SIMULATION-BASED ANALYSIS OF LEARNING AND REACTION DELAYS'S IMPACT ON THE PERFORMANCE OF MULTI-ECHELON SUPPLY CHAINS

by
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B.S., Chemical Engineering, Boğaziçi University, 2020

Submitted to the Institute for Graduate Studies in
Science and Engineering in partial fulfillment of
the requirements for the degree of
Master of Science

Graduate Program in Industrial Engineering
Boğaziçi University
2024

ACKNOWLEDGMENTS

First and foremost, I would like to express my deepest gratitude to my thesis supervisor, Assoc. Prof. Gönenç Yücel, for his invaluable and continued guidance throughout this study. His endless patience and support have been a source of great comfort and encouragement, making this journey both rewarding and inspiring.

I also want to thank Assoc. Prof. Aybek Korugan and Assist. Prof. Özge Karanfil for their participation on my thesis committee. Their invaluable feedback, and expert guidance have significantly enhanced the quality of my work. I am also grateful to the members of the Department of Industrial Engineering. Their insights and expertise have greatly contributed to my learning experience and growth throughout my entire education.

I would like to extend my heartfelt gratitude to my family for their unwavering support and encouragement throughout this journey. To my parents, your constant motivation and belief in me have been my rock during challenging times. Thank you for always being there. Your love and support have been invaluable to me. This achievement would not have been possible without you. I am incredibly grateful for everything you've done for me in my entire life. I would not be standing where I am today, nor be the person I am, without your guidance and constant faith in me.

Last but not least, I want to express my deepest gratitude to my two best friends, Merve and Utku. Your constant support and understanding have been a source of great strength throughout this journey. Thank you for being a shoulder to cry on when needed and for uplifting me with your encouragement. Your belief in me and your presence have made this challenging process much more manageable. I am truly thankful for having you both by my side.

ABSTRACT

SIMULATION-BASED ANALYSIS OF LEARNING AND REACTION DELAYS'S IMPACT ON THE PERFORMANCE OF MULTI-ECHELON SUPPLY CHAINS

Supply chains are networks of actors that facilitate the flow of goods from producers to consumers. Effectively managing the supply chain enhances overall performance and leads to improved customer satisfaction, greater inventory stability, and cost efficiency. This research employs system dynamics modeling to explore the internal dynamics of a two-echelon supply chain system and extends it to include a third echelon—a distributor—to investigate the effects of inventory management parameters on supply chain performance. The simulation-based approach of system dynamics is well-suited for analyzing the dynamic nature of supply chain problems over time. It enables a comprehensive study of how supply chain performance evolves and adapts to diverse changes, offering insights into long-term dynamics and behaviors. It explores how the behavior of supply chain actors in response to a sudden increase in customer demand impacts overall supply chain performance. It focuses on three key inventory management parameters that shape the internal dynamics of the supply chain: learning delay, inventory adjustment times, and shipment delay. A series of experiments is conducted systematically by changing the duration of these parameters to gain insights into the best configuration for different actors. By examining different combinations of these parameters, the research aims to understand how various actor behaviors impact overall supply chain performance, particularly in terms of responsiveness, the ability to fulfill orders on time, and the fluctuations in inventory levels. The study highlights that the behavior of supply chain actors does not only affect their own performance but also significantly impacts other actors in the chain. The study also explores the trade-off between stability and responsiveness in supply chain management by examining different configurations of inventory management behaviors among supply chain actors.

ÖZET

ÖĞRENME VE TEPKİ GECİKMELELERİNİN ÇOK KADEMELİ TEDARİK ZİNCİRİNİN PERFORMANSI ÜZERİNDE ETKİSİNİN SİMÜLASYON TABANLI ANALİZİ

