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Procurement and Inventory Control Mechanisms for Critical Raw Materials in Semiconductor Supply Chains

Boqing Li

Applied Materials South East Asia Pte. Ltd, 8 Upper Changi Road North 506906, Singapore

Corresponding Author Email: alan_lbq@outlook.com

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ABSTRACT

With the continuous advancement of global technological innovation, the semiconductor industry-serving as a fundamental enabler of information technology, telecommunications, automotive systems, and other sectors-has been increasingly challenged by complex supply chain management issues. Particular difficulties have emerged in the procurement and inventory control of critical raw materials, where firms are required to manage uncertainties in supply, fluctuations in demand, and risks associated with global market volatility. While existing studies have predominantly focused on optimizing isolated segments of the semiconductor supply chain-such as inventory control models based on demand forecasting or procurement strategies-the effectiveness of these traditional approaches is often constrained under conditions of high complexity and uncertainty. In response, this study aims to investigate the mechanisms for the procurement and inventory control of critical raw materials within the semiconductor supply chain. Emphasis is placed on enhancing supply chain resilience and responsiveness by optimizing procurement decisions and inventory management strategies. The research is structured around two primary themes: procurement of critical raw materials and strategic inventory control mechanisms in semiconductor supply chains. The findings are expected to contribute to the theoretical enrichment of supply chain management literature and to provide practical guidance for semiconductor enterprises operating in volatile market environments.

1. INTRODUCTION

The semiconductor industry has been regarded as a foundational pillar of global technological advancement, with widespread applications across computing, telecommunications, and the automotive sector [1-3]. Within the semiconductor supply chain, the procurement and inventory management of critical raw materials have remained pressing challenges that require immediate resolution. As semiconductor technologies continue to evolve and market demands undergo rapid transformation, the stable supply and rational inventory control of raw materials have become increasingly vital [4-6]. In response to these dynamics, the present study seeks to explore the mechanisms for the procurement and inventory control of critical raw materials in the semiconductor supply chain. The primary objective is to enhance the resilience and efficiency of the supply chain through scientifically informed procurement decisions and inventory management strategies. This approach is intended to support optimal resource allocation and strengthen market competitiveness in the context of growing global supply chain uncertainties.

Existing research on procurement and inventory management in semiconductor supply chains has primarily concentrated on the development of quantitative models and the application of optimization algorithms. Conventional methodologies have frequently relied on inventory control models driven by demand forecasting to minimize inventory costs and improve inventory management [7, 8]. However, such methods have often proven inadequate when confronted with the complex market environment and uncertainties inherent in real-world scenarios. First, many prior studies have assumed demand to be known and stable, despite the fact that demand within the semiconductor market is highly volatile and inherently difficult to predict [9-12]. Second, the majority of existing models have focused on the procurement and inventory management of single-material categories, neglecting the integrated handling of multiple types of critical raw materials. This narrow scope has limited the applicability of such models, particularly when addressing cross-industry demands and technological shifts [13, 14]. Furthermore, insufficient attention has been paid to the multi-tiered and multi-nodal complexity and uncertainty of the supply chain, including supplier management, global logistics, and unexpected supply disruptions [15-19]. As a result, current research approaches have exhibited notable limitations in practice, falling short of addressing the dynamic demands of the semiconductor market and the complexity of globalized supply chains.

This study is structured around two core components concerning the procurement and inventory control mechanisms of critical raw materials within the semiconductor supply chain. First, the procurement of critical raw materials in the semiconductor supply chain was examined. Emphasis was placed on how stable material supply can be secured on a global scale through optimized procurement strategies and effective supplier management. Key factors such as procurement diversification, long-term supply agreements, and supplier risk assessment were investigated. Quantitative analytical methods were employed to optimize procurement decisions, thereby addressing market uncertainty and volatility. Second, strategic inventory control mechanisms tailored to the semiconductor supply chain were proposed. Taking into account the industry-specific characteristics-particularly the high value and elevated risk of prolonged material overstock-inventory control strategies were developed for critical raw materials. Data-driven forecasting methods and flexible inventory control approaches were integrated to optimize inventory turnover and cost efficiency, while enhancing the responsiveness and adaptability of the supply chain. The present research addresses a gap in the existing literature by providing an integrated analysis of procurement and inventory management within the semiconductor supply chain. In addition to enriching the theoretical understanding of supply chain management, actionable strategic recommendations are expected to be derived for industrial application. By incorporating both procurement and inventory control dimensions, the study aims to strengthen supply chain resilience in semiconductor enterprises operating in increasingly complex market conditions. Furthermore, theoretical and practical insights are anticipated to support efficient and cost-effective global supply chain operations. The methodologies and conclusions presented may also offer valuable reference for supply chain management practices in other high-technology industries.

2. PROCUREMENT OF CRITICAL RAW MATERIALS IN THE SEMICONDUCTOR SUPPLY CHAIN

2.1 The role of procurement of critical raw materials in the semiconductor supply chain

The production of semiconductor products depends heavily on a range of high-precision, technologically demanding raw materials, including silicon wafers, rare earth metals, and photoresists. These materials are characterized by complex sourcing channels, substantial price volatility, and high supply risks. As such, procurement of critical raw materials is essential not only to ensure supply continuity but also to facilitate uninterrupted production planning and maintain stringent quality control standards. Under conditions of globalized competition, procurement processes must be effectively managed, and stable, long-term partnerships with high-quality suppliers must be established to guarantee that raw materials reach production lines at appropriate times and competitive prices. In addition, procurement requires accurate assessment of market supply-demand dynamics and reliable forecasting of raw material price fluctuations. Through the formulation of proactive procurement strategies, the risks associated with supply shortages and cost escalations can be mitigated, thereby preventing production delays and safeguarding cost efficiency. Consequently, procurement plays a decisive role in enabling semiconductor enterprises to secure a competitive edge in an increasingly dynamic global marketplace.

Moreover, the procurement of critical raw materials within semiconductor supply chains necessitates seamless collaboration and information sharing across all supply chain tiers. Due to the highly specialized nature of production in the semiconductor industry, procurement decisions function as a critical link between upstream suppliers and downstream manufacturing processes. Through the implementation of precise procurement strategies, timely material availability can be ensured, inventory levels optimized, and redundant stock reduced, resulting in lower warehousing costs. Furthermore, procurement must also incorporate a balanced consideration between outsourcing and in-house production. Scientific decisions must be made based on technical requirements, cost control objectives, and supply stability considerations. Within this framework, semiconductor enterprises can achieve optimal integration of global supply chain resources, reduce external exposure to risks, and strengthen their position within the market through precision procurement management.

