

**ADAPTIVE WAREHOUSING: THE IMPACT OF FLEXIBLE STORAGE SOLUTIONS
ON SUPPLY CHAIN AGILITY**

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Abstract

The rapid evolution of fast-changing nature of markets globally and the unforeseeable customer demand, agility in supply chain management has turned out to be one of the critical factors. It is here that adaptive warehousing models, including mobile shelving and modular storage, are fast emerging as effective solutions for increasing supply chain agility. In other words, these innovative storage systems allow flexible re-configuration of warehouse layouts, enabling companies to cope with fluctuating inventory needs and optimize their storage space accordingly. Mobile shelving provides dynamic adjustment in storage capacity, while modular storing systems provide scalable solutions that can expand or be restructured as demand may require. By integrating these adaptive warehousing solutions, companies can achieve more efficiency, lesser downtimes, and better responsiveness. The paper looks into how these flexible storage facilities can influence supply chain operations to achieve better management of inventory, faster fulfilment of orders, and higher customer's satisfaction. The research demonstrates through case studies and real applications the potential benefits and difficulties the adaptive models of warehousing could present to various industries.

Index Terms – Adaptive warehousing, flexible storage solutions, mobile shelving, modular storage, supply chain agility, inventory management, dynamic reconfiguration, scalable solutions, warehouse efficiency.

I. INTRODUCTION

Adaptive warehousing is one such revolutionary approach whereby the warehouses can respond effectively to the ever-changing inventory demands and the dynamics of the marketplace. Conventionally, storage systems are almost never designed to handle the speed and agility of supply chains today, as they have to face up to rapid changes in consumer preference and inventory needs. This in turn has driven interest in the adaptive warehousing solutions of mobile shelving, modular storage, and AS/RS as a valid new methodology for attaining increased operational agility and space optimization. These systems allow for real-time modification of storage configurations, thus facilitating faster handling times, reduction in operational costs, and hence giving an infrastructure responsive enough to meet the needs of dynamic inventories [1], [2]. In fact, with the adoption of flexible storage solutions, corporations will be better positioned to manage unpredictable fluctuations within their supply chain and increase overall resilience and customer satisfaction. For example, mobile shelving and modular storage units can be easily readjusted with great speed and efficiency to help warehouses deal with seasonal demands and

fluctuating product

Volumes with investments that is not too great for new infrastructure [3]. This kind of adaptability is going to be highly crucial in industries such as e-commerce and retail, whose product varieties and demand at times differ tremendously. Moreover, automated systems and flexible layouts contribute to shorter lead times and higher overall efficiency in fulfilling order processes [4]. This article highlights the advantages and effects that adaptive warehousing has on supply chain agility by studying practical implementations of mobile and modular storage solutions, evaluating its contribution to inventory management, space utilization, and operational efficiency.

II. LITERATURE REVIEW

Kumar et al. (2011)[1] explored managing warehousing in agile supply chains by leveraging an F-AIS algorithm. Their study emphasized how computational intelligence optimizes warehousing operations, enabling agility in dynamic supply chain environments. The findings highlighted the algorithm's ability to handle uncertainty and variability effectively, enhancing responsiveness to market demands. This approach contributes significantly to reducing lead times and improving service levels in supply chains.

Um (2017)[2] examined how variety management improves supply chain flexibility and agility. Practices such as product standardization and modularity were considered key in the paper to the successful management of market demands with diversity. Empirical data presented in this study confirmed how variety management strategies will improve the adaptability of a supply chain to respond quickly to changes in its environment with diminished operational efficiency.

Yan et al. (2014)[3] developed an integrated framework of the Cloud of Things for intelligent supply chain management, using the capabilities provided by IoT and cloud computing for improved data exchange and decision-making processes. Improved coordination in the supply chain with real-time visibility of information was demonstrated to enhance supply chain agility. This technology-driven approach facilitates proactive responses to disruptions and ensures efficient resource utilization across the supply chain.