Tedarik zincirleri, üreticilerden tüketicilere mal akışını yöneten organizasyon ağlarıdır. Tedarik zincirinin etkin bir şekilde yönetilmesi genel performansı artırır, müşteri memnuniyetini, envanter stabilitesini ve maliyet verimliliğini iyileştirir. Bu araştırma, sistem dinamikleri modellemesini kullanarak iki seviyeli tedarik zinciri sisteminin iç dinamiklerini keşfetmekte ve bunu üçüncü bir seviye olan bir distribütörü de dahil ederek envanter yönetimi parametrelerinin tedarik zinciri performansı üzerindeki etkilerini araştırmaktadır. Sistem dinamiklerine dayalı simülasyon yaklaşımı, zaman içinde tedarik zinciri problemlerinin dinamik doğasını analiz etmek için uygun bir yöntemdir. Bu yaklaşım, tedarik zincirinin performansının nasıl evrildiğini ve çeşitli değişikliklere nasıl adapte olduğunu kapsamlı bir şekilde incelemeyi sağlar, uzun vadeli dinamikler ve davranışlar hakkında içgörüler sunar. Araştırma, müşteri talebinde ani bir artışa yanıt olarak tedarik zinciri aktörlerinin davranışlarının genel tedarik zinciri performansı üzerindeki etkilerini araştırmaktadır. Tedarik zincirinin iç dinamiklerini şekillendiren üç temel envanter yönetimi parametresine odaklanmaktadır: öğrenme gecikmesi, envanter ayarlama süreleri ve sevkiyat gecikmesi. Bu parametrelerin süresini değiştirerek yapılan bir dizi deney, farklı aktörler için en iyi yapılandırmanın anlaşılmasına yönelik içgörüler sağlamaktadır. Bu parametrelerin farklı kombinasyonlarını inceleyerek, araştırma çeşitli aktör davranışlarının genel tedarik zinciri performansı üzerindeki etkilerini, özellikle yanıt verme yeteneği, zamanında siparişleri yerine getirme yeteneği ve envanter seviyelerindeki dalgalanmalar açısından anlamayı amaçlamaktadır. Çalışma, tedarik zinciri aktörlerinin davranışlarının sadece kendi performanslarını değil, zincirdeki diğer aktörleri de önemli ölçüde etkilediğini vurgulamaktadır. Ayrıca, tedarik zinciri yönetiminde stabilite ile yanıt verme arasındaki dengeyi araştırarak, tedarik zinciri aktörleri arasındaki farklı envanter yönetimi davranışlarının farklı yapılandırmalarını incelemektedir.

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LIST OF ACRONYMS/ABBREVIATIONS

CLD	Causal Loop Diagram
DI	Distributor Inventory
DIAT	Distributor Inventory Adjustment Time
RI	Retailer Inventory
RIAT	Retailer Inventory Adjustment Time
SD	System Dynamics
SDAT	Distributor Supply Line Adjustment Time
SI	Serviceable Inventory
SIAT	Serviceable Inventory Adjustment Time
SRAT	Retailer Supply Line Adjustment Time

1. INTRODUCTION

A supply chain can be defined as an integrated system in which several business establishments including suppliers, manufacturers, distributors, and retailers work together toward the goal of converting raw materials to specified end-products and delivering these to customers (Beamon, 1998). Supply chains aim to meet customer demand while using resources efficiently, optimizing costs, reducing lead times, and enhancing service levels. Supply chain operations are crucial for the functioning of many businesses and industries. Effectively managing the intricacies of the supply chain enhances overall performance and leads to improved customer satisfaction, and competitive advantage (Bozarth et al., 1998). According to Naylor et al. (1999), a supply chain can only be considered efficient if the main purpose is reducing cost and resources are allocated effectively, with no waste on activities that do not contribute value. According to Flint (2004), the main purpose of an efficient supply chain is to deliver the product to the customer in good condition, on time, and at a low cost.

Supply chains may seem straightforward at first glance but they are complex and not easy to manage due to their interconnected and dynamic nature. Firstly, supply chains consist of many players such as suppliers, manufacturers, wholesalers, distributors, retailers, and customers, and each one of them has its own goals, behaviors, and constraints. Synchronizing all their actions and managing the supply chain efficiently while meeting customer demand can be challenging (Mentzer et al., 2001). Another point is that there is no single entity centrally managing the entire supply chain; the overall outcome is a result of the interactions and behaviors of all the individual players (Vorst et al., 2000). Secondly, supply chains face numerous uncertainties and variations such as fluctuations in demand, disruption in production or transportation, changing market conditions, and variability in lead times. These variations may cause bullwhip effects, imbalance in inventories, and operational inefficiencies (Lee et al., 1997). Changes in customer preferences, globalization, and intense competition between businesses are making supply chains even more complex (Sarimveis et al., 2008).