2.2 Characteristics of procurement of critical raw materials under the semiconductor supply chain management model

In contrast to traditional inventory-based procurement models, the procurement of critical raw materials within the semiconductor supply chain emphasizes demand-driven order procurement. Given the pronounced volatility in supply and pricing of key semiconductor raw materials such as silicon wafers and rare earth metals, procurement activities must be initiated based on accurate demand forecasting and real-time market dynamics. This order-driven approach minimizes excess inventory accumulation, reduces inventory holding costs, and enables a rapid response to market fluctuations. By facilitating the acquisition of raw materials on an as-needed basis, unnecessary capital lock-up and material waste can be avoided. Compared to the inventory-driven practices of conventional procurement models, procurement management in the semiconductor sector requires tighter integration and real-time coordination across all supply chain nodes to improve overall efficiency and operational agility.

Procurement of critical raw materials under the semiconductor supply chain management model also necessitates the deep integration of external resources and the establishment of long-term collaborative partnerships. While traditional procurement models often focus on optimizing internal processes and negotiating pricing with suppliers, the procurement of semiconductor raw materials typically involves sourcing from a globally distributed network of suppliers. The availability of these materials is often constrained by production technologies, supplier capacities, and geopolitical or regulatory risks. As a result, the formation of stable, long-term strategic partnerships with key suppliers has become imperative. In some cases, joint participation in product development and technological advancement has also been required. Through the sharing of market intelligence, demand forecasts, and inventory data, semiconductor enterprises can achieve more precise production planning and enhanced coordination across the supply chain. Furthermore, close collaboration with suppliers is essential for jointly identifying opportunities to reduce procurement costs and improve product quality, while simultaneously reinforcing the resilience and stability of the supply chain. Such collaborative efforts are critical in mitigating the impacts of market uncertainties and external disruptions.

2.3 Objectives of procurement of critical raw materials under the semiconductor supply chain management model

Under the semiconductor supply chain management model, the objectives of procurement of critical raw materials extend beyond isolated concerns such as cost control or efficiency enhancement. Instead, a comprehensive and systematized objective framework was adopted, aimed at optimizing the entire supply chain's performance and enhancing the flexibility and responsiveness of production operations, as illustrated in Figure 1.

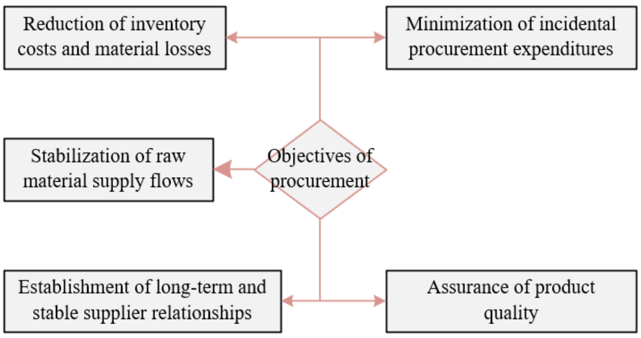

Figure 1. Objectives of procurement of critical raw materials under the semiconductor supply chain management model

a) Reduction of inventory costs and material losses was identified as one of the primary objectives of procurement in the semiconductor industry. Due to the high capital intensity associated with the storage of semiconductor products and materials, precise procurement planning is required to prevent excessive inventory accumulation. Through refined inventory management and demand-driven procurement practices, unnecessary stockpiling can be minimized, thereby reducing capital lock-up. This, in turn, contributes to improved cash flow and faster market responsiveness.

b) Ensuring a stable flow of critical raw material supplies was regarded as a vital function of procurement. Semiconductor production relies on the precise supply of materials, and any shortage in the supply chain can immediately disrupt production lines, compromise order fulfillment, and negatively affect profitability. Thus, the continuous and stable provision of raw materials constitutes a core procurement objective. Achieving this requires the implementation of highly coordinated supply chain mechanisms and the establishment of long-term cooperative relationships with key suppliers to ensure both the reliability and timeliness of supply.

c) The establishment of long-term and stable supplier relationships was also recognized as a core objective of procurement within the semiconductor supply chain. In semiconductor manufacturing, procurement is not merely a transactional activity but a collaborative process involving joint problem-solving and production optimization with suppliers. By fostering strong partnerships with suppliers that consistently provide cost-effective raw materials, stable supply continuity can be maintained, and greater control over procurement costs can be achieved. Close cooperation with suppliers enhances mutual benefits and contributes to the overall stability and risk resilience of the supply chain.

d) Another critical objective of procurement is the assurance of product quality. The quality of semiconductor products is intrinsically linked to the quality of the raw materials procured, particularly where high-precision materials are concerned. These materials exert significant influence on the performance of semiconductor components. It is therefore imperative that rigorous quality control be enforced at the procurement stage, ensuring that all incoming materials conform to production specifications. Failure to ensure material quality at this stage may result in production defects or compromised product integrity [20].

e) The reduction of incidental expenditures associated with the procurement process constitutes an additional strategic priority. Beyond the cost of the raw materials themselves, procurement activities typically incur supplementary expenses such as transportation fees, administrative charges, and communication costs. By streamlining procurement procedures, enhancing process efficiency, and eliminating unnecessary intermediaries, these ancillary costs can be substantially minimized, thereby improving the overall cost-effectiveness of procurement operations.

2.4 Procurement process of critical raw materials under the semiconductor supply chain management model

Under the semiconductor supply chain management model, the process of procurement of critical raw materials is a complex and highly coordinated system engineering task, involving the close collaboration of multiple departments and operational stages. This process goes far beyond the transactional act of acquiring materials; it serves as a critical function to ensure the continuity of production and the enforcement of quality control. As illustrated in Figure 2, a wide range of essential information is required to support the execution of procurement. This process can be elaborated across four key dimensions:

a) Demand identification

The identification of material demand constitutes the starting point of the procurement process and fundamentally shapes the direction of subsequent procurement activities. In semiconductor manufacturing, raw material needs are primarily driven by production plans and include a variety of components, specialty chemicals, and high-precision materials. Effective demand identification relies on accurate forecasting of both the types and quantities of materials required. This requires not only short-term production planning but also long-term consideration of technological evolution and production upgrades. Close collaboration among procurement, production, engineering, and research and development (R&D) departments is essential to ensure accurate alignment with future material requirements. Such coordination is critical to preventing either shortages or excess inventory.

b) Supplier identification

Supplier identification represents another core component of procurement. Given the stringent quality requirements and the specificity of raw materials used in semiconductor fabrication, the selection of appropriate suppliers is of critical importance. Evaluation criteria extend beyond pricing and encompass factors such as delivery reliability, quality assurance capabilities, production consistency, and overall service quality. Supplier selection is typically conducted through formal mechanisms such as bidding, site audits, and performance evaluations, with preference given to those demonstrating strong qualifications and a proven ability to ensure long-term, stable supply. In particular, technical capability and innovation potential often serve as decisive criteria for supplier selection in the semiconductor sector. Consequently, enhanced technical dialogue and cooperation between procurement teams and suppliers is required to ensure the evolving demands of semiconductor enterprises can be met.

c) Order and contract finalization

Once the supplier has been selected, the procurement team proceeds to the stage of order and contract finalization. At this stage, contractual terms are formally established, including delivery schedules, pricing structures, payment conditions, and quality standards. In the semiconductor industry, ensuring the accuracy and enforceability of orders is of critical importance, as any delays or quality issues in the supply of raw materials can severely disrupt the production process. Therefore, in addition to conventional provisions concerning pricing and delivery timelines, the contract must include detailed material quality specifications and clearly defined quality acceptance criteria. To mitigate potential risks, clauses addressing penalties for delivery failures must also be incorporated, along with stipulations that require suppliers to maintain continuous quality management and improvement throughout the duration of the partnership.

d) Delivery monitoring and management

The monitoring and management of the delivery process represent key components in ensuring the success of procurement activities. Given the lengthy production cycles and the high precision required in material usage within the semiconductor sector, even minor delivery delays can result in significant disruptions to the production schedule or even full-scale stoppages. Consequently, rigorous oversight of the supplier's delivery performance must be maintained. It is essential to ensure that raw materials are delivered punctually, in the correct quantities, and in compliance with specified quality standards. This phase extends beyond mere tracking of delivery timelines to include the inspection and acceptance of materials during transit, thereby ensuring that the integrity and performance characteristics of the raw materials are not compromised during transportation.

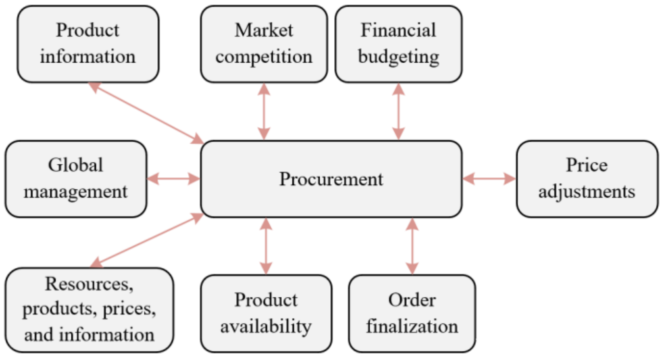

Figure 2. Information required for procurement of critical raw materials under the semiconductor supply chain management model

The detailed process flow of procurement of critical raw materials under the semiconductor supply chain management model is illustrated in Figure 3.

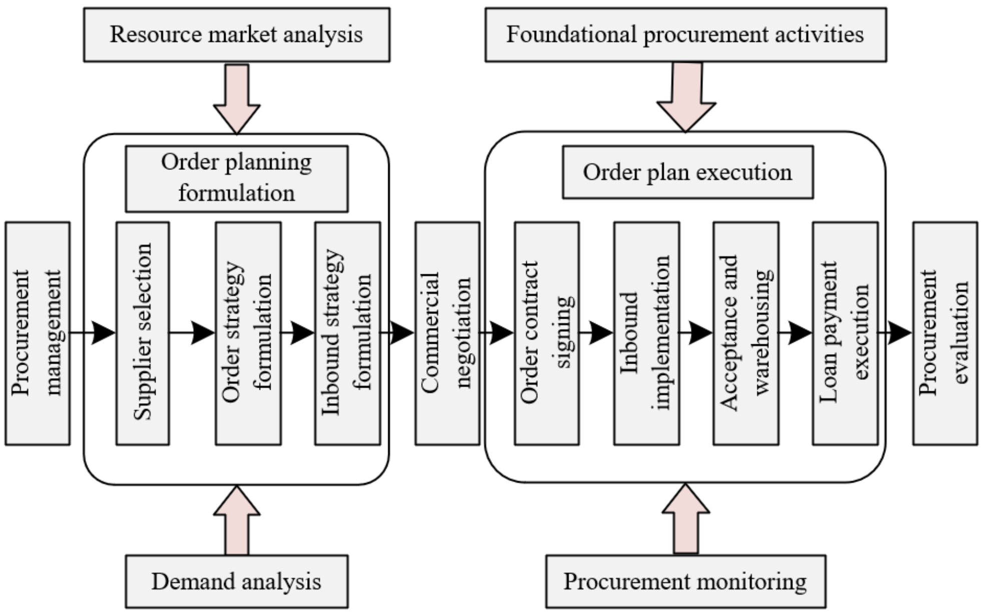

Figure 3. Detailed process flow of procurement of critical raw materials under the semiconductor supply chain management model

3. STRATEGIC INVENTORY CONTROL MECHANISMS IN THE SEMICONDUCTOR SUPPLY CHAIN

3.1 Overview of strategic inventory control methods in the semiconductor supply chain

Within the semiconductor supply chain, the primary objective of strategic inventory control is to ensure the sufficient availability of critical raw materials and semi-finished products throughout the production process while optimizing inventory levels to minimize costs and mitigate associated risks. Due to the extended production cycles, technological complexity, and high demand volatility characteristic of the semiconductor industry, considerable challenges have been posed to inventory management. To address the varying nature of independent demand and dependent demand, differentiated inventory control strategies have typically been adopted by semiconductor enterprises. In the case of independently demanded materials—such as finished products or certain critical electronic components—demand is highly uncertain and often difficult to forecast. In response to this uncertainty, inventory control methods based on demand forecasting and quantitative analysis have been implemented. These include models such as the Economic Order Quantity (EOQ) model and dynamic inventory optimization models, which aim to fulfill production requirements while minimizing inventory overstock and capital immobilization.

For inventory associated with dependent demand, more precise control methods have been employed. Such demand is typically derivable from product structure and specific ratios in the production process. For instance, in semiconductor manufacturing, the quantity of certain raw materials or components required is directly linked to the production schedule and material consumption rates of the primary product. Accordingly, inventory management strategies based on Material Requirements Planning (MRP) and Manufacturing Resource Planning (MRPII) systems have been utilized. These systems enable the automatic calculation of optimal procurement quantities and inventory replenishment levels for various raw materials and components, based on the progression of primary product manufacturing and associated material usage.

3.2 Strategic inventory control of independent demand in the semiconductor supply chain

Within the framework of strategic inventory control in the semiconductor supply chain, independent demand inventory models are generally categorized into two types: continuous and periodic review inventory systems, each exhibiting distinct applications within the semiconductor industry. The continuous review inventory system is particularly suited for raw materials and components characterized by high demand variability and extended production lead times. In semiconductor manufacturing, key components such as chips, integrated circuits, and other high-precision elements often experience significant fluctuations in demand and therefore require continuous monitoring and management. In such cases, real-time inventory tracking must be implemented, and the appropriate reorder point (EPO) must be established. Once inventory levels drop below the predefined reorder threshold, a replenishment order is triggered immediately. This system minimizes the risk of stockouts and is especially critical for high-value components with long production cycles.

In contrast, the periodic review inventory system is applicable to raw materials and components with relatively stable demand patterns and predictable supply cycles. In the semiconductor industry, this includes materials such as base chemicals and standardized electronic components, whose consumption remains consistent over time. Under this system, inventory levels are reviewed at fixed intervals—such as monthly or quarterly—to determine whether replenishment is required. This model is typically applied to non-core materials used in production processes, and the replenishment decisions for these materials are made at fixed time intervals, such as monthly or quarterly. Periodic review allows enterprises to maintain adequate inventory levels without requiring continuous monitoring, thereby reducing complexity and capital lock-in while maintaining overall supply chain stability. For the semiconductor supply chain, this approach facilitates efficient inventory management and helps reduce inventory control complexity and costs.

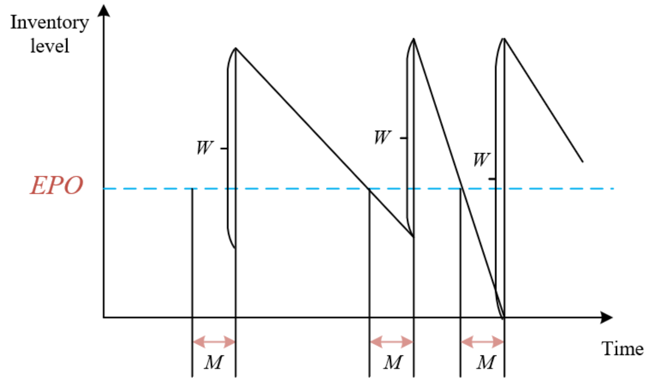

Figure 4. Fixed-order quantity model for strategic inventory control of independent demand in the semiconductor supply chain

The quantitative reorder method is particularly well-suited for critical semiconductor components that require precise inventory control and strict adherence to replenishment timelines. The core principle of this method lies in establishing a fixed EPO and order quantity based on known demand patterns and supply conditions. When the inventory level declines to the predetermined EPO, a replenishment process is automatically triggered. This ensures continuous availability of inventory and prevents production delays or disruptions in the supply chain caused by stockouts. The corresponding model is illustrated in Figure 4. This method typically involves two key steps:

a) Determination of the EPO

In semiconductor manufacturing, the demand for materials such as wafers and chip packaging components is often subject to fluctuation. As a result, it is essential to initiate replenishment once inventory levels drop to a specified threshold. The EPO is calculated by considering both the average daily demand and the lead time required for replenishment. Let W denote the order quantity per cycle and M denote the lead time. The basic formula for calculating the EPO is expressed as:

$$EPO = E \times M \tag{1}$$

In practical applications, the impact of safety stock must also be considered, particularly in the presence of demand variability or potential delays in supply. When this factor is included, the EPO calculation is modified to incorporate the safety inventory level T, ensuring that production requirements can still be met during unforeseen supply disruptions. For instance, semiconductor companies may rely on historical data or predictive models to estimate the daily demand for each critical raw material. By multiplying the estimated daily demand by the projected lead time, the EPO can be determined. Once inventory falls below this threshold, the system is configured to automatically trigger a replenishment order, thereby preventing interruptions in production during the lead time period.

$$EPO = EO + T \tag{2}$$

b) Determination of the order quantity (W)

The order quantity (W) refers to the amount of inventory to be procured during each replenishment cycle. In the semiconductor industry, this is typically determined using the EOQ model. The core principle of the EOQ model is to minimize total inventory cost by balancing three primary components: purchasing cost, ordering cost, and holding cost. The objective is to identify an optimal order quantity that satisfies production requirements while avoiding excess inventory accumulation. Several factors must be considered in calculating the optimal order quantity W. First, the annual demand must be estimated, which is typically derived from market forecasts, production schedules, and sales projections. Second, the ordering cost per transaction and the annual holding cost per unit must be quantified, usually based on the firm's operational expenditure structure. By applying the EOQ formula, the optimal order quantity W can be computed. This facilitates inventory cost minimization while maintaining sufficient stock levels to support uninterrupted production. In the context of the semiconductor industry—where long production cycles and complex supply chains are the norm—an accurately determined order quantity can prevent excessive capital investment in inventory while sustaining the efficiency of the production line. Let SXZ denote the total inventory cost, N represent the unit value of the item, and Q denote the annual holding cost as a percentage of the unit value. Let E represent the annual demand, and T the fixed cost per order.

$$SXZ = EN + \frac{1}{2}WNQ + \frac{E}{W}T \tag{3}$$

To determine the minimum economic order quantity W, the economic order quantity is denoted as W_0, the ordering cost per order as T, the annual demand as E, and the annual holding cost per unit as $G=NQ$. By differentiating the function SXZ with respect to W, the economic order quantity can be derived using the following expression:

$$W_0 = \sqrt{\frac{2TE}{G}} \tag{4}$$

The periodic review model is suitable for raw materials and semi-finished products that exhibit relatively stable and predictable demand patterns. Unlike the fixed-order quantity model, the periodic review model focuses on assessing inventory and initiating replenishment at regular, predefined intervals. This approach has been particularly effective in the semiconductor industry for managing items such as standardized electronic components and chemical inputs, where demand remains relatively constant. Its adoption reduces the complexity of inventory management.

The core principle of the periodic review model is to conduct inventory assessments at fixed time intervals (denoted as S), such as monthly or quarterly. At the end of each review period, the inventory balance is compared to a predetermined maximum inventory level (R). If the current inventory level (U) is below R, a replenishment order is issued to restore the inventory up to the target level. In this context, the order quantity W is calculated as the difference between R and U, such that $W = R - U$. Through this mechanism, semiconductor enterprises can maintain inventory within an optimal range—minimizing capital tie-up from overstocking while simultaneously preventing stockouts that could disrupt production schedules.

In practical applications, the periodic review model has been found to be particularly well-suited for semiconductor materials that are characterized by long production cycles and relatively stable inventory management requirements. For instance, certain foundational raw materials—such as standardized electronic components and basic chemicals—exhibit predictable consumption patterns in manufacturing and are typically associated with stable lead times. Based on historical consumption data and demand forecasting, appropriate review intervals (S) and maximum inventory levels (R) can be established to ensure that sufficient inventory is available at the end of each cycle to support uninterrupted production. Furthermore, because the periodic review model eliminates the need for continuous inventory tracking and instead relies on scheduled evaluations and replenishments, its management cost is relatively low. This feature renders it particularly effective for managing high-volume semiconductor materials with low demand variability. Specifically, let S denote the ordering interval. The economic ordering interval can be calculated using the following expression:

$$SXZ = EN + \frac{T}{S} + \frac{EQNS}{2} \tag{5}$$

The first derivative of the annual total cost with respect to S was set to zero, yielding the economic ordering interval:

$$S_0 = \sqrt{\frac{2T}{ENQ}} = \sqrt{\frac{2T}{EG}} \tag{6}$$

Additionally, the maximum inventory level (R) can be expressed as:

$$R = E\left(S + M\right) \tag{7}$$

3.3 Strategic Just-in-Time (JIT) inventory management in the semiconductor supply chain

Within the semiconductor supply chain, JIT inventory management serves as a highly effective control mechanism that significantly enhances supply chain efficiency and responsiveness. The core principle of JIT is demand-driven coordination, whereby inventory levels are minimized across all stages of the supply chain through precise demand planning and synchronization. The ultimate objective is to approach a "zero-inventory" state. This approach is particularly critical in the semiconductor industry, where production cycles are extended, technological advancements occur rapidly, and frequent production scheduling and supply chain coordination are required. The implementation of strategic JIT inventory management is not limited to inventory reduction alone. Rather, it involves the meticulous control of supply chain elements to reduce total operational costs while simultaneously increasing market responsiveness and improving supply chain agility.

Under the framework of strategic JIT management, every stage of the semiconductor supply chain is required to fulfill production demands at the right time, in the right quantity, and with minimal inventory. To achieve this, highly integrated relationships must be established between semiconductor manufacturers and their suppliers. These relationships rely on accurate demand forecasting and real-time information sharing to ensure that essential raw materials and components are delivered punctually and in appropriate quantities throughout each phase of the production process.

The production of semiconductor products is characterized by long lead times and multiple complex manufacturing processes, where any delay or inventory accumulation at a single stage may lead to production setbacks or full disruption of the overall schedule. To address this challenge, semiconductor enterprises must rely on real-time data exchange systems and highly accurate demand forecasting mechanisms to closely monitor market needs, production progress, and inventory status. At the core of JIT inventory management lies a pull-based control mechanism, wherein the production and delivery activities of upstream suppliers are triggered by the actual demand from downstream manufacturers. This approach ensures that overstocking and stockouts are simultaneously avoided. Through such a demand-driven replenishment mechanism, the consumption of materials during production is aligned precisely with supplier delivery schedules, enabling a substantial reduction in overall inventory levels throughout the manufacturing process.

The successful implementation of the JIT model in the semiconductor supply chain is contingent upon seamless information sharing and close collaboration among all stakeholders. Given the involvement of multiple suppliers and production units across stages—from raw material procurement through wafer fabrication, chip packaging, and testing, to final product delivery—tight coordination at each stage is imperative. To achieve this, enterprises are required to establish robust supply chain management systems that facilitate real-time data transmission and transparent information flow. These systems ensure that each stage of the supply chain is capable of responding rapidly to actual demand signals. This information-sharing infrastructure allows all participants in the supply chain to quickly understand demand fluctuations and production status, enabling timely operational adjustments. For example, critical raw materials used in semiconductor production—such as silicon wafers and chemical reagents—are subject to strict quality and delivery time requirements. Under the JIT framework, suppliers must be able to accurately monitor production progress and inventory needs, and schedule their own production and delivery accordingly. Real-time access to production plans enables suppliers to synchronize delivery timing and quantities with precision, thereby enhancing the responsiveness of the entire supply chain and preventing disruptions caused by delayed information or inaccurate forecasting.

3.4 Collaborative inventory control in the context of semiconductor supply chain management

The semiconductor industry is characterized by long production cycles, high demand volatility, rapid technological advancement, and frequent coordination across multiple enterprises and geographic regions. As such, inventory management within the semiconductor supply chain is no longer a matter of isolated stock control, but rather a comprehensive strategic issue involving demand forecasting, supplier relationship management, and logistics optimization. To enhance overall supply chain performance and remain competitive in an increasingly demanding global market, the adoption of advanced inventory control methodologies has become essential.

The core objective of inventory control in semiconductor supply chains is to optimize inventory levels, enhance responsiveness, and maximize inventory utilization efficiency, all while maintaining a high level of customer service and minimizing inventory-related costs. In this context, inventory is not merely viewed as stored goods but as a strategically managed resource that must be tightly aligned with dynamic demand signals and production cycle requirements. The overarching goal of strategic inventory management in this environment is to maximize supply chain effectiveness under conditions of uncertainty, ensuring that stockouts are avoided during production while simultaneously preventing excess inventory that may result in capital waste and increased storage costs. Specifically, this approach seeks to achieve the following:

a) Inventory reduction

Inventory levels are to be minimized as much as possible without compromising the ability to meet production and customer demand. This reduces warehousing and administrative costs.

b) Response speed enhancement

Through precise demand forecasting and dynamic inventory control, supply chain responsiveness must be improved. This ensures that fluctuations in market demand or production schedules can be swiftly addressed, thereby preventing supply chain disruptions caused by stock imbalances—whether shortages or surpluses.

c) Enhancement of customer service levels

Inventory control must ensure the ability to fulfill customer demand in real time, minimizing delivery delays or order losses caused by stockouts. This directly contributes to increased customer satisfaction.

d) Optimization of supply chain efficiency

Through collaboration and coordination across all stages of the supply chain, from raw material procurement to final product delivery, operational efficiency must be improved while maintaining lean inventory levels.

One advanced inventory control strategy that plays a critical role in the semiconductor supply chain is Vendor-Managed Inventory (VMI). Under the VMI model, inventory is managed directly by the supplier, who assumes responsibility for monitoring the customer's inventory levels and proactively managing replenishment based on shared real-time data, including inventory status, production progress, and demand forecasts. This model effectively reduces the inventory management burden on semiconductor enterprises while enhancing supply chain efficiency. It is especially suitable for raw materials and components that exhibit high demand variability or involve long production lead times. For example, semiconductor manufacturing requires large volumes of precision components and chemical substances, both of which typically have extended lead times and impose significant logistical requirements. Through real-time monitoring of downstream inventory and production activity, suppliers operating under a VMI framework are able to accurately forecast demand and replenish inventory proactively, thereby avoiding production interruptions caused by material shortages. In addition, VMI allows for the centralization of procurement and transportation processes, leading to cost reductions, decreased inventory accumulation, and improved supply chain responsiveness. In the context of the semiconductor industry, VMI enables uninterrupted production while minimizing excess inventory, thus reducing capital lock-up and improving the overall capital efficiency of the supply chain.

Joint Managed Inventory (JMI) is an inventory control approach that emphasizes collaborative coordination among all nodes of the supply chain. By jointly formulating inventory plans, participating entities within the supply chain can achieve resource sharing and optimization, thereby enhancing overall supply chain efficiency. In the context of the semiconductor supply chain—characterized by numerous production stages and intricate interdependencies between suppliers and customers—independent inventory control often leads to the bullwhip effect, resulting in excessive or insufficient inventory across different stages. Through the synchronization of demand forecasting and inventory planning among supply chain partners, JMI provides an effective means of mitigating such imbalances. In practice, JMI is implemented through shared demand information, coordinated replenishment planning, and risk-sharing mechanisms. For instance, in semiconductor production, demand for certain raw materials and components may be highly variable. If each node in the supply chain acts independently, mismatches in supply and demand may occur, leading to bottlenecks or overstocking at specific stages. Under the JMI framework, joint decision-making guided by a central coordination mechanism allows all parties to align production planning with actual market demand. This ensures inventory levels are appropriately distributed across the entire supply chain, reducing variability and enhancing system-wide stability.

Both VMI and JMI serve as critical strategies within strategic inventory management for semiconductor supply chains. VMI enables suppliers to manage downstream inventory using real-time data acquisition and analytics, thereby reducing inventory levels while ensuring uninterrupted production. In contrast, JMI fosters collective participation and coordination across supply chain nodes, eliminating inventory fluctuations caused by information asymmetry or demand volatility. This joint approach optimizes overall inventory levels and mitigates the impact of localized stock issues on broader supply chain performance. A major challenge in strategic inventory management within the semiconductor sector lies in maintaining flexibility and stability in the face of globalization and intense market competition. To address this challenge, semiconductor enterprises are increasingly adopting advanced demand forecasting techniques, real-time data analytics platforms, and highly integrated supply chain management systems. These technologies enable rapid adjustment of inventory strategies in response to dynamic market conditions, thereby reducing risk while enhancing the agility and responsiveness of the supply chain.

4. RESULTS AND ANALYSIS

Based on the data presented in Table 1, significant fluctuations in procurement quantity, cumulative inventory, and procurement cost were observed across the various procurement stages for electronic specialty gases within the semiconductor supply chain. Notably, the procurement quantity exhibited marked variation across intervals. For example, during the first stage, the procurement volume was 12,356 kg, whereas in the second stage, it increased sharply to 162,541 kg. This variation reflects differing procurement demands across distinct time periods within the supply chain. In terms of cumulative inventory, a rising trend was observed from the first to the fourth stage, increasing from 223,514 kg to 332,659 kg. However, a substantial decrease occurred in the fifth and sixth stages, with inventory dropping to 32,445 kg in the final stage. This sharp decline may indicate the presence of potential issues in inventory planning, such as overstock or shortfall. Regarding procurement cost, an upward trend was recorded in alignment with increased procurement quantities. Costs rose from USD 74,136 in the first stage to USD 247,590 in the sixth stage. This pattern suggests that procurement cost is highly sensitive to fluctuations in material demand.

Table 1. Optimal economic procurement quantity and procurement cost of electronic specialty gases in the semiconductor supply chain

Procurement Interval	S_1=30	S_2=40	S_3=43	S_4=40	S_5=43	S_6=42
New procurement quantity (kg)	12356	162541	44582	37854	36521	41265
Cumulative inventory (kg)	223514	326589	332659	332651	332154	32445
Procurement cost (USD)	74136	975246	267492	227124	219126	247590

Table 2. Optimal economic procurement quantity and procurement cost of silicon wafers in the semiconductor supply chain

Procurement Interval	S_1=30	S_2=30	S_3=15	S_4=12	S_5=13	S_6=11	S_7=10
New procurement quantity (wafers)	124585	145265	32154	31256	38452	32152	33562
Cumulative inventory (wafers)	162548	86542	85623	88956	85621	87452	91425
Procurement cost (million USD)	3737	4357	964	937	1153	964	1006
Procurement interval	S_8=11	S_9=11	S_{10}=11	S_{11}=12	S_{12}=12	S_{13}=12	S_{14}=12
New procurement quantity (wafers)	38562	36521	35628	38562	36521	33652	37845
Cumulative inventory (wafers)	91245	85623	88956	84521	88956	92512	90245
Procurement cost (million USD)	1156	1095	106	1156	1095	1009	1135

Table 3. Procurement quantity and procurement cost of rare earth metals in the semiconductor supply chain

Procurement Interval	S_1=30	S_2=30	S_3=26	S_4=25	S_5=28	S_6=25	S_7=23
New procurement quantity (g)	122352	162541	124152	123215	127895	125214	124541
Cumulative inventory (g)	215485	235215	245652	215263	245212	263521	24117
Procurement cost (million USD)	13385	17781	1358	13479	13991	13698	13624

Table 4. Optimal procurement quantity and procurement cost of photoresist in the semiconductor supply chain

Procurement Interval	S_1=30	S_2=43	S_3=23	S_4=22	S_5=23	S_6=30	S_7=30
New procurement quantity (tons)	132562	142562	34521	37541	36521	35621	35621
Cumulative inventory (tons)	23514	178562	185236	165213	245621	263521	24115
Procurement cost (million USD)	6495	6985	1691	1839	1789	1745	1745

Table 5. Phase I results of strategic inventory control implementation in the semiconductor supply chain

		Inventory Control Metrics	Before Implementation	Phase I Result	Target Value
Key Evaluation Metric	Performance Evaluation Criteria	Average inventory days (materials center)	23	12	11
		In-stock rate at logistics center	No	93%	94%
		Order item fulfillment rate	93%	92%	94%
		On-time delivery rate of products	101%	103%	101%
		Invoice accuracy	98%	101%	102%
	Process Evaluation Criteria	Order correction rate	No	16%	103%
		Time to issue order	No	25 min	No
		Time to confirm order	No	46 min	No
		Inventory utilization	No	Yes	Yes

Table 6. Performance improvements in Phase II of the strategic inventory control mechanism in the semiconductor supply chain

		Inventory Control Metrics	Before Implementation	Phase I Result	Five Months After Improvement	Target Value
Key Evaluation Metric	Performance Evaluation Criteria	Average inventory days (materials center)	23	12	15	11
		In-stock rate at logistics center	No	93%	97%	94%
		Order item fulfillment rate	93%	92%	92%	94%
		On-time delivery rate of products	101%	103%	101%	101%
		Invoice accuracy	98%	101%	102%	102%
	Process Evaluation Criteria	Order correction rate	No	16%	9%	11%
		Time to issue order	No	25 min	16 min	No
		Time to confirm order	No	46 min	21 min	No
		Inventory utilization	No	Yes	Yes	Yes

The data in Table 1 reveal that the observed fluctuations in procurement quantity, inventory levels, and procurement costs present notable challenges for inventory control and procurement strategy formulation within the semiconductor supply chain. In particular, stages characterized by significant procurement volatility—such as S_2 and S_6—are associated with marked increases in procurement cost, which may be attributed to sudden shifts in demand and insufficient responsiveness of the supply chain. The substantial decline in inventory observed during Stages 5 and 6 further suggests that inventory has not been managed effectively, potentially resulting in accelerated depletion and elevated procurement costs. These findings underscore the need for the implementation of flexible inventory control mechanisms and dynamic procurement strategies. To address these challenges, the adoption of accurate demand forecasting models and strengthened supplier collaboration frameworks is essential. These measures would help ensure stable material availability despite fluctuations in demand, while simultaneously mitigating procurement cost escalation and the risk of inventory overstock or shortfall. Moreover, it is recommended that supplier management be enhanced and procurement diversification strategies be employed to buffer the impact of market volatility. Such approaches would support the optimization of procurement decisions, increase the responsiveness of the supply chain, and improve overall operational agility.

The data presented in Table 2 indicate that the procurement quantity, cumulative inventory, and procurement cost associated with silicon wafers exhibit notable fluctuations across different stages of the semiconductor supply chain. During the initial stages (S_1 and S_2), the procurement quantities reached 124,585 and 145,265 wafers, respectively, accompanied by relatively high inventory levels. However, in subsequent stages—particularly from S_3 to S_6—the procurement quantities declined significantly to the range of approximately 32,000–38,000 wafers, while inventory levels remained comparatively stable, suggesting a gradual inventory drawdown. Regarding procurement cost, higher costs were observed in the initial stages, reaching 3,737 and 4,357 million USD. In contrast, a substantial decline in cost occurred in S_3 (964 million USD), followed by a slight upward trend in later stages, peaking again at 1,156 million USD. Notably, during S_3 and S_4, a nonlinear relationship between procurement quantity and cost became apparent. Overall, the frequent fluctuations in procurement quantity and inventory levels, accompanied by dynamic procurement costs, reflect the challenges faced in semiconductor supply chain management.

The data presented in Table 2 highlight several critical challenges in the procurement and inventory management of silicon wafers. Foremost among these is the instability and frequent fluctuation in procurement quantities, which appear to contribute significantly to the volatility of procurement costs and, consequently, to the overall efficiency of the supply chain. For example, during procurement intervals S_3 and S_4, a substantial reduction in procurement quantities was recorded. Despite this decline, inventory levels remained relatively stable or even showed marginal increases, while procurement costs decreased sharply. This discrepancy suggests that procurement planning may not have been accurately aligned with actual market demand, leading to a mismatch between inventory accumulation and cost efficiency. In addition, changes in inventory levels reflect a degree of inconsistency in inventory control strategies within the semiconductor supply chain. Specifically, in periods where procurement volume declined, inventory was not depleted at a corresponding rate, indicating a risk of long-term inventory accumulation. Such imbalances may lead to elevated operational costs. To address these challenges and optimize the procurement and inventory control mechanisms for silicon wafers, the deployment of more accurate demand forecasting models and flexible procurement strategies is essential—particularly for raw materials with slower turnover rates. Moreover, given the observed volatility in procurement costs, enhanced collaboration with suppliers is strongly recommended. The use of long-term procurement agreements and supplier diversification strategies would help ensure a stable supply of critical raw materials during periods of fluctuating demand. Finally, the application of data-driven predictive models and dynamic inventory management systems is expected to significantly improve inventory turnover, minimize unnecessary stockpiling, and mitigate cost fluctuations, thereby increasing supply chain responsiveness and overall operational agility.

The data presented in Table 3 demonstrate substantial fluctuations in the procurement quantity, inventory levels, and procurement costs associated with rare earth metals across different procurement intervals in the semiconductor supply chain. In the initial intervals (S_1 and S_2), procurement quantities were relatively high, at 122,352 g and 162,541 g, respectively. During these stages, cumulative inventory also increased, rising from 215,485 g to 235,215 g. In subsequent intervals, procurement volumes began to decline—reaching 124,152 g in S_3 and 123,215 g in S_4—while inventory exhibited a mixed trend, peaking at 245,652 g in S_3 before falling to 215,263 g in S_4. With regard to procurement costs, the early intervals were associated with higher expenditures, at 13,385 million USD and 17,781 million USD, respectively. In contrast, although procurement quantities continued to fluctuate in the later stages, procurement costs exhibited relative stability, ranging from 1,358 to 13,991 million USD. Overall, both procurement volume and inventory levels displayed a pattern of moderate fluctuation, and procurement cost trends generally followed these variations.

The data in Table 3 indicate that significant fluctuations were observed in the procurement quantity, cumulative inventory, and procurement cost of rare earth metals, suggesting a high degree of uncertainty in procurement and inventory management within the semiconductor supply chain. In the initial procurement intervals, elevated procurement volumes contributed to inventory accumulation. However, in subsequent intervals, the reduction in procurement volumes did not result in a proportional decrease in inventory. In some stages, inventory levels even rebounded. Such accumulation of inventory may lead to resource waste and an increase in storage and handling costs. The volatility of procurement costs further reflects the instability of supply chain operations. Notably, in stages where procurement volumes declined, procurement costs did not exhibit a corresponding reduction. This may imply that supplier-side costs were not effectively managed, or that inventory levels were not adequately aligned with actual market demand. To improve the procurement and inventory control of rare earth metals, more granular demand forecasting and precisely scheduled procurement planning are required to mitigate the risk of overstock. At the same time, enhanced collaboration with suppliers should be established—long-term contractual agreements and diversified sourcing strategies would help stabilize supply availability and reduce exposure to price volatility. When integrated with data-driven predictive models and dynamic inventory control systems, these strategies can substantially improve inventory turnover, reduce excessive stock accumulation, and stabilize procurement cost variation. Collectively, such approaches are expected to enhance the flexibility and adaptability of the semiconductor supply chain.

The data in Table 4 reveal notable fluctuations in procurement quantity, inventory levels, and procurement costs associated with photoresist across various procurement intervals in the semiconductor supply chain. During the first two intervals (S_1 and S_2), procurement quantities were high—132,562 tons and 142,562 tons, respectively—leading to a significant increase in cumulative inventory from 23,514 tons to 178,562 tons. However, in subsequent intervals, procurement volumes dropped substantially, reaching a low of 34,521 tons in S_3, before stabilizing around 35,621 tons in later stages. Cumulative inventory experienced a complex trend: a decline in S_3 and S_4 (to 185,236 tons and 165,213 tons, respectively), followed by a sharp increase in S_5 and S_6 (to 245,621 tons and 263,521 tons, respectively). In the initial stages, procurement costs were relatively high, at 6,495 million USD and 6,985 million USD. As procurement quantities decreased and inventory levels fluctuated, procurement costs declined to 1,691 million USD and 1,839 million USD in S_3 and S_4, before rebounding slightly to 1,789 million USD. Overall, the data suggest a close correlation between procurement volume and inventory dynamics, with procurement costs also being influenced by both variables.

The data presented in Table 4 suggest a marked degree of volatility in the procurement and inventory management of photoresist materials, particularly in the correlation between procurement quantities and inventory levels. In the early intervals, large procurement volumes led to significant inventory accumulation. However, in the subsequent intervals, despite a reduction in procurement quantities, inventory levels continued to fluctuate considerably. Notably, during stages S_3 through S_6, dramatic shifts in inventory levels were observed, which may indicate misalignment between procurement planning and actual demand. Procurement cost volatility further reflects limitations in the supply chain's responsiveness to demand variation. Specifically, in stages where procurement quantities declined, procurement costs did not demonstrate a corresponding downward trend. This may be attributed to capital being tied up in excess inventory, resulting in increased storage and management costs. To optimize the procurement and inventory control of photoresist materials, it is essential that more flexible procurement strategies be adopted. Procurement volumes should be dynamically adjusted based on accurate demand forecasting to prevent inventory overstocking. Additionally, the establishment of long-term supply agreements, the strengthening of supplier relationships, and the development of diversified supplier networks are recommended to enhance procurement stability and ensure uninterrupted supply chain operations. By integrating data-driven forecasting techniques and dynamic inventory control systems, inventory turnover can be significantly improved, excess inventory pressure reduced, and cost fluctuations mitigated. These measures are expected to enhance the agility and responsiveness of the semiconductor supply chain.

As shown in Table 5, significant improvements were observed across multiple key performance indicators following the Phase I implementation of the strategic inventory control mechanism within the semiconductor supply chain. For instance, the average inventory holding period at the materials center was reduced from 23 days to 12 days, approaching the target of 11 days, indicating enhanced inventory turnover efficiency. The in-stock rate at the logistics center was improved to 93%, close to the target of 94%. Although the order item fulfillment rate slightly decreased from 93% to 92%, it remained near the target level of 94%. Furthermore, the on-time delivery rate rose from 101% to 103%, surpassing the performance benchmark, which reflects improved logistics responsiveness. The invoice accuracy also improved from 98% to 101%, nearing the target of 102%, indicating enhanced accuracy in invoicing processes. From a process performance perspective, the order correction rate reached 16%, showing that there is still a certain need for correction during the order processing. The time to issue an order and the time to confirm an order were reported as 25 and 46 minutes, respectively. Although no predefined benchmarks were provided, these figures illustrate the speed of order handling achieved during the implementation phase.

The data presented in Table 5 indicate that the implementation of the Phase I strategic inventory control mechanism resulted in substantial improvements across several key performance indicators. The notable reduction in average inventory days and the increase in storage rate at the logistics center suggest that refined inventory management practices and enhanced supply chain responsiveness have contributed to the reduction of inventory backlogs and the optimization of turnover rates. Simultaneously, improvements in the on-time delivery rate and invoice accuracy demonstrate that enhancements in inventory and logistics management have translated into increased operational efficiency across the supply chain. However, a slight decrease in the order fulfillment rate and a relatively high order correction rate indicate that there remains room for improvement in order management and process control. To further optimize overall supply chain performance, it is recommended that the second phase of implementation focus on reducing the order correction rate and improving the order fulfillment rate. Moreover, by leveraging advanced automation tools and data-driven decision-making systems, it should be possible to further shorten order processing times, thereby enhancing overall supply chain efficiency and achieving a higher level of precision.

According to the data presented in Table 6, the second-phase implementation of the strategic inventory control mechanism resulted in substantial improvements across multiple performance indicators, reaching or approaching predefined targets. The average inventory days at the material center were reduced from 23 days to 12 days during the first phase and then increased slightly to 15 days in the second phase. Although the target value of 11 days was not fully achieved, the result remained within an acceptable range. The inventory availability rate at the logistics center improved significantly from 93% to 97%, surpassing the target value of 94%, which reflects the effectiveness of the enhanced inventory management strategies. The order fulfillment rate stabilized at 92%, slightly lower than the target value of 94%, but still close to the target level. The on-time delivery rate and invoice accuracy both reached 101% and 102%, respectively—consistent with their corresponding targets. Notably, the order correction rate was reduced from 16% in the first phase to 9% in the improvement phase, substantially below the target threshold of 11%. The time required to issue orders was shortened from 25 minutes to 16 minutes, and order confirmation time was reduced significantly to 21 minutes, indicating further enhancement in order processing efficiency. The inventory utilization status remained stable and was consistently marked as "yes," suggesting that the inventory continued to be effectively leveraged.

Based on the data presented in Table 6, the second phase of the strategic inventory control mechanism yielded significant results, particularly in inventory management and process optimization. Although the average inventory days at the material center slightly deviated from the target value, overall inventory turnover efficiency was enhanced. The increase in inventory availability at the logistics center, combined with reduced order processing times, indicated improvements in supply chain responsiveness and operational efficiency. The reduction in the order correction rate and the shortened order confirmation time demonstrated that the order management process had undergone substantial optimization, allowing for faster responses to market demand fluctuations and changes in order volume. However, the slight decline in the order fulfillment rate suggested that further refinement in supply chain planning and demand forecasting remained necessary. To sustain and enhance these improvements, greater emphasis should be placed on improving the accuracy of forecasting models and incorporating dynamic adjustment mechanisms. Additionally, increased flexibility must be embedded within inventory control strategies to better accommodate market uncertainties and volatility. Such efforts are expected to further strengthen overall supply chain efficiency and responsiveness.

5. CONCLUSION

This study is centered on the procurement and inventory control mechanisms of critical raw materials within the semiconductor supply chain, with focused analyses conducted on two core dimensions: critical raw material procurement and inventory control strategies. Regarding procurement, emphasis was placed on how stable access to critical raw materials on a global scale can be ensured through the implementation of rational procurement strategies, supplier management practices, long-term supply agreements, and supplier risk assessments. Quantitative analytical methods were employed to optimize procurement decision-making in the face of market volatility and uncertainty, thereby securing the continuity and reliability of material supply. With respect to inventory control, strategies tailored to the characteristics of the semiconductor industry were proposed, particularly for managing high-value materials with a high risk of long-term accumulation. Data-driven forecasting methods and adaptive inventory control strategies were applied to improve inventory turnover rates, reduce holding costs, and enhance supply chain responsiveness and flexibility in response to fluctuating market demands.

Based on the experimental results and data analyses presented earlier, the outcomes of both the first and second implementation phases demonstrate that the introduction of strategic inventory control mechanisms effectively improved turnover efficiency, mitigated inventory backlog, and optimized logistics and order-processing performance to some extent. Specifically, the reduction in average inventory days at material centers and the increase in inventory availability at logistics hubs indicate clear enhancements in inventory management. Moreover, improvements in order processing time and correction rates reflect refined adjustments within order management procedures. However, the alignment between procurement and order fulfillment remains an area requiring further improvement, especially under market volatility. The ongoing challenge lies in dynamically adjusting procurement and inventory strategies based on accurate demand forecasts.

The findings presented in this study hold considerable practical significance and academic value. Through a comprehensive investigation of critical raw material procurement and inventory control mechanisms within the semiconductor supply chain, actionable strategies for supply chain optimization were proposed that are applicable not only to the semiconductor industry but also to other high-technology sectors. The results demonstrate that refined procurement strategies, diversified supplier management, and flexible, data-driven inventory control methods can significantly enhance the ability of semiconductor enterprises to respond to material shortages and market fluctuations, thereby improving overall supply chain stability and adaptability.

However, certain limitations of this study should be acknowledged. First, the analyses have primarily relied on theoretical frameworks and case-based data. Broader empirical investigations and real-world data validation are recommended to further substantiate and generalize the findings. Second, although several optimization strategies were proposed, in practical implementation of dynamic procurement and inventory adjustments under varying market conditions remains a complex challenge, meriting further research. Future research directions may be pursued in the following areas: a) enhancing predictive accuracy and supply chain responsiveness by integrating real-time market dynamics into planning models; b) employing artificial intelligence and big data analytics to further refine procurement decisions and inventory control strategies; c) addressing globalized supply chain risks, including supplier diversification and geopolitical uncertainties, and assessing their impact on supply chain resilience; and d) advancing the understanding of how to balance environmental sustainability and cost-efficiency within the supply chain, particularly under constraints imposed by resource scarcity and increasing environmental pressures, to realize a green transformation in supply chain practices.

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