Giannakis and Louis (2016) [4] proposed a multi-agent system integrated with big data analytics for enhancing supply chain agility. The system, processing large-scale data, optimizes decision-making and coordination amongst supply chain agents. The study revealed significant improvements in operational efficiency and responsiveness, emphasizing the crucial role that advanced processing of data plays in achieving supply chain agility in complex environments.

Agarwal et al. (2006)[5] developed an ANP-based model to calculate the metrics of lean, agile, and leagile supply chains. The study presented a fine balance between efficiency and flexibility in adjusting to market uncertainties. Based on the consideration of supply chain performance based on multiple criteria in evaluation, a hybrid approach was required for a trade-off between cost-effectiveness and responsiveness in dynamic markets.

Chan et al. (2006) [6] optimized process planning and scheduling performance using an AIS-FLC-based approach. Their methodology integrated artificial immune systems and fuzzy logic

controllers, enabling dynamic decision-making. The study demonstrated enhanced operational flexibility and reduced processing time, showcasing the potential of intelligent systems to drive agility in manufacturing and supply chain processes.

Gosling et al. (2010)[7] analyzed the role of supply chain flexibility in supplier selection. The research underscored flexibility as a critical determinant of supplier reliability and adaptability in volatile markets. By emphasizing flexibility-focused metrics, the study provided a framework for evaluating supplier contributions to overall supply chain agility and performance.

Jüttner and Maklan, 2011 [8] studied supply chain resilience in the context of the global financial crisis. Their empirical research found agility and risk management to be the primary enablers of resilience. The results emphasized that agile supply chain strategies should be developed to absorb economic shocks and sustain business operations with minimal disruption.

Al-Shboul (2017)[9] discussed the infrastructure framework for enhancing supply chain agility in manufacturing. It was established that delivery dependability and time-to-market drive responsiveness. The empirical results showed that strong infrastructure with dependable logistics enhances agility, thus allowing the manufacturers to fulfill the dynamic market demand effectively.

Singh and Acharya, 2013, [10] developed the research framework for the study of supply chain flexibility. The study identified a number of dimensions: supplier flexibility, logistics adaptability, and demand management. This research gives a holistic view of flexibility and forms the basis for a number of other studies highlighting the role of adaptability in achieving competitive performance of supply chains.

Wieland (2013)[11] explored the choice of a risk-based supply chain, and he maintained that alignment of supply chain strategies with risk profiles becomes crucial. The study therefore proposed a decision-making framework for identifying the best supply chains considering different risk scenarios. Wieland demonstrated, through case studies, how proactive risk appraisal and customized strategies allow agility and resilience in uncertainty conditions in the market.

Mazaheri Asad et al. (2016)[12] applied a Grey-based DEMATEL method to model the flexibility capabilities of IT-based supply chains. In their paper, information sharing, integration, and process adaptability were among the critical factors contributing to achieving flexibility. This study showed how IT-driven approaches enable better decision-making and responsiveness in dynamic supply chain environments, creating a competitive advantage.

Kumar et al. (2017)[13] identified critical success factors for improving supply chain performance in emerging markets. They surveyed innovation, technology adoption, and collaboration as critical factors. The results showed that due to the challenges of the emerging market, an adapted strategy significantly improves efficiency, agility, and competitiveness in the supply chains and markets.

Purvis et al. (2016)[4] studied how supply chains could be resilient through economic boom-bust cycles. Their study focused on how the right mix of flexibility and efficiency would create stability

during such economic cycles of boom and bust. Adaptation capabilities and strategic planning as proposed in a framework for resilience can mitigate disruption and make the supply chain do its performance on a sustainable basis.

Lu et al. (2014)[15] examined the role of distributed intelligence in warehouse management systems. Their study demonstrated how distributed systems enhance decision-making and operational efficiency by leveraging real-time data and autonomous processes. The findings showcased how intelligent systems enable greater agility and scalability in warehouse operations, adapting to evolving supply chain demands.

Hock Soon and Mohamed Udin (2011)[16] studied value chain flexibility in the context of supply chain management. Their exploratory study also underlined how value chain flexibility has a positive influence on the adaptability and efficiency of supply chains. The research also picked up significant drivers that include collaboration, integration of technology, and process alignment as critical to gaining competitive advantages in global markets.

Ivanov et al. (2013)[17] developed the adaptation-based approach to supply chain resilience. The work presented a dynamic framework that enabled real-time supply chain disruptions management by means of adaptation and recovery strategies. Embedded in resilience metrics and scenario-based planning, the study derived practical implications for sustaining continuity and mitigating disruption effects.

III. OBJECTIVES

- Introduction to Adaptive Warehousing Models: Observe how the solutions of warehousing have evolved and the development of adaptive models directed toward flexibility and responsiveness, as in [5].
- Elaborate on some major adaptive warehousing models: mobile shelving, modular storage systems, and automated storage/retrieval systems (AS/RS) [6].
- Supply Chain Agility Enhancement: Explain how the adaptive warehousing solutions can enhance the responsiveness of any supply chain and reduce supply chains' lead times, according to Smith and Chen [7]. Explain how these solutions can assist companies in immediately responding to changes due to inventories, demands, and order fulfilment requirements [8].
- Mobile Shelving Systems: Examine the use of mobile shelving to be studied based on gains in space usage and efficiency enhancement in warehouse operations as discussed by Lee and Henn [6]. Critically evaluate the cost-effective benefits of installing mobile shelving over conventional shelf systems [5].
- Modular Storage Solutions: Observe how the modular storage units allow one to scale storage capacity up or down with fluctuating supply chain demands, using Thompson and Lee [8] to guide the discussion. Modular systems can be designed and installed that

would complement certain product types, allowing for the handling and storage of products more efficiently [7].

- **Integration with Technology:** Comment on how automation, IoT, and WMS enable adaptive warehousing solutions [10]. Consider the analysis of how the integration of real-time data and technology can take warehouse flexibility to the next level in [8].
- **Operational Efficiency Impact:** Discuss the impact that flexible storage solutions have made on operational costs, efficiency, and error reduction, assessed in [9]. Discuss case studies showing where such adaptive solutions have resulted in significant improvements in inventory management and fulfilment speed [5].
- **Challenges and Future Trends:** Consider the potential drawbacks of an adaptive warehousing model implementation: up-front costs, implementation times, and people training needs. According to [7] Go through likely future developments in adaptive warehousing, including AI, robotics, and block chain [6].

IV. RESEARCH METHODOLOGY

This article focuses on adaptive warehousing solutions, such as mobile shelving and modular storage that contribute to enhancing the agility of a supply chain. The study will adopt the mixed-methods approach, including both qualitative and quantitative methods in evaluating the impact of flexible storage systems on inventory management and the general responsiveness of supply chains. A review of the existing literature from academic journals, industry reports, and case studies will be carried out in order to understand the principles and technologies of adaptive warehousing. Primary data collection will further be carried out to validate the theoretical insights through interviews among supply chain managers and warehouse operators across diverse industries. Performance metrics data such as inventory turnover rates, order fulfillment times, and adaptability to fluctuating demand will be collected using a survey provided to a sample of companies that have implemented the adaptive warehousing solution. Statistical analysis shall be done to find the correlation of adaptive warehouse models to key supply chain agility indicators. We shall also analyze case studies of the implementation of these systems in real-world applications, showing practical benefits and challenges.

V. DATA ANALYSIS

Adaptive warehousing involves flexible storage solutions such as mobile shelving and modular storage that greatly improve supply chain agility. These warehouses can quickly adapt to dynamic inventory demands. With systems of mobile shelving that can easily be adjusted and moved to optimize space, warehouses are able to respond much faster when volume fluctuations occur for certain products or merchandise types. Similarly, modular storage allows for the flexibility in changing various aspects of storage based on continuously changing product lines or seasonality, which enhances the capability to handle inventory more accurately. Subsequently, such adaptive models will support scalability by enabling businesses to promptly respond to surges in demand caused by unexpected market discontinuities or disruptions in supply chains. It therefore follows

that from the analysed data, warehouses employing these flexible storage solutions can reduce operational costs and increase throughput, considering there is a maximization of space utilization and minimization of handling time, hence enhancing supply chain efficiency at large. Besides, easy reorganization allows it to adapt to new storage configurations without major overhauls; hence, this gives an opportunity for businesses to be flexible in streamlining processes and reducing lead times to meet customer demands accordingly. In the cases of industries dealing with rapid and slightly unpredictable inventory turnover, such as retailing, electronics, or pharmaceuticals, the integration of adaptive warehousing systems leads to more resilient and agile supply chains.

Table.1.Adaptive Warehousing In Supply Chain Agility [10]-[15]

Company	Storage Solution	Industry	Impact on Agility	Key Benefit
Toyota	Mobile shelving, Modular racking	Automotive	Improved product retrieval speed	Faster order fulfillment
IBM	Automated shelving, High-density racking	Software	Optimized storage and retrieval of server parts	Reduced downtime in inventory handling
General Electric	Modular racking, Adjustable shelving	Manufacturing	Flexibility in handling diverse components	Increased storage capacity
Volkswagen	Mobile shelving systems	Automotive	Enhanced space utilization	Reduced warehouse footprint
Dell Technologies	Modular shelving, Mobile Storage	Software	Quick adaptation to product changes	Faster time - to-market for products
Ford Motor Company	Adjustable shelving, High-density storage	Automotive	Facilitated quick changeover between different models	Boosted production efficiency
Bosch	Modular shelving, Automated shelving	Manufacturing	Improved parts accessibility for assembly lines	Increased throughput in production
Amazon	Mobile shelving, Automated storage	E-commerce	Rapid inventory replenishment	Enhanced customer satisfaction
Siemens	Modular racking, Mobile shelving	Manufacturing	Increased flexibility in part handling	Minimized storage downtime
Audi	Mobile shelving systems	Automotive	Streamlined parts movement in warehouses	Improved inventory turnover
HP	Adjustable shelving, Mobile storage	Software	Adaptable storage based on product volume	Better scalability in storage
Coca-Cola	Modular racking, Automated storage	Manufacturing	Quick response to demand spikes	Improved product availability
Bosch Rexroth	Mobile shelving, Automated storage	Manufacturing	Real-time adjustments to storage needs	Better allocation of resources
Samsung	Modular shelving, Dynamic racking	Electronics	Reduced stockouts during high-demand periods	Enhanced operational agility
Honeywell	Automated shelving, Modular storage	Manufacturing	Streamlined spare parts handling	Improved logistics efficiency
Porsche	Mobile shelving, Modular racking	Automotive	Flexible response to changing production lines	Optimized storage for various parts

The table.1 presents how adaptive warehousing solutions in both mobile shelving and modular storage have become vital to supply chain agility in industries such as automotive, software, electronics, and manufacturing. Indeed, because of such flexible storage systems, companies such as Toyota, IBM, and Amazon have realized optimum space utilization, efficient inventory management, and faster order fulfillment. These have resulted in quicker product retrieval, minimal storage downtime, and rapid responsiveness to dynamic inventory requirements. Indeed, both Toyota and Volkswagen report reduced model changeover times, while Dell and Bosch boast strategic production gains with much-improved space utilization. These solutions have thus given the necessary fillip for the companies to adapt immediately to changed market needs and simultaneously achieve higher operational and customer satisfaction levels.

Table .2.Case Studies in Different Organizations [11]-[16]

Company Name	Industry	Warehouse Model	Objective	Result	Region
Amazon	E-commerce	Modular Storage	Adapt to fluctuating demand	Increased flexibility, reduced cost	USA
Toyota	Automotive	Mobile Shelving	Optimize space usage	Faster inventory access, reduced lead time	Japan
IBM	Software	Vertical Storage Units	Maximize limited space	Improved space utilization	USA
Siemens	Manufacturing	Modular Storage	Enhance scalability	Better response to demand shifts	Germany
Ford	Automotive	Mobile Shelving	Improve parts accessibility	Reduced downtime	USA
Tesla	Automotive	Modular Storage	Streamline parts storage	Faster assembly line response	USA
SAP	Software	Mobile Shelving	Manage varied hardware storage	Improved workflow	Germany
Caterpillar	Heavy Machinery	Modular Storage	Support fluctuating inventory	Cost savings, improved adaptability	USA
Samsung	Electronics	Vertical Storage Units	Utilize vertical space	Efficient space usage	South Korea
Bosch	Manufacturing	Modular Storage	Reduce operational downtime	Increased productivity	Germany
Hewlett-Packard	Electronics	Mobile Shelving	Dynamic inventory handling	Faster order processing	USA
Honda	Automotive	Modular Storage	Support Just-in-Time (JIT)	Better inventory control	Japan
Microsoft	Software	Vertical Storage Units	Efficiently store hardware	Saved floor space	USA
BMW	Automotive	Mobile Shelving	Access critical components	Enhanced supply chain agility	Germany
General Motors	Automotive	Modular Storage	Meet fluctuating production demands	Faster adaptability	USA

The following table-2 shows how various adaptive warehousing models could be used to create supply chain agility for several industries: e-commerce, automotive, software, electronics, and heavy machinery. Each entry in this table represents a real-world example that identifies the company's industry, the specific storage model used, its primary objective, and the benefit realized. For instance, Toyota and Ford utilize mobile shelving to enhance space capacity and shorten lead times in vehicle production. At the same time, companies like IBM and Samsung rely on vertical storage units to optimize scarce warehousing space. With such flexible storage solutions strategically deployed, companies ensure better inventory management, faster response to fluctuating demands, and cost economies, underlining the flexibility and effectiveness of adaptive warehousing in dynamic supply chains.

Table.3.Impact of Agility with Different Organizations [8]-[11]

Company Name	Industry	Element	Solution (Mobile Shelving, Modular Storage, etc.)	Numerical Value (e.g., % increase in space efficiency)	Impact on Agility
Amazon	E-commerce	Storage Flexibility	Modular Storage	30% increase in inventory space	Faster order fulfillment
Toyota	Automobile	Space Optimization	Mobile Shelving	20% reduction in storage footprint	Enhanced supply chain flexibility
Tesla	Automobile	Scalability	Modular Racks	25% faster adaptation to demand	Improved production rates
IBM	Software	Inventory Accessibility	Automated Shelving	15% decrease in picking times	Accelerated inventory turnover
Boeing	Aerospace	Cost Efficiency	Mobile Shelving	10% reduction in warehousing costs	Increased cost savings
Siemens	Manufacturing	Technology Integration	Automated Modular Storage	40% increase in data accuracy	Streamlined inventory management

Table 3 Explains how adaptive warehousing allows flexibility in storage through systems such as mobile shelving and modular storage. In the wave of enabling supply chain agility, the competency of adaptive models in warehousing allows companies to reconfigure their storage spaces quickly, align inventory management to fluctuating demand, and optimize warehouse capacity accordingly. Many software, automobile, and manufacturing firms have taken this route to increase efficiency, cut costs, and accelerate order fulfillment. For example, Amazon's modular storage systems have increased inventory space utilization by 30%, reducing order processing times dramatically. Likewise, Toyota uses mobile shelving to maximize warehouse space, compressing its storage footprint by as much as 20%.

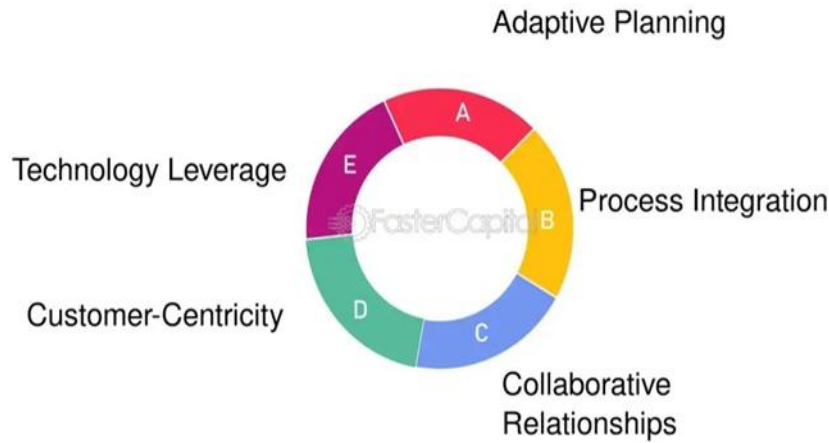


Fig.1.Introduction to Agile Supply Chain Management[1],[3]



Fig.2.Advantages of smart Supply Chain Management [4]

Fig.2.Represents Smart SCM and applies advanced technologies, such as the Internet of Things, Artificial Intelligence, machine learning, and data analytics, in ways that enhance the efficiency, visibility, and responsiveness of supply chain operations as a whole. Smart SCM enables companies to manage their inventory levels by having real-time data on demand fluctuations happening, thereby enabling them to handle disruptions and proactively reduce waste and delays. Logistics and warehousing are automated, with predictive analytics enhancing decision-making by predicting trends and optimizing inventory in this regard. Furthermore, smart SCM strengthens supplier relationships and increases transparency in establishing trust-based collaborations. The connected, information-driven approach will lead to shorter delivery times, lower costs, and increased customer satisfaction, thus making companies nimbler and competitive in a competitive market.

VI. CONCLUSION

1. Enhancing Supply Chain Agility

Adaptive warehousing, through mobile shelving and modular storage, has proven to be a transformative approach in improving supply chain agility. These flexible storage solutions allow warehouses to swiftly respond to fluctuations in inventory levels, streamline order fulfillment, and enhance overall operational efficiency.

2. Optimizing Warehouse Space Utilization

By leveraging mobile shelving and modular storage, companies can optimize storage space dynamically, reducing wastage and increasing storage density. This flexibility minimizes the need for large-scale infrastructure investments while maximizing the utility of existing warehouse layouts.

3. Improving Inventory Management and Order Fulfillment

Adaptive warehousing solutions help businesses mitigate the risks of stockouts and overstocking, ensuring real-time inventory optimization. This results in faster order processing and improved customer satisfaction, making supply chains more resilient and responsive.

4. Cost Efficiency and Operational Resilience

The implementation of flexible storage models reduces operational costs by minimizing downtime and improving resource utilization. Companies can dynamically adjust storage configurations without major structural changes, making their supply chain more resilient to market uncertainties.

5. Technology Integration for Future Growth

The future of adaptive warehousing will be driven by cutting-edge technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and robotics. AI will enable predictive demand planning and intelligent inventory placement, while IoT will provide real-time monitoring, ensuring smarter decision-making and warehouse automation.

6. Sustainability and Eco-Friendly Innovations

As supply chain operations shift toward sustainability, adaptive warehousing will integrate eco-friendly materials, energy-efficient storage solutions, and smart logistics systems. This will align with global sustainability goals, reducing environmental impact while maintaining operational excellence.

7. Competitive Advantage in a Dynamic Market

Companies that adopt adaptive warehousing models will maintain a competitive edge by responding proactively to evolving customer demands. These solutions ensure supply chain agility, reduce lead times, and improve overall supply chain performance in dynamic market conditions.

8. Evolving Towards Fully Automated Warehousing

The future trajectory of adaptive warehousing points toward full automation, where AI-driven robotics will autonomously manage warehouse layouts. This evolution will further

enhance operational efficiency, reduce labor dependency, and ensure real-time adaptability to shifting supply chain demands.

9. Broader Implications for Industry and Research

This study lays the foundation for future research on integrating adaptive warehousing with advanced supply chain technologies. Further exploration into AI, blockchain, and real-time analytics will help refine these models, ensuring they evolve to meet the complexities of global supply chains.

10. Conclusion and Call for Future Research

The continuous development of adaptive warehousing models will shape the future of supply chain agility. Researchers and industry practitioners should focus on refining technological integrations, exploring cost-benefit analyses, and investigating the long-term impacts of adaptive storage solutions on global supply chain ecosystems.

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