coordination mechanism is designed to meet the minimum requirements of manufacturers and suppliers, and to maximize customer satisfaction. For the semiconductor supply chain, the diversity of customer demand and the high requirements on product quality and delivery time make the optimization of customer satisfaction a key factor. By prioritizing customer satisfaction, the competitiveness and customer loyalty of semiconductor products in the market can be ensured. Meanwhile, during the optimization process, the objectives of manufacturer profit and supplier profit are also effectively considered. By setting a minimum target satisfaction for each tier, it ensures that each decision-maker can achieve overall optimization under the condition of meeting the minimum requirements. Finally, based on the Nash equilibrium principle, the model further explores whether there is room for improvement in each tier's objectives by appropriately relaxing some decision variable constraints.

3.1 Equilibrium satisfaction solution

In the solution of the three-tier management and collaborative decision optimization model in the supply segment of the semiconductor supply chain, the specific idea of obtaining equilibrium satisfaction based on the max-min method starts from independently solving the objective function of each tier. Each decision-maker—customer, manufacturer, and supplier—performs independent optimization under constraints, considering only their own objective, and solves for their respective ideal solutions. Customer satisfaction, manufacturer profit, and supplier profit are quantified by their respective membership functions, and η^{D1}, η^{D2}, and η^{D3} represent the satisfaction values of each tier decision-maker. In the semiconductor supply chain, customers have high requirements on product quality, delivery time, and technical support, so customer satisfaction as the primary objective needs to be given priority. Manufacturers and suppliers focus respectively on their own production costs, profit maximization, and supply capability, so their objective functions focus on profit optimization. After each tier independently solves the problem, a set of objective values and satisfaction values is obtained, which serve as the basis for the next step of decision-making.

(1) Interactive Negotiation Between the First Two Tiers

In the model, customer satisfaction is expressed through the objective membership function $\omega(D_1)$, and the satisfaction with respect to decision variables (such as product pricing, delivery time, etc.) is also quantified by the decision variable membership function $\omega(a_1)$. The first-tier decision-maker performs optimization under its own objective and constraints, derives an ideal solution, and calculates the corresponding satisfaction value η^{D1}. This satisfaction value and the objective membership function will serve as constraints for the second-tier decision-maker during optimization, ensuring that the second-tier decisions can be adjusted and optimized within the range of customer satisfaction. To obtain an effective solution, the max-min method should be applied. Let:

$$\eta = MIN\left\{\omega\left(D_1\right), \omega\left(D_2\right), \omega\left(a_1\right)\right\} \tag{5}$$

In the second-tier decision optimization, the manufacturer and supplier need to consider the constraints provided by the first-tier decision-maker, including the customer satisfaction objective membership function $\omega(D_1)$ and the decision variable membership function $\omega(a_1)$. The second-tier decision-makers will maximize their own profits while ensuring that their decisions meet the customer satisfaction requirements provided by the first tier. To obtain an effective solution, the max-min method is used to transform the second-tier problem into a single-tier programming model. During the solution process, it is necessary to maximize the overall satisfaction η of all decision-makers' objectives and decision variables.

$$\begin{aligned}
&MAX\ \eta \\
&s.t.\omega\left(D_1\right) \geq \eta \quad \omega\left(D_2\right) \geq \eta \quad \omega\left(a_1\right) \geq \eta \\
&h_2\left(a_1, a_2, a_3\right) \leq 0 \quad a_1, a_2, a_3 \geq 0
\end{aligned} \tag{6}$$

In practical applications of the semiconductor supply chain, due to the uncertainty of customer demand, conflicts of interest between manufacturers and suppliers, and the complexity of products, this interactive and collaborative optimization process is very important. After obtaining the result of the second-tier decision, the solution result will be fed back to the first-tier decision-maker for evaluation. If the first-tier decision-maker is satisfied with the result, the optimization process ends and the result is passed to the third-tier decision-maker. If the first tier is not satisfied, the decision-maker needs to adjust the objective membership function or satisfaction level, and pass the adjusted membership function back to the second-tier decision-maker. Upon receiving the feedback from the first tier, the second-tier decision-makers also need to adjust their own membership functions and satisfaction levels according to the satisfaction level of the first tier and re-optimize until both the first and second-tier decision-makers can accept the final result.

(2) Three-Tier Interactive Negotiation

When solving the three-tier management and collaborative decision optimization model in the supply segment of the semiconductor supply chain, the first step of obtaining equilibrium satisfaction based on the max-min method is to pass the objective membership functions and decision variable membership functions of the first-tier customer and the second-tier manufacturer and supplier to the third-tier decision-maker. The membership functions of the customer satisfaction and the profit objectives of the supplier and manufacturer become constraints at this stage and are input into the optimization model of the third tier. This means that the third-tier decision-makers not only need to maximize their own profit objectives, but also must consider the customer satisfaction and the profit requirements of the manufacturer. Similarly, let:

$$\eta = MIN\left\{\omega\left(D_1\right), \omega\left(D_2\right), \omega\left(D_3\right), \omega\left(a_1\right), \omega\left(a_2\right)\right\} \tag{7}$$

Further, transform the single-tier programming model with the objective of maximizing the overall satisfaction of all decision-makers' objectives and decision variables. In the semiconductor supply chain, the decision-makers include customers, manufacturers, and suppliers, and there are certain conflicts and coordination needs among the three parties' objectives. The application of the max-min method means to seek an equilibrium solution by maximizing the overall satisfaction of customer satisfaction, manufacturer profit, and supplier profit. This new single-tier programming model integrates the objectives of the three parties and obtains a balance point by maximizing the satisfaction of all decision-makers, so as to achieve an optimal solution commonly accepted by the three parties. The new single-tier programming model expression is:

$$\begin{aligned}
&MAX\ \eta \\
&s.t.\omega\left(D_1\right), \omega\left(D_2\right), \omega\left(D_3\right), \\
&\omega\left(a_1\right), \omega\left(a_2\right) \geq \eta \quad h_3\left(a_1, a_2, a_3\right) \leq 0 \\
&a_1, a_2, a_3 \geq 0 \quad 0 \leq \eta \leq 1
\end{aligned} \tag{8}$$

After obtaining the solution of the new single-tier programming model, the result needs to be fed back to the first and second-tier decision-makers for evaluation. If all three tiers of decision-makers are satisfied with the current solution, then the solution process ends and proceeds to the next step. If any tier of decision-makers is not satisfied with the result, corresponding adjustments need to be made. For example, if the customer is not satisfied with the current product quality or delivery time, the customer will adjust its satisfaction requirements, modify the objective membership function, and pass the adjusted result to the second-tier decision-maker. Similarly, if the supplier or manufacturer is dissatisfied with the result, they will also adjust their own objectives and decision variable membership functions and re-input them into the optimization model. Through such interactive adjustments, each tier maximizes its own objective while considering the objectives of other tiers, thus achieving final coordination and win-win results.

Finally, through the iterative solution of the max-min method, the equilibrium solution (a_1,a_2,a_3) and equilibrium satisfaction λ of the three-tier objective programming are obtained. In this process, the three decision-makers set their respective minimum expected satisfaction values $(\sigma_1,\sigma_2,\sigma_3)$ based on the obtained equilibrium satisfaction λ and proceed to the next step of the solution process.

3.2 Priority optimization of the first-tier objective

In the three-tier management and collaborative decision optimization model of the semiconductor supply chain, the priority optimization of the first-tier objective is crucial to ensure that customer satisfaction is fully guaranteed. Due to the specific and diverse demands of customers for semiconductor products, encompassing aspects such as product quality, delivery time, and technical support, optimizing customer satisfaction should be the primary goal in supply chain decision-making. To prioritize the optimization of customer satisfaction, the supply chain coordination center will first ensure that customer demands for products are met, and then proceed with subsequent decisions. Specifically, the priority optimization of the first-tier objective is reflected in the decision-making process by adjusting the customer satisfaction membership function and setting priorities, so that the tier of customer satisfaction becomes a prerequisite for other decision objectives. This optimization method not only considers the basic needs of customers but also ensures that customer satisfaction, as a constraint, fully guides the decisions of the second tier, avoiding the sacrifice of basic customer needs while satisfying the profits of suppliers or manufacturers, thereby enhancing the overall efficiency and stability of the supply chain.

(1) Maximizing the First-Tier Objective

One of the specific steps in the priority optimization of the first-tier objective is to consider customer satisfaction as the most important goal, maximizing customer satisfaction while ensuring that the objectives of manufacturers and suppliers are reasonably met. First, the first-tier decision-maker establishes a single-tier planning model, prioritizing the maximization of customer satisfaction under the premise of considering the minimum satisfaction of manufacturers and suppliers. This means that the first-tier decision-maker needs to adopt corresponding decision strategies, such as adjusting product quality and delivery time, to meet customer demands while ensuring that the minimum satisfaction levels of lower-tier decision-makers are not compromised. For the semiconductor supply chain, the diversity and high requirements of customer demands make optimization in aspects such as product quality and delivery time particularly important.

$$\begin{aligned}&MAX\,\sigma_1\\&s.t.\omega(D_1)\ge\sigma_1\quad\omega(D_2)\ge\sigma_2\\&\omega(D_3)\ge\sigma_3\quad\omega(D_1),\omega(D_2)\ge\eta\\&h_1(a_1,a_2,a_3)\le0\quad a_1,a_2,a_3\ge0\end{aligned}\tag{9}$$

In the actual operation of the supply chain, due to conflicts of interest among decision-makers at various tiers, the optimal solution of the first-tier decision-maker may not be achievable in practice. Therefore, to address the issue of infeasible solutions caused by conflicts of interest, the first-tier decision-maker needs to adjust the model according to the actual situation, relax some constraints or adjust the objective membership function to find a feasible solution. For example, the first-tier decision-maker may moderately relax certain requirements of customer satisfaction, allowing for some compromise to ensure that the operation of the entire supply chain is not overly restricted. In the semiconductor supply chain, the profit objectives of manufacturers and suppliers often conflict with customer satisfaction, especially in aspects such as product pricing and delivery time. Therefore, the first-tier decision-maker needs to flexibly adjust decisions to balance customer satisfaction with the overall efficiency of the supply chain.

(2) Optimization Using Adjustment Mechanism

When the model has no feasible solution, the first-tier decision-maker, in order to achieve its minimum satisfaction goal σ_1, will, when necessary, reduce the target satisfaction of the lower two tiers of decision-makers. The core of this adjustment mechanism lies in appropriately adjusting the target satisfaction values of the lower two tiers of decision-makers to ensure that the first-tier decision-maker can maximize the customer satisfaction objective while maintaining the acceptability of the final solution by the lower-tier decision-makers. In specific operations, the first-tier decision-maker will adjust the minimum satisfaction of manufacturers and suppliers to ensure that their satisfaction levels are not lower than the equilibrium satisfaction η obtained through the max-min method. In this process, manufacturers and suppliers in the semiconductor supply chain usually have strong profit demands. Therefore, adjusting their target satisfaction requires careful consideration to ensure that their profit expectations are not excessively compressed, avoiding intensified conflicts of interest. Next, to ensure the feasibility of the model and the acceptability of the lower-tier decision-makers, the first-tier decision-maker will minimize the reduction range of the lower-tier target satisfaction, i.e., minimize the value of β. The specific operation of this step is to further optimize the adjustment parameters under the constraints that the first-tier target satisfaction and the lower-tier target satisfaction are not lower than the equilibrium satisfaction, so that the reduction range is minimized. Manufacturers and suppliers in the semiconductor supply chain are highly sensitive to profits. Therefore, when the first-tier decision-maker adjusts the lower-tier satisfaction, it needs to accurately calculate the minimum adjustment amount to avoid excessive profit losses or supply chain instability. The model expression is as follows:

$$\begin{aligned}&MIN\,\beta\\&s.t.\omega(D_1)\ge\sigma_1\quad\omega(D_2)\ge\sigma_2-\beta\ge\eta\\&\omega(D_3)\ge\sigma_3-\beta\ge\eta\quad\omega(a_1)\ge\eta\\&\omega(a_2)\ge\eta\quad h_1(a_1,a_2,a_3)\le0\\&h_2(a_1,a_2,a_3)\le0\quad h_3(a_1,a_2,a_3)\le0\\&a_1,a_2,a_3\ge0\quad 0\le\beta<1\end{aligned}\tag{10}$$

Let Ξ be the ratio of the actual target satisfaction of the lower two tiers to the minimum expected satisfaction obtained in the first step. To fully optimize the solution obtained by the model, let:

$$\Xi=\frac{MIN\{\omega(D_u)\}}{\sigma},u=2,3\tag{11}$$

$$\Xi\in\left[\Xi^{\#},\Xi^{*}\right]\tag{12}$$

If $\Xi>\Xi^*$, it indicates that the first-tier decision-maker still needs to further improve its own target satisfaction. The set σ_1 can be increased by 1%, and the model is solved again until $\Xi\in[\Xi^{\#},\Xi^{*}]$.

If $\Xi<\Xi^*$ and $\Delta<\Delta^{\#}$, the minimum satisfaction value of the lower-tier targets should be increased, let:

$$\sigma_e=\sigma\cdot\Xi^{\#}\tag{13}$$

Then further solve the model:

$$\begin{aligned}&MAX\,\eta\\&s.t.\omega(D_1),\omega(D_2),\omega(D_3),\omega(a_1),\omega(a_2)\ge\eta\\&\omega(D_u)\ge\sigma_u\,(u\ne e)\quad\omega(D_e)\ge\sigma_e\\&h_1(a_1,a_2,a_3)\le0\quad h_2(a_1,a_2,a_3)\le0\\&h_3(a_1,a_2,a_3)\le0\quad a_1,a_2,a_3\ge0\ \ 0\le\eta\le1\end{aligned}\tag{14}$$

If the above equation has a feasible solution, proceed to overall optimization. Otherwise, reduce the set σ_1 by 1% and solve the model again until $\Xi \in [\Xi^{\#}, \Xi^{*}]$. Finally, the satisfaction of each tier's objectives and decision variables can be obtained: $i^*(D_1)$, $i(D_2)$, $i''(D_3)$, $i^*(a_1)$, $i^*(a_2)$.

3.3 Overall optimization of the three-tier objectives

After the interactive collaborative optimization, a solution satisfactory to all three tiers of decision-makers has been obtained. However, this solution does not fully consider the potential improvement space among the various objectives. Especially in the second step, due to the non-compensatory nature of the max-min operator while maximizing the satisfaction of the primary objective, there may still be room for further optimization of other objectives. Therefore, the first step of overall optimization is to seek further Pareto improvement on the premise that the satisfaction of each tier's objective is not lower than the result of the second step. Specifically, among customer satisfaction, manufacturer profit, and supplier profit, decision-makers need to balance customer demands and the profit objectives of supply chain members through a flexible coordination mechanism, avoiding damage to the interests of other objectives while pursuing one particular objective. In the semiconductor supply chain, customers have high requirements for product quality and delivery time, while manufacturers and suppliers have strong demands regarding price, delivery time, and profit. Therefore, the overall optimization process must emphasize coordination among the three, ensuring a mutually beneficial situation among the three tiers of decision-makers.

In actual operation, the optimization of the semiconductor supply chain not only involves the adjustment of objective satisfaction but also requires refined management of the interests of each tier of decision-makers. To achieve overall optimization, the key to the first step is to fine-tune the result obtained from the second step, ensuring that while meeting the minimum satisfaction of lower-tier decision-makers, the potential space for benefit improvement is explored and realized. Specifically, the profit objectives of manufacturers and suppliers may be improved by optimizing production scheduling, adjusting pricing strategies, or optimizing supply chain resource allocation. The improvement of customer satisfaction may be achieved by enhancing product quality, shortening delivery time, or providing better after-sales services.

The first step in the overall optimization process is to use the principle of Pareto improvement. Based on the objective satisfaction obtained in the second step as the starting point of negotiation, a Nash cooperative solution form is used to design the objective function. Through Nash bargaining theory, the cooperative solution form can effectively promote the interest balance among decision-makers at each tier, thereby providing theoretical support for the overall optimization of the three-tier objectives. In the semiconductor supply chain, the objectives of customers, manufacturers, and suppliers usually conflict. Customers have strict requirements for product quality and delivery time, while manufacturers and suppliers have their own demands in terms of profit, production scheduling, and pricing. By using the Nash cooperative solution as the optimization objective function, three-tier decision-makers can find a balance of their respective interests in the process of seeking Pareto improvement, thus achieving the joint improvement of customer satisfaction, manufacturer profit, and supplier profit. The corresponding objective function is:

$$\begin{aligned}&\left[\omega(D_1)-\omega^*(D_1)\right]\left[\omega(D_2)-\omega^*(D_2)\right]\\&\left[\omega(D_3)-\omega^*(D_3)\right]\end{aligned} \tag{15}$$

After the optimization of the previous two steps, the feasible domain of the third step may be greatly restricted, resulting in a smaller solution space. Therefore, after the second step has appropriately relaxed the objective satisfaction, the third step must further improve the rigidity of the constraint conditions to ensure that more possible optimal solutions can be explored. Specifically, at this stage, by appropriately relaxing the constraints on decision variables, more flexibility and adjustment space are allowed, thereby providing a broader solution space for optimization. In the actual operation of the semiconductor supply chain, this step may involve moderate adjustments to production planning, inventory management, or logistics scheduling. For example, allowing a certain degree of delivery time extension or appropriately lowering some quality standards, so that manufacturers and suppliers can obtain more profit space while ensuring product quality. By reducing the satisfaction of decision variables and introducing the adjustment parameter α, constraint conditions can be flexibly adjusted to obtain a more reasonable optimal solution.

$$\omega(a_k) \geq \omega^*(a_k) - \alpha, k = 1,2,3 \tag{16}$$

Finally, based on the relaxed constraints and the Nash cooperative solution, the decision optimization model of the third step is established. The objective of this optimization model is to explore solutions that can achieve greater benefits while maintaining a balance among customer satisfaction, manufacturer profit, and supplier profit. In the semiconductor supply chain, the optimization model of the third step not only requires the optimization of customer satisfaction and the profits of manufacturers and suppliers but also needs to consider the coordination efficiency of each link of the supply chain. For example, by optimizing raw material procurement, production processes, logistics configuration, etc., the operational efficiency of the entire supply chain can be further improved, thus providing a more acceptable and superior solution for the three tiers of decision-makers. The expression of the decision optimization model in the third step is as follows:

$$\begin{aligned}&MAX\left\{\begin{aligned}&\left[\omega(D_1)-\omega^*(D_1)\right]\left[\omega(D_2)-\omega^*(D_2)\right]\\&\left[\omega(D_3)-\omega^*(D_3)\right]\end{aligned}\right\}\\&s.t.\omega(a_k) \geq \omega^*(a_k)-\alpha, k=1,2,3\\&\omega(D_u) \geq \omega^*(D_u), u=1,2,3\\&h_1(a_1,a_2,a_3) \leq 0 \quad h_2(a_1,a_2,a_3) \leq 0\\&h_3(a_1,a_2,a_3) \leq 0\\&a_1,a_2,a_3 \geq 0 \quad 0 \leq \eta \leq 1\end{aligned} \tag{17}$$

4. EXPERIMENTAL RESULTS AND ANALYSIS

In the multi-tier supply chain management and collaborative optimization model of the semiconductor supply chain, the data listed in Table 1 reflects the key parameters of various parties in the supply chain. First, the weight of the defect rate in the customer satisfaction calculation indicates that the defect rate has a significant impact on customer satisfaction, and this factor will directly affect the optimization of supply chain decisions. Parameters such as the manufacturer's and supplier's unit costs in the table reflect the cost differences between manufacturers and suppliers during the production process. The supplier's cost is lower, so in some decisions, the manufacturer may tend to choose the supplier for production. In addition, the temporary order quantity received by the collaborative center, the product sales price, and the accessory sales price reveal the impact of market demand on the production and sales strategies of the supply chain. The relationships between the manufacturer and supplier, such as costs, defect rates, and compensations, need to be balanced through the collaborative optimization model. The investment in funds and the supplier's investment in reducing defect rates reflect the investments made in the supply chain to ensure product quality. Under this framework, the initial defect rate level shows the initial state of product quality management, and through the manufacturer and supplier's penalty mechanism, it effectively guides each party's focus on quality control. Additionally, factors such as the number of accessories required to produce one final product and the unit cost of random sampling accessories by the manufacturer involve accessory management and control, and it also means that in a multi-tier supply chain, how to reasonably arrange production and sampling processes, reduce production costs while improving product quality, is the core task of the optimization decision model. These data not only showcase the cost structure of the supply chain but also emphasize the criticality of quality control and cooperation mechanisms.

Table 1. Model parameter values

Collaborative Center Parameters		**Manufacturer Parameters**		**Supplier Parameters**	
Weight of defect rate in the customer satisfaction calculation formula φ	0.5	Manufacturer's unit cost z_2	11	Unit production cost of the supplier z_3	5
Temporary increase in order quantity received by the collaborative center F_0	1569	Product sales price o_2	72	Sales price of the components o_3	22
Constant X	412	Manufacturer's unit cost for random sampling accessories ξ	2	Initial capital investment by the supplier to reduce the defective rate g_0	1241
		Unit compensation $\zeta1$ from manufacturer to customer when defects are found	142	Defective rate of components produced by the supplier when the investment is g_0: Φ_0	11%
		Punishment $\zeta2$ from manufacturer to supplier when defects are found	16		
		Number of accessories required to produce one final product h	1		

Table 2. First-tier independent solution results

Collaborative Center		
Variables	**Optimal Value**	**Worst Value**
Product quantity delivered to customers W (coordinated by the center)	325.2	374
Customer satisfaction D_1	4.38%	0

Table 3. Second-tier independent solution results

Manufacturer		
Variables	**Optimal Value**	**Worst Value**
Product quantity delivered to customers W (coordinated by the center)	412	0
Proportion of accessories sampled by manufacturer j	0.5	0.1
Number of accessories produced by supplier w	425.368	0
Investment by supplier to reduce defect rate g	2124	517
Manufacturer's profit D_2	6235.32	0

Table 4. Third-tier independent solution results

Supplier		
Variables	**Optimal Value**	**Worst Value**
Product quantity delivered to customers W (coordinated by the center)	362.2	387.25
Proportion of accessories sampled by manufacturer j	0.1	0.114
Number of accessories produced by supplier w	378	412.365
Investment by supplier to reduce defect rate g	512	1895.235
Supplier's profit D_3	1236.98	0

The results shown in Tables 2, 3, and 4 reflect the decision-making and optimization at different tiers for the collaborative center, manufacturer, and supplier, respectively. First, the collaborative center variables in Table 2 reveal the impact of coordinated decisions on the overall operation of the supply chain. In the optimal solution, the collaborative center delivers 325.2 units of products, with a customer satisfaction of 4.38%, while in the worst solution, the delivery quantity drops to 374 units, and customer satisfaction drops to 0. This indicates that the efficiency of the collaborative center's decisions directly affects product delivery and customer satisfaction, highlighting the importance of demand forecasting, order management, and customer service in supply chain optimization. Tables 3 and 4 present the decision optimization results at the manufacturer and supplier tiers, respectively. The manufacturer variables in Table 3 show that in the optimal solution, the manufacturer delivers 412 products, with a 50% sample rate for accessories, and the supplier produces 425.368 accessories with an investment of 2124. The worst solution shows the possible extreme outcomes of the manufacturer's decisions (e.g., delivery quantity drops to 0, profit becomes 0), emphasizing the critical role of production and quality control. The supplier variables in Table 4 show that in the optimal solution, the supplier produces 378 accessories, with an investment of 512 to reduce the defect rate, and a profit of 1236.98. In the worst solution, the supplier's production quantity is 0, the investment drops to 1895.235, and the profit is 0.

Table 5. Interaction negotiation results of the first two tiers of the model

Effective Solution		Satisfaction Value	
Product quantity delivered to customers W (coordinated by the center)	324	Unit cost for the manufacturer to sample components ξ	0.912564
Proportion of accessories sampled by manufacturer j	0.5	First-level membership function $\omega(D_1)$	98.623%
Number of accessories produced by supplier w	318.2	Second-level membership function $\omega(D_2)$	91.245%
Investment by supplier to reduce defect rate g	1897.3	Limitation on the quantity of products delivered by the coordination center $\omega(W)$	98.36%
		Limitation on the proportion of components sampled by the manufacturer $\omega(j)$	99.27%

Table 6. First-step objective priority optimization results of the model

Effective Solution		Satisfaction Value	
Product quantity delivered to customers W (coordinated by the center)	347	Unit cost for the manufacturer to sample components ξ	0.6235
Proportion of accessories sampled by manufacturer j	0.339	First-level membership function $\omega(D_1)$	82.36%
Number of accessories produced by supplier w	358	Second-level membership function $\omega(D_2)$	61.54%
Investment by supplier to reduce defect rate g	935.214	Third-level membership function $\omega(D_3)$	62.89%
		Limitation on the quantity of products delivered by the coordination center $\omega(W)$	78.96%
		Limitation on the proportion of components sampled by the manufacturer $\omega(j)$	62.35%
		Tolerance range for the supplier's investment in reducing the defective rate $\omega(g)$	71.25%

Table 7. Optimization results for maximizing the first-tier objective of the model

Effective Solution		Satisfaction Value	
Product quantity delivered to customers W (coordinated by the center)	338	Unit cost for the manufacturer to sample components ξ	0.1789
Proportion of accessories sampled by manufacturer j	0.45	First-level membership function $\omega(D_1)$	91.23%
Number of accessories produced by supplier w	352	Second-level membership function $\omega(D_2)$	62.58%
Investment by supplier to reduce defect rate g	824.69	Third-level membership function $\omega(D_3)$	62.46%
		Limitation on the quantity of products delivered by the coordination center $\omega(W)$	63.87%
		Limitation on the proportion of components sampled by the manufacturer $\omega(j)$	91.25%
		Tolerance range for the supplier's investment in reducing the defective rate $\omega(g)$	77.62%

Table 5 presents the interaction negotiation results of the first two tiers in the semiconductor supply chain multi-tier supply chain management and collaborative optimization model, providing key data for collaborative optimization decisions. First, the decision of the collaborative center plays a core role in this model, determining the quantity of products delivered to customers (W=324), while coordinating the manufacturer's unit cost of sampled accessories (ξ=0.912564) and sampling proportion (j=0.5). This decision reflects the trade-off between product quality control by the supply chain parties, while considering cost-effectiveness and maximizing customer satisfaction. The first-tier membership function ($\omega(D_1)$=98.623%) reflects the positive response of customer satisfaction to the decision, indicating that customers have high satisfaction with the products provided by the supply chain. In addition, the restrictions on the manufacturer's sampling proportion and unit cost ($\omega(j)$=99.27%) also indicate that the manufacturer has relatively relaxed limits in quality control, while still being able to control costs while ensuring quality. From the supplier's perspective, the number of accessories produced by the supplier (w=318.2) and the investment to reduce the defect rate (g=1897.3) shown in Table 5 reflect how the supplier makes cost investments and quality control in the production optimization process. Despite the high investment, the supplier is still able to ensure high production efficiency and low defect rate, meeting the overall demand of the supply chain. With the support of the second-tier membership function ($\omega(D_2)$=91.245%), the manufacturer and supplier collaborate to maximize the overall supply chain benefit. The restriction on the quantity of products delivered by the collaborative center ($\omega(W)$=98.36%) indicates strict control over the delivery quantity in the decision process, ensuring the supply chain's responsiveness and stability.

Table 6 presents the first-step objective priority optimization results in the semiconductor supply chain multi-tier collaborative optimization model, providing key decision variables and satisfaction values. In this optimization process, the collaborative center adjusts the product quantity delivered to customers (W=347) to balance demand and production capacity in the supply chain, while the manufacturer's unit cost of sampled accessories (ξ=0.6235) and sampling proportion (j=0.339) reflect the trade-off between cost control and product quality assurance. The first-tier membership function ($\omega(D_1)$=82.36%) indicates that customer satisfaction is high under this optimization plan, suggesting that although the manufacturer's sampling proportion is low, customers are still relatively satisfied with the product quality and delivery. The number of accessories produced by the supplier in this optimization plan is 358, with an investment of 935.214, which shows that the supplier made moderate investment to reduce the defect rate, optimizing the production process and achieving certain quality control effects. This plan reflects how, in a multi-tier supply chain, collaborative optimization algorithms can be used to coordinate the interests of all parties and improve overall supply chain efficiency. The second-tier and third-tier membership functions ($\omega(D_2)$=61.54%, $\omega(D_3)$=62.89%) reflect that the supplier and manufacturer must make compromises in budget and production capacity while meeting quality requirements. The restriction on the product quantity delivered by the collaborative center ($\omega(W)$=78.96%) and the restriction on the manufacturer's sampling proportion (ω(j)=62.35%) demonstrate strict control over the constraints in the optimization process. The tolerance range for the supplier's investment to reduce defect rate ($\omega(g)$=71.25%) indicates that the supplier needs to allocate funds reasonably to ensure the effective control of the defect rate in the optimization process. Overall, this optimization process aims to precisely control the parameters of all parties, reduce costs, and enhance the responsiveness and stability of the supply chain, while meeting customer requirements for quality and delivery, fully reflecting the value of multi-tier collaborative management and decision optimization.

Table 7 presents the optimization results for maximizing the first-tier objective in the semiconductor supply chain multi-tier management and collaborative optimization model. Through the optimization process, the coordination center decided that the product quantity delivered to customers would be 338, a number set to maximize customer satisfaction ($\omega(D_1)$ = 91.23%), reflecting a high level of customer satisfaction. In this optimization plan, the manufacturer's sampling rate for accessories was set at 0.45, indicating that the manufacturer moderately reduced the investment in quality inspection while ensuring product quality, balancing cost and quality requirements. Furthermore, the supplier's production quantity was 352, and the investment was 824.69, which is relatively low for reducing the defective rate, likely aiming to optimize production efficiency while maintaining cost control. Overall, this optimization plan strikes a rational balance between production, quality control, and cost, showing strong supply chain efficiency while meeting customer demands. The second-tier and third-tier membership functions ($\omega(D_2)$=62.58%, $\omega(D_3)$=62.46%) indicate that the manufacturer and supplier still need to make compromises during the optimization process, particularly regarding the trade-off between reducing defective rates and production efficiency. The coordination center's limit on product delivery quantity ($\omega(W)$=63.87%) is relatively low, indicating that in this optimization, the delivery quantity was not the core objective, and other factors such as quality control and cost management played important roles. The manufacturer's limit on sampling rate ($\omega(j)$=91.25%) shows that the sampling rate remains at a relatively high level while ensuring product quality, while the supplier's tolerance range for reducing defective rates investment ($\omega(h)$=77.62%) emphasizes the financial constraints, highlighting the comprehensive consideration of funds and quality control across the supply chain during decision-making. These results reflect that in a complex semiconductor supply chain, decisions at all tiers must be highly coordinated to maximize overall benefits, addressing multiple constraints and demands in practical operations.

Table 8. Optimization results after using the adjustment mechanism for each step

Membership Function \ Adjustment Round	1	2	3	4
First-Tier Membership Function $\omega(D_1)$	0.9256	0.9125	0.9236	0.9321
Second-Tier Membership Function $\omega(D_2)$	0.6234	0.6123	0.5864	0.5784
Ratio of Actual Satisfaction for Second-Tier to Minimum Expected Satisfaction from First Step	0.8879	0.8546	0.8452	0.8326
Third-Tier Membership Function $\omega(F_3)$	0.6235	0.6128	0.5896	0.5798
Ratio of Actual Satisfaction for Third-Tier to Minimum Expected Satisfaction from First Step	0.8894	0.8546	0.8452	0.8321

Table 9. Overall optimization results of the objective

Effective Solution		Satisfaction Value	
Product quantity delivered to customers W (coordinated by the center)	338	Unit cost for the manufacturer to sample components ξ	0.1
Proportion of accessories sampled by manufacturer j	0.4896	First-level membership function $\omega(D_1)$	0.9362
Number of accessories produced by supplier w	354	Second-level membership function $\omega(D_2)$	0.6124
Investment by supplier to reduce defect rate g	779.3	Third-level membership function $\omega(D_3)$	0.6238
		Limitation on the quantity of products delivered by the coordination center $\omega(W)$	0.5185
		Limitation on the proportion of components sampled by the manufacturer $\omega(j)$	0.9862
		Tolerance range for the supplier's investment in reducing the defective rate $\omega(g)$	0.8123

Table 8 presents the multiple optimization results after applying the adjustment mechanism, demonstrating the application and evolution of the multi-tier supply chain management and collaborative optimization model in the semiconductor supply chain. Through the adjustment mechanism, the satisfaction value of the first-tier membership function $\omega(D_1)$ fluctuated across different adjustment rounds, with the highest value reached in the fourth round (0.9321). This result shows that through continuous optimization and adjustment of decision parameters, customer satisfaction gradually improved. In particular, the coordination center achieved a better balance between supply chain management and product delivery quality during the optimization process. The second-tier membership function $\omega(D_2)$ and third-tier membership function $\omega(D_3)$ showed a downward trend in each optimization, particularly in the third and fourth rounds, where they decreased to 0.5864 and 0.5784, as well as 0.5896 and 0.5798. This suggests that as the optimization adjustments progressed, the supplier and manufacturer faced more trade-offs in their production and quality control processes, particularly in reducing the defective rate and improving production efficiency, which might have led to a decrease in satisfaction due to resource constraints. The "ratio of actual satisfaction for second-tier to minimum expected satisfaction from first step" and the "ratio of actual satisfaction for third-tier to minimum expected satisfaction from first step" showed similar downward trends (from 0.8879 to 0.8326, and from 0.8894 to 0.8321, respectively), reflecting that as the adjustment mechanism was gradually introduced, supply chain processes faced increasing challenges in meeting expected goals. This decline may be due to additional constraints and higher optimization targets creating more complex decision-making pressures. However, despite the overall decrease in satisfaction, continuous optimization through the adjustment mechanism still effectively enhanced the overall supply chain's responsiveness and stability.

Table 9 presents the key decision results after the overall optimization of the objective in the multi-tier supply chain management and collaborative optimization model for semiconductor supply chains. According to the optimization results, the coordinating center decides to deliver 338 products to customers, while the manufacturer's sampling proportion of parts is 0.4896. This decision ensures both product quality and some cost control. In this optimization plan, the first-tier membership function's satisfaction value ($\omega(D_1)$ = 0.9362) is relatively high, indicating a significant improvement in customer satisfaction. Furthermore, the number of parts produced by the supplier is 354, and the supplier's funding for reducing the defect rate is 779.3. This funding reflects a reasonable investment in quality control by the supplier, balancing product quality and production efficiency. Overall, this optimization plan successfully coordinates customer demand, production costs, and quality control, reflecting efficient collaboration across the various stages of the multi-tier supply chain. The second-tier membership function ($\omega(D_2)$ =0.6124) and third-tier membership function ($\omega(D_3)$ =0.6238) show moderate satisfaction levels, suggesting that the supplier and manufacturer need to compromise on cost control and defect rate reduction during the production and quality management processes. The coordinating center's restriction on the number of products delivered ($\omega(W)$ =0.5185) is relatively low, indicating that the primary goal in this optimization is not to maximize delivery quantity, but rather to achieve a more comprehensive optimization by improving quality and reducing costs. At the same time, the manufacturer's restriction on the proportion of parts sampled ($\omega(j)$ =0.9862) is close to 1, indicating that the manufacturer has minimized the sampling cost while ensuring quality. Additionally, the supplier's tolerance for funding to reduce the defect rate ($\omega(g)$ =0.8123) is relatively relaxed, showing moderate tolerance for financial input, reflecting how various stages in the supply chain consider both inputs and outputs in a complex environment.

Table 10. Comparison of results from three-step optimization of the model

Membership Function \ Adjustment Round	1	2	3
First-tier membership function $\omega(D_1)$	0.8256	0.9254	0.9321
Second-tier membership function $\omega(D_2)$	0.6234	0.5896	0.6125
Third-tier membership function $\omega(F_3)$	0.6259	0.5812	0.6235

Table 10 shows the optimization results of the membership functions after each adjustment in the three-step optimization process of the model. From the data, it can be observed that the first-tier membership function $\omega(D_1)$ started at 0.8256 after the first adjustment, increased to 0.9254 after the second adjustment, and reached 0.9321 after the third adjustment, showing significant growth. This indicates that as the optimization process progresses, customer satisfaction continues to improve, and the best optimization effect is achieved after the third adjustment. In contrast, the second-tier membership function $\omega(D_2)$ fluctuated greatly during the optimization process, from 0.6234 in the first adjustment to 0.5896 in the second, and then rising back to 0.6125 in the third. This reflects that the manufacturer and supplier's production and quality control were somewhat constrained by resources and costs, leading to fluctuations in the satisfaction level of the second-tier objective. The third-tier membership function $\omega(D_3)$ showed a similar trend to the second-tier, starting at 0.6259 in the first adjustment, decreasing to 0.5812 in the second, and then increasing again to 0.6235 in the third. This indicates that the supplier also faces challenges in balancing defect rate reduction and funding investment. Although there was some recovery in the third optimization, the overall improvement was not as significant as the first-tier satisfaction.

Through the analysis of the experimental results above, the following conclusions can be drawn: in the multi-tier supply chain management and collaborative optimization model for semiconductor supply chains, the improvement of the customer satisfaction first-tier objective is the most significant. The optimization mechanism effectively improved product delivery quality, achieving a high satisfaction level ($\omega(D_1)$ = 0.9321). However, the optimization results of the second and third tiers show that, although there was some improvement in production efficiency and quality control for the manufacturer and supplier after multiple adjustments, their optimization effects were more fluctuating due to resource and funding constraints. They were unable to maintain the same continuous growth in customer satisfaction. Particularly in balancing defect rate reduction and funding investment, the downstream segments of the supply chain face greater optimization challenges. Therefore, while the optimization model performs well in improving overall supply chain efficiency, balancing resource allocation and cost control among different stages remains a key area for further optimization.

5. CONCLUSION

This paper conducted a systematic study on multi-tier supply chain management and collaborative optimization in semiconductor supply chains and proposed an optimization model based on three-tier management and collaborative decision-making for supply chain stages. By constructing a multi-tier supply chain management framework that includes upstream raw material suppliers, midstream manufacturers, and downstream distributors, combined with a collaborative decision-making model, this paper successfully optimized the behaviors of suppliers at each tier, aiming to improve decision-making efficiency, reduce costs, and enhance the responsiveness and stability of the supply chain in practical supply chain management. By employing advanced optimization algorithms, this paper not only provided an effective theoretical basis for supply chain management in the semiconductor industry but also offered new ideas and methods for supply chain optimization in related fields. The research results indicate that through a collaborative optimization mechanism, customer satisfaction can be improved while ensuring quality, and effective coordination and resource allocation across the supply chain stages can be achieved, thereby improving the overall efficiency and stability of the supply chain.

Despite the significant research results, there are certain limitations in this paper. First, the assumptions of the optimization model may not fully align with the actual conditions of all semiconductor supply chains, especially in supply chain environments with varying scales and regions, where the applicability of the model might be restricted. Secondly, some external factors, such as market demand fluctuations and policy changes, might have been overlooked in the optimization process, and these factors could affect the model's prediction accuracy. Future research could address these limitations, further expanding the model’s applicability and enhancing its adaptability to external uncertainties. Additionally, future research could introduce more complex nonlinear optimization algorithms to explore how to better achieve collaborative optimization and optimal resource allocation in higher complexity supply chain systems, adapting to the ever-changing global supply chain environment and new challenges brought about by technological advancements.

REFERENCES

[1] Chaudhuri, R., Singh, B., Agrawal, A.K., Chatterjee, S., Gupta, S., Mangla, S.K. (2024). A TOE-DCV approach to green supply chain adoption for sustainable operations in the semiconductor industry. International Journal of Production Economics, 275: 109327. https://doi.org/10.1016/j.ijpe.2024.109327

[2] Bennett, H.S. (2007). Will future measurement needs of the semiconductor industry be met? Journal of research of the National Institute of Standards and Technology, 112(1): 25-38. https://doi.org/10.6028/jres.112.002

[3] Kamakura, N. (2022). From globalising to regionalising to reshoring value chains? The case of Japan’s semiconductor industry. Cambridge Journal of Regions, Economy and Society, 15(2): 261-277. https://doi.org/10.1093/cjres/rsac010

[4] Hsiao, J., Weng, M.C., Su, S.C. (2008). The relationship between organizational structure, supply chain management, and organizational performance: a study on the semiconductor industry. Journal of Information and Optimization Sciences, 29(2): 217-240. https://doi.org/10.1080/02522667.2008.10699801

[5] Jiang, W.Y., Quan, X., Zhou, S. (2010). Historical, entrepreneurial and supply chain management perspectives on the semiconductor industry. International Journal of Innovation and Technology Management, 7(1): 1-18. https://doi.org/10.1142/S0219877010001805

[6] Ryu, S., Kwak, K., Lee, S. (2024). The growth patterns of firms in the industrial value chain using the hidden markov model: Evidence from the Korean semiconductor industry. Computers & Industrial Engineering, 192: 110187. https://doi.org/10.1016/j.cie.2024.110187

[7] Mönch, L., Uzsoy, R., Fowler, J.W. (2018). A survey of semiconductor supply chain models part III: Master planning, production planning, and demand fulfilment. International Journal of Production Research, 56(13): 4565-4584. https://doi.org/10.1080/00207543.2017.1401234

[8] Uzsoy, R., Fowler, J.W., Mönch, L. (2018). A survey of semiconductor supply chain models Part II: demand planning, inventory management, and capacity planning. International Journal of Production Research, 56(13): 4546-4564. https://doi.org/10.1080/00207543.2018.1424363

[9] Yang, J., Xie, H., Yu, G., Liu, M. (2021). Antecedents and consequences of supply chain risk management capabilities: An investigation in the post-coronavirus crisis. International Journal of Production Research, 59(5): 1573-1585. https://doi.org/10.1080/00207543.2020.1856958

[10] Mellat-Parast, M. (2013). Supply chain quality management: An inter-organizational learning perspective. International Journal of Quality & Reliability Management, 30(5): 511-529. https://doi.org/10.1108/02656711311315495

[11] Sunmola, F., Burgess, P., Wertheim-Heck, S. (2024). Challenges and hotspots in food supply chain quality management practices. Total Quality Management & Business Excellence, 35(11-12): 1296-1330. https://doi.org/10.1080/14783363.2024.2367607

[12] Wee, H.M., Peng, S.Y., Wee, P.K. (2010). Modelling of outsourcing decisions in global supply chains. An empirical study on supplier management performance with different outsourcing strategies. International Journal of Production Research, 48(7): 2081-2094. https://doi.org/10.1080/00207540802644852

[13] Akamp, M., Müller, M. (2013). Supplier management in developing countries. Journal of Cleaner Production, 56: 54-62. https://doi.org/10.1016/j.jclepro.2011.11.069

[14] Waqas, U., Abd Rahman, A., Ismail, N.W., Kamal Basha, N., Umair, S. (2023). Influence of supply chain risk management and its mediating role on supply chain performance: Perspectives from an agri-fresh produce. Annals of Operations Research, 324(1): 1399-1427. https://doi.org/10.1007/s10479-022-04702-7

[15] Florescu, M.S., Ceptureanu, E.G., Cruceru, A.F., Ceptureanu, S.I. (2019). Sustainable supply chain management strategy influence on supply chain management functions in the oil and gas distribution industry. Energies, 12(9): 1632. https://doi.org/10.3390/en12091632

[16] Seuring, S.A. (2006). Supply chain controlling: Summarizing recent developments in German literature. Supply Chain Management: An International Journal, 11(1): 10-14. https://doi.org/10.1108/13598540610642420

[17] Ramdas, K., Spekman, R.E. (2000). Chain or shackles: Understanding what drives supply-chain performance. Interfaces, 30(4): 3-21. https://doi.org/10.1287/inte.30.4.3.11644

[18] Meshalkin, V.P., Rakitina, O.V. (2017). Optimal dynamic logistic planning of the supply chain of a gas condensate stabilization plant. Theoretical Foundations of Chemical Engineering, 51: 392-403. https://doi.org/10.1134/S0040579517040224

[19] Sawik, T. (2019). Two-period vs. multi-period model for supply chain disruption management. International Journal of Production Research, 57(14): 4502-4518. https://doi.org/10.1080/00207543.2018.1504246

[20] Mahmoudi, H., Fazlollahtabar, H. (2014). An integer linear programming for a comprehensive reverse supply chain. Cogent Engineering, 1(1): 939440. https://doi.org/10.1080/23311916.2014.939440