Supply chains are intricate dynamic systems and customer demand is a primary driver of their internal dynamics. The effectiveness of supply chains heavily relies on how managerial decisions are made according to the changes in demand. The fact that every actor in the supply chain has its own way of making decisions adds another layer of complexity to supply chain management. Different decision-making styles and priorities may lead to conflicts, inefficiencies, and suboptimal results within the supply chain.

A supply chain consists of a forward flow of materials and a backward flow of information as illustrated in Figure 1.1.

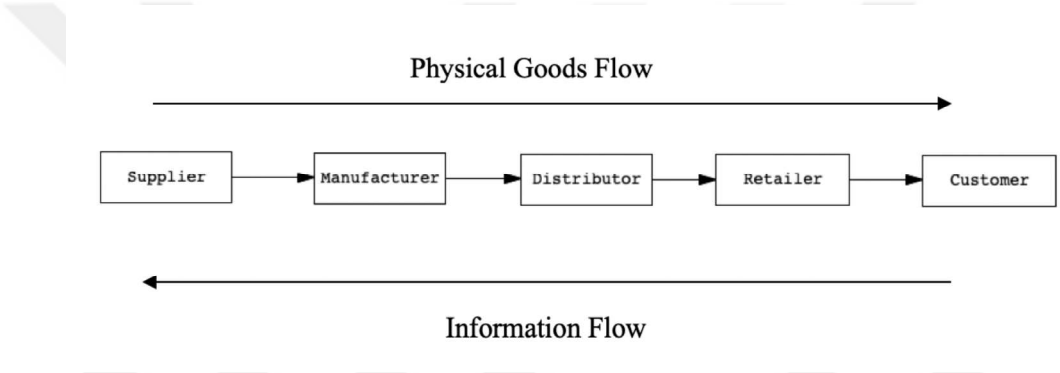

Figure 1.1. Supply chain forward and backward flows.

Forward flow refers to the physical movement of products from suppliers to manufacturers, then to distributors, retailers, and finally to customers. On the other hand, backward flow refers to the transmission of information about orders, sales, and inventory levels from downstream actors such as retailers to upstream actors like suppliers. This information transfer allows upstream actors to make informed decisions and adjust their plans or strategies according to downstream organizations. In numerous instances, inadequate information sharing has led to poor performance within the supply chain (Kaipia, 2009). Additionally, most actors prefer locally optimized quick solutions over long-term strategic decisions which result in suboptimal outcomes in terms of overall supply chain performance. A supply chain should be considered as a whole system rather than several different actors or a sum of them. Suppliers, distributors, and retailers make their decisions individually but also, they all interact with each other via physical and information flow and produce an overall supply chain behavior. If a system is taken apart and the interactions between actors are severed, the entire supply chain loses its inherent characteristics, and the

individual actors also lose their unique attributes (Maani et al., 2007, Li et al., 2011, Ackoff, 1993). When downstream actors place orders without considering other actors, high order variability and inventory fluctuations may occur due to inadequate information sharing. Some studies indicate that information sharing may reduce the bullwhip effect leading to a reduction in order variability and fluctuations (Yanfeng, 2007, Chen et al., 2000).

Supply chains are dynamic systems that consist of several players and often exhibit instabilities. Changes in one part of the system may affect the entire supply chain. When customer demand changes, the players in the supply chain adjust their new orders accordingly. The behavior of a supply chain cannot be entirely comprehended by analyzing its parts in isolation since the behavior emerges from the interactions of these parts. Due to non-linear relationships such as lead times, capacity constraints, replenishment decisions, and interactions within the supply chain, small changes may give rise to unanticipated outcomes which some people consider as side effects of players' actions. According to Sterman (2000), there are no side effects in real life. The effects that people cannot think of in advance are claimed to be side effects due to the limited and imperfect comprehension of the system. Another reason is that cause and effect are not always closely linked in time and space. Therefore, it is crucial to enhance our comprehension of these dynamically intricate supply chain systems.

In summary, key objectives in a supply chain can be summarized as customer satisfaction, inventory management, cost optimization, and lead time reduction. Meeting customer expectations in terms of quality and delivering products on time while maintaining sufficient inventory is a challenging task for businesses. It requires careful planning and coordination across the supply chain to ensure that the right products are available when and where they are needed. Demand fluctuations can cause stockouts during high-demand periods which leads to a decrease in customer satisfaction or excess inventory during low-demand periods which increases holding costs. Increasing the level of inventories would provide greater flexibility in responding to fluctuations in customer demand while enhancing responsiveness. However, there is a trade-off between high inventory levels and the efficiency of the supply chain. Increasing inventory levels cause high costs in terms of storage and capital. Safety stocks act as a buffer to enable responses to fluctuations in demand variability. As Hopp et al. (2004) state high inventory levels often indicate

inefficiencies in the supply chain and reducing variability might be a better solution strategy than increasing inventory. It is also important to reduce expenses and lead times while increasing profitability.

Overall, the complexity of supply chains stems from the dynamic interactions among different actors and inherent uncertainties associated with demand and supply. Managing supply chains involves coordinating various activities across different stages such as production, inventory management, and distribution, navigating dynamic interactions among multiple actors and uncertainties in demand and supply within an inherently complex system. Factors such as lead times, order quantities, and demand forecasting further contribute to the complexity. Investigating a supply chain in detail provides valuable insights for actors while enabling them to optimize their behaviors and enhance overall supply chain performance. Consequently, the intricate nature of supply chains presents an intriguing and multifaceted subject for research, since understanding the internal dynamics and the resulting effects of demand changes can be hard to comprehend.

2. PROBLEM DESCRIPTION

Supply chains are intricate networks of interconnected actors working together closely, forged through strategic partnerships and collaboration (Chen et al., 2004). Recognizing supply chains as complex systems, Maani et al. (2007) define systems as collections of interacting parts functioning as a whole, emphasizing that disassembling a system compromises its essential properties.

Internal dynamics in a supply chain, characterized by feedback loops, lead times, and nonlinear relationships, influence the behavior and performance of the system as a whole. Feedback loops create interconnected relationships between different stages of the supply chain, where changes in one part of the system can affect other parts (Sterman, 1989). Lead times represent the time it takes for orders to be processed, produced, and delivered, influencing inventory levels and responsiveness (Disney and Towill (2003). Nonlinear relationships introduce complexities, as small changes in input variables can lead to disproportionate effects on output variables (Forrester, 1961).

The behavior of supply chain actors, such as manufacturers, distributors, and retailers, has a substantial influence on the variability of inventory levels and the overall performance of the supply chain (Lee et al., 1997; Chen et al., 1998; Sterman, 2000). Decision-making processes related to ordering, production, and inventory management play a crucial role in shaping inventory dynamics (Chopra & Meindl, 2007). The timing and magnitude of orders placed by each actor can amplify inventory fluctuations (Lee et al., 1997).

Retailers, distributors, and manufacturers significantly impact supply chain dynamics through their ordering behavior and inventory adjustments. The decisions made by one actor within the supply chain can influence the actions of others. Retailers typically base their orders on factors like current inventory levels, customer demand forecasts, and lead times. Distributors aggregate these orders and place orders with manufacturers, considering factors such as production capacity and lead times. Manufacturers, in turn, adjust their production schedules based on incoming orders and inventory levels. However, variations in ordering patterns and inventory adjustments among these actors can lead to inventory fluctuations.

Therefore, inventory adjustments across all supply chain stages is essential for reducing inefficiencies and improving overall performance (Lee et al., 1997; Chen et al., 1998; Disney and Towill, 2003).

Responsiveness refers to the ability to react swiftly to customer demand or market changes to maintain a competitive edge (Holweg, 2005), while efficiency focuses on cost reduction and eliminating non-value-added activities (Naylor et al., 1999). While increasing inventory levels to meet the changing customer demand may enhance responsiveness, it compromises supply chain efficiency due to storage and capital costs. Thus, striking a balance between responsiveness and efficiency involves trade-off decisions by management. Achieving the right balance between responsiveness and efficiency remains a challenging goal for supply chain management, as it entails trade-offs between increased responsiveness and reduced efficiency, and vice versa.

Supply chain inventories often experience fluctuations and instabilities, commonly referred to as the bullwhip effