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The Impact of Inventory Management Innovations on Industry 4.0 Manufacturing Strategies

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Abstract: In general, the goal of inventory management mechanisms is to develop inventory ordering rules that ensure optimal inventory levels. By "optimal inventory level," we mean a level where stock is always available when needed, while storage costs are minimized. To achieve this, a thorough understanding of inventory-related costs is essential for determining the economical level. In addition to classical and widely used inventory management mechanisms, many companies also employ mixed or hybrid inventory strategies, which are based on the combination of elements from different systems. In Industry 4.0 manufacturing, determining the inventory levels of raw materials and semi-finished products presents a significant challenge for logistics professionals. Developments in Logistics 4.0, as well as advanced hybrid inventory management mechanisms, can provide substantial support to professionals in optimizing inventory levels.

Keywords: logistics; Industry 4.0; inventory control

1 INTRODUCTION

The continuous advancement of industrial production and the increasing prevalence of digitalization are driving innovations aimed at enhancing supply chain efficiency. In the era of Industry 4.0, inventory management strategies are undergoing a significant transformation, with the primary objective of ensuring more flexible, cost-effective, and sustainable operations. Through intelligent systems, data analytics, and automation, companies can optimize their inventory management processes, minimize excess stock, and respond more swiftly to market fluctuations. Hybrid inventory mechanisms are a critical component of innovative inventory management, integrating elements of traditional push and pull strategies [1]. These models enable businesses to dynamically adjust their inventory levels in response to actual demand while leveraging the capabilities of automated forecasting and predictive analytics. Such approaches are particularly relevant to Industry 4.0 manufacturing strategies, especially in Make-to-Order (MTO) systems, where production is exclusively driven by incoming customer orders. This model significantly reduces warehousing costs and losses resulting from overproduction [2].

2 THE MAKE TO ORDER PRODUCTION SYSTEM

In the dynamically evolving field of modern manufacturing driven by Industry 4.0 principles, the make-to-order (MTO) production system has emerged as a strategic approach to meeting customer demands with increased efficiency and flexibility [3-5]. The MTO system is a manufacturing strategy in which products are produced based on specific customer orders rather than being manufactured in anticipation of future demand. This approach contrasts with traditional manufacturing models such as make-to-stock (MTS), where goods are produced based on forecasted demand. MTO enables a high degree of product customization to meet unique customer requirements [6]. Products must be tailored to individual specifications, offering a personalized experience for customers. Unlike MTS models, MTO minimizes the need for large inventories. Production begins only when an order is received, reducing excess inventory and associated storage costs. MTO provides greater flexibility in responding to changes in customer preferences and market trends [7].

Manufacturers can quickly adapt to fluctuations in demand, making this an agile approach.

2.1 The Advantages of Make-to-Order (MTO) Production

Innovative inventory management strategies have a significant impact on a company’s competitiveness and operational efficiency [8]. Production tailored to individual customer needs increases customer satisfaction and loyalty, as consumers receive products that precisely meet their expectations. This not only strengthens customer relationships but also ensures a stable market position for the company in the long run. By optimizing inventory management, companies can reduce excess stock, leading to cost savings while minimizing losses from obsolete products. Lower inventory levels also contribute to more efficient financial management, as capital is not tied up in unnecessary stock but can be utilized in other strategically important areas, such as innovation or development. The ability to quickly adapt to market changes is also a key factor in today’s dynamic business environment. Companies that can respond flexibly to demand fluctuations and introduce new products rapidly gain a competitive advantage. Therefore, innovative inventory management solutions not only result in cost reduction and more efficient operations but also contribute to sustainable growth and strengthening market position.

2.2 Challenges of Make-to-Order Production

In a modern manufacturing environment, producing customized products presents several challenges that can impact a company's operations and competitiveness. One of the most critical factors is manufacturing lead time, which can be particularly problematic for complex or highly customized products. Longer lead times not only slow down order fulfillment but also affect customer satisfaction, making effective planning and optimized production processes essential. Another challenge associated with customization is the increased complexity of manufacturing, which requires enhanced coordination and precise planning. Meeting unique customer demands often necessitates specialized raw materials, flexible production processes, and advanced technological solutions, all of which can complicate seamless production. To manage these challenges, companies must implement efficient manufacturing strategies, such as advanced scheduling systems and digital production tools.

Additionally, cost management is a crucial factor, as balancing customization with cost efficiency is essential for maintaining profitability. Excessive customization can drive up material and labor costs and increase manufacturing complexity, which may render the business model unprofitable in the long run. Therefore, companies must develop strategies that align customization with cost efficiency, ensuring sustainable and profitable operations.

2.3 Implementation Strategies

The development of efficient and competitive manufacturing processes requires well-functioning communication, the implementation of advanced planning systems, supplier collaboration, and continuous improvement. Clear and transparent communication channels between sales, production, and customer service play a crucial role in accurately understanding and fulfilling customer demands. Ensuring proper information flow allows all relevant departments to have up-to-date data, minimizing misunderstandings and delays caused by errors. To enhance manufacturing efficiency, the introduction of advanced planning and scheduling systems is essential. These tools enable the optimization of production workflows, the reduction of manufacturing lead times, and the more efficient utilization of resources. Automated planning solutions not only help maximize production capacity utilization but also contribute to faster and more accurate order fulfillment. Close collaboration with suppliers is also fundamental to maintaining uninterrupted production. Ensuring the timely availability of raw materials and components reduces the risk of delays and enhances the stability of production processes. Efficient supplier relationships enable companies to respond more quickly to changing demands and ensure continuous supply. Finally, the principle of continuous improvement plays a key role in increasing efficiency and reducing costs. Regular process reviews and optimization measures allow companies to fine-tune manufacturing operations, eliminate inefficiencies, and integrate innovations. Constant development and the application of modern technologies ensure that the company remains competitive in the long run, even in a rapidly changing market environment. Make-to-order (MTO) represents a customer-centric approach that aligns production with specific demand signals. While it presents challenges, the benefits of increased customer satisfaction, reduced inventory levels, and enhanced market responsiveness make it an attractive strategy for businesses striving for agility in today's competitive markets. As technology continues to advance, the integration of smart manufacturing practices and digital tools further enhances the efficiency of make-to-order strategies.

3 THE BASIC INVENTORY MECHANISMS

The fluctuation of inventory levels at the product level is primarily determined by two key factors: the demand for the specific item and its supply pattern. It is evident that inventory levels are influenced not only by when and how much demand arises for the product, but also by the timing and quantity of replenishment orders placed by the system [9]. The demand pattern is mainly shaped by the company's marketing department, whereas the logistics department is responsible for managing the supply pattern—namely, the inventory control mechanism applied. This mechanism dictates when and how much of a particular stock-keeping unit should be reordered, thereby ensuring the continuous availability of the product in the future [10, 11].

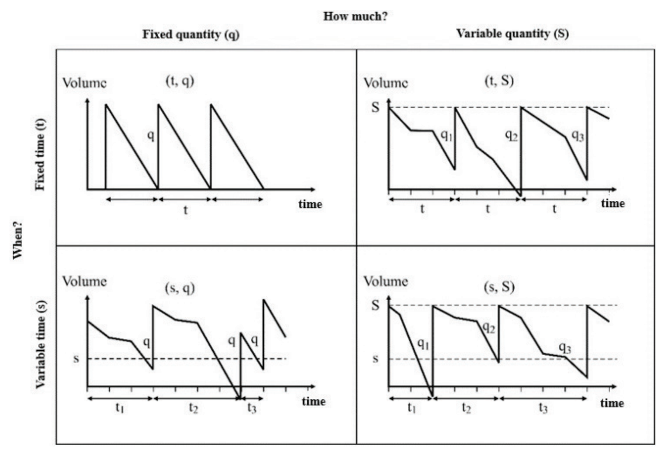

Figure 1 Basic inventory mechanism [12]

Fixed-time-based models (top row) are easier to plan but may not adapt well to demand fluctuations. Variable-time-based models (bottom row) are more flexible and respond to actual needs, potentially leading to more efficient inventory management. Fixed-quantity strategies (left column) provide greater predictability, while variable-quantity strategies (right column) can optimize inventory costs. [13]. Fig. 1 clearly illustrates the differences between inventory strategies and aids in selecting the appropriate method within the supply chain.

4 HYBRID INVENTORY MECHANISM

In the ever-evolving landscape of supply chain management, adopting hybrid inventory control methods has become a strategic necessity for companies aiming to enhance the efficiency of their inventory processes. This chapter explores the concept of hybrid inventory systems by examining their key features, benefits, and practical implementation. Essentially, hybrid mechanisms integrate elements from multiple traditional inventory management models, forming a more flexible and adaptable system. Their goal is to balance the operational efficiency of conventional approaches with the agility of modern, responsive methods.

4.1 General Characteristics

One of the most important characteristics of hybrid inventory mechanisms is flexibility, which allows companies to efficiently adapt to demand fluctuations. By integrating features from both push and pull inventory systems, these mechanisms enable inventory strategies to be simultaneously forward-planning and reactive, ultimately enhancing the overall efficiency and responsiveness of the supply chain. Another key factor is risk reduction, which is achieved through the diversification of inventory management strategies. A company that relies solely on a single inventory management approach is more exposed to market fluctuations and supply disruptions. Hybrid mechanisms enable companies to leverage the advantages of multiple strategies, minimizing the negative effects of stockouts, overproduction, or excessive storage costs.

The main objective of hybrid inventory mechanisms is to enhance inventory management efficiency by adapting strategies to the unique requirements of different product categories or market segments. This method enables companies to balance cost reduction with maintaining high service levels, while continuously improving the overall effectiveness of their inventory operations.

4.2 Benefits of Implementing Hybrid Inventory Mechanisms

The implementation of hybrid inventory mechanisms provides multiple advantages, significantly contributing to a company's efficiency and competitiveness. One of the most notable benefits is the improvement of service levels, as the combination of various inventory management models enables companies to meet customer demands more accurately and quickly. This not only enhances customer satisfaction but also strengthens long-term customer relationships. Cost efficiency is another key advantage of hybrid mechanisms. Adjusting inventory levels according to product features and demand trends can result in substantial cost reductions by minimizing excess storage and handling costs. This is particularly important in industries where inventory-related costs represent a significant proportion of total expenses. Hybrid mechanisms offer significant advantages in risk management by varying inventory strategies, which helps reduce the impact of supply chain disruptions, demand fluctuations, and market uncertainty. By avoiding reliance on a single inventory method, companies can achieve greater stability and resilience in their operations. Flexibility is one of the most critical factors contributing to the effectiveness of hybrid mechanisms. These solutions allow companies to quickly adapt to changing market conditions, enabling them to maintain their competitive advantage and effectively respond to fluctuations in demand or supplier conditions.

In corporate operations, two fundamental and relatively simple inventory control systems — or their combination — have become widely adopted [9]:

- Continuous review system: in this approach, inventory levels are monitored on an ongoing basis, allowing decisions to be made at any time based on current stock status and demand. The two main decision parameters are the order quantity (q) and the reorder point (s), which represents the inventory level that triggers a replenishment order for a fixed quantity. This model is commonly referred to as the (s, q) inventory system.
- Periodic review system: this method involves checking inventory levels at regular, predefined intervals — such as weekly or monthly. The order quantity is determined based on the stock level recorded at the time of review. Here, the quantity to be ordered is calculated as the difference between the target maximum inventory level (S) and the actual available inventory (I_a) at the review point. This type of system is known as the (t, S) inventory model.

5 DESCRIPTION OF HYBRID INVENTORY MECHANISMS IN MAKE-TO-ORDER (MTO) MANUFACTURING SYSTEMS

The use of hybrid inventory strategies in Make-to-Order (MTO) production brings various advantages, including decreased inventory levels, more efficient production workflows, and higher levels of customer satisfaction. However, implementing and maintaining such a system can present significant challenges, particularly in aligning manufacturing and logistics processes. We only deal with three hybrid variants, as the combination of (t, q) and (t, S) (combined fixed order system) is not suitable for MTO systems. This is because Make-to-Order (MTO) production is characterized by manufacturing products only after receiving customer orders, which leads to highly variable demand. As a result, MTO systems generally require more flexible, event-driven hybrid inventory management models.

5.1 Combination of (*t*, *q*) and (*s*, *S*) – Adaptive Periodic System

Its operation is characterized by conducting inventory checks at predetermined intervals (t), but if the current stock level drops below a predefined threshold (s), an immediate order is triggered, even before the scheduled replenishment time. The advantage of this system is that it balances scheduled inventory replenishment and demand-driven ordering. The system's efficiency is particularly beneficial in a Make-to-Order (MTO) manufacturing environment, where production is solely based on incoming orders. The adaptive inventory management mechanism ensures continuous monitoring of raw material and component stocks while allowing replenishment to occur in a timely and flexible manner. This minimizes excess inventory costs and reduces production delays caused by stock shortages.

By combining scheduled and immediate ordering strategies, this system enables companies to respond effectively to fluctuating demand while maintaining supply chain stability and production continuity.

Let $I_{(t)}$ represent the inventory level as a function of time. Inventory depletion occurs based on the demand function $D_{(t)}$:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \quad (1)$$

where $O_{(t)}$ follows two replenishment rules.

Replenishment follows two conditions:

- *Scheduled replenishment:*

$$O_{(t)} = q, \text{ if } t = nT, n \in \mathbb{N}, \quad (2)$$

meaning that a fixed quantity q is ordered at the end of every T interval.

- *Immediate replenishment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } I_{(t)} \leq s, \quad (3)$$

meaning that if the inventory level drops below s, an immediate order is triggered to restore stock up to S.

This inventory model offers multiple advantages for MTO-based manufacturing:

- Balancing fixed-interval and demand-driven replenishment: The combination of time-based (t, q) and event-driven (s, S) policies ensures continuous inventory availability.
- Minimized inventory holding costs: The system replenishes stock only when necessary, reducing storage and carrying costs.
- Quick response to demand fluctuations: In MTO production, demand variability can be managed effectively through dynamic ordering strategies.

This hybrid inventory management system ensures supply chain stability, while minimizing excess stock and reducing production delays caused by material shortages.

5.2 Combination of (*s*, *q*) and (*s*, *S*) – Flexible Minimum Order System

This system generates a fixed quantity order (q) when the inventory level reaches the threshold (s), but if demand is higher than average, the order quantity can be increased up to the maximum stock level (S). Its advantage lies in its ability to flexibly handle demand fluctuations, ensuring continuous supply while minimizing stockouts. In a Make-to-Order (MTO) manufacturing environment, ensuring the availability of raw materials while minimizing storage costs is crucial. In this model, when inventory reaches the threshold (s), a fixed order (q) is triggered, but if demand forecasts indicate increased demand, the order quantity can be adjusted up to the maximum stock level (S). This system ensures continuous raw material availability, responds flexibly to demand changes, and minimizes inventory holding costs, as additional stock is procured only when necessary, contributing to efficient inventory management and cost optimization. Again, let $I_{(t)}$ represent the inventory level at time (t). The inventory level follows the equation:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \quad (4)$$

where $D_{(t)}$ represents demand at time (t), and $O_{(t)}$ follows two replenishment rules.

Replenishment follows two conditions:

- *Fixed minimum order:*

$$O_{(t)} = q, \text{ if } I_{(t)} \leq s, \quad (5)$$

when inventory falls below s, a fixed quantity q is ordered.

- *Dynamic order adjustment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } I_{(t)} \leq s \text{ and } \hat{D}_{(t)} > \mu, \quad (6)$$

if inventory falls below s and the forecasted demand $\hat{D}_{(t)}$ exceeds the average demand μ\muμ, the system replenishes stock up to the maximum level S.

This inventory model offers multiple advantages for MTO-based manufacturing:

- The system guarantees that raw materials are available when production begins, preventing disruptions.
- By dynamically adjusting order quantities, it minimizes stockouts and ensures production continuity.
- Stock replenishment occurs only when necessary, reducing excess inventory and storage costs.

This hybrid inventory control model optimally balances supply stability and cost efficiency, making it an effective solution for MTO-based production environments.

5.3 Combination of (*t*, *S*) and (*s*, *q*) – Hybrid Time-Based and Event-Driven Model

This model places orders at regular intervals (t) to replenish inventory up to the maximum stock level (S). However, if the inventory level drops below a critical threshold (s) before the scheduled replenishment, an emergency order is triggered, replenishing stock with a fixed quantity (q). The key advantage of this system is that it effectively integrates both time-driven and demand-driven inventory management, creating an optimal balance between scheduled and immediate replenishments. In a Make-to-Order (MTO) production environment, this model is particularly effective. Certain raw materials are ordered at fixed intervals (t) to maintain continuous supply, ensuring that production has the necessary inputs. However, if the stock level of a material drops below the predefined threshold (s) before the scheduled replenishment, an emergency order is placed to restock a fixed quantity (q), preventing potential disruptions in the production process. This system provides several benefits for MTO production. Scheduled orders help reduce the risk of stockouts while simultaneously lowering ordering costs. Additionally, the event-driven ordering mechanism ensures that production does not come to a halt due to sudden increases in demand, maintaining operational continuity. Moreover, this hybrid approach enhances inventory planning within the supply chain, supporting more efficient resource allocation and sustainable inventory management. Again, let $I_{(t)}$ represent the inventory level at time (t). The inventory level follows the equation:

$$I_{(t)} = I_{(t-1)} - D_{(t)} + O_{(t)}, \tag{7}$$

where $D_{(t)}$ represents demand at time (t), and $O_{(t)}$ follows two replenishment rules.

Replenishment occurs in two ways:

- *Time-based replenishment:*

$$O_{(t)} = S - I_{(t)}, \text{ if } t = nT, n \in \mathbb{N}. \tag{8}$$

This means that at the end of every T interval, inventory is replenished up to the maximum level (S), regardless of demand fluctuations.

- *Event-driven emergency order:*

$$O_{(t)} = q, \text{ if } I_{(t)} \le s, \tag{9}$$

If inventory drops below the critical threshold (s) before the next scheduled replenishment, an immediate order is triggered to restock a fixed quantity (q). This inventory model offers multiple benefits for MTO production environments. The time-based replenishment mechanism reduces the risk of stockouts while keeping ordering costs lower due to scheduled orders. Meanwhile, the event-driven ordering strategy ensures that production does not halt in the event of sudden demand surges, maintaining operational continuity. Additionally, this hybrid approach enhances inventory planning within the supply chain, enabling more efficient resource allocation and sustainable inventory management. Time-based ordering strategies ensure continuous material availability, while event-driven restocking helps manage demand fluctuations more effectively. Overall, the combination of (t, S) and (s, q) creates a balance between scheduled and emergency replenishments, ensuring smooth manufacturing processes and optimized inventory management in MTO-based production environments.

5.4 Mathematical Model on Hybrid Inventory Strategy in MTO Environments

In a Make-to-Order (MTO) production environment, inventory management aims to minimize shortages of raw materials and components. This adaptive inventory mechanism adjusts dynamically to demand fluctuations:

- *The demand function $D_{(t)}$ may be deterministic or stochastic:*

$$D_{(t)} \sim N(\mu, \sigma^2) \text{ (assuming normally distributed demand)} \tag{10}$$

- *The optimal minimum inventory level s^* and maximum inventory level S^* can be estimated as follows:*

$$s^* = \mu L + z\sigma\sqrt{L}, \tag{11}$$

$$S^* = s^* + q. \tag{12}$$

Where $D_{(t)}$ demand as a function of time: represents the demand at a specific time (t), L the lead time, z the standard normal distribution value corresponding to the desired service level, $N(\mu, \sigma^2)$ assumes that demand follows a normal distribution, defined by two parameters: μ expected demand (the long-term average demand level observed over time), σ demand standard deviation (indicates how much demand may fluctuate around the average value. A higher standard deviation implies greater variability in demand), σ^2 demand variance (the square of the standard deviation, measuring the extent of demand fluctuations).

5.5 Practical Example of Hybrid Inventory Mechanism in an MTO Environment

To demonstrate the practical applicability of the proposed hybrid inventory mechanism, this section presents a real-life inspired (fictional) example based on an MTO production environment. A manufacturing company operating under an MTO production strategy produces customized electronic components. The company's raw material, a special type of microchip, is procured from an external supplier. The following data are available:

- Average weekly demand (μ) = 200 units
- Standard deviation of demand (σ) = 50 units
- Lead time (L) = 2 weeks
- Desired service level = 95% → z = 1.65
- Fixed order quantity (q) = 300 units
- Maximum stock level (S) = calculated
- Review period (T) = 2 weeks
- Safety stock threshold (s) = calculated.

According to the hybrid inventory model described earlier, the optimal minimum and maximum inventory levels are calculated as:

$$s^* = \mu L + z\sigma\sqrt{L} \tag{13}$$

$$S^* = s^* + q \tag{14}$$

$$s^* = 200 \cdot 2 + 1.65 \cdot 50 \cdot \sqrt{2} = 400 + 116{,}7 \approx 517 \text{ units} \tag{15}$$

$$S^* = 517 + 300 = 817 \text{ units} \tag{16}$$

From an operational perspective, it can be concluded that the company is required to apply a hybrid inventory mechanism. The example illustrates a hybrid inventory strategy that combines both time-based and event-driven mechanisms. In this system, the company reviews its inventory levels every two weeks. If the inventory remains above the safety threshold of 517 units during this period, no action is taken. However, if the inventory level drops below 517 units at any time within the review period, an emergency replenishment order is triggered to restore the stock level up to 817 units, ensuring continuity in production. Regardless of emergency replenishments, a fixed order of 300 units is also placed at the end of every two-week review period, following a regular ordering rhythm. This combination of scheduled and demand-responsive ordering enhances both supply chain stability and responsiveness in a Make-to-Order (MTO) production environment.

6 CONCLUSION

The digitalization of industrial production and the expansion of the Industry 4.0 era have radically transformed supply chain and inventory management strategies. Through intelligent systems, data analytics, and automation, companies can optimize their processes, reduce excess inventory, and respond more quickly to market changes. This study provides a detailed analysis of how traditional push and pull strategies are integrated into a hybrid inventory mechanism, which is particularly beneficial in Make-to-Order (MTO) manufacturing systems, where production is initiated solely based on incoming orders. The objective of this innovative approach is to achieve greater flexibility, cost efficiency, and sustainability, while simultaneously enhancing customer satisfaction and strengthening market competitiveness. The study examines various inventory management mechanisms and then presents their combinations in the form of different hybrid systems. These models enable the simultaneous application of scheduled and demand-driven ordering mechanisms, optimizing inventory levels, minimizing storage costs, and reducing the risk of production disruptions and delays caused by stockouts. Furthermore, mathematical models are used to determine optimal reorder points and inventory levels, allowing companies to effectively manage demand fluctuations and ensure a stable supply of raw materials necessary for uninterrupted production.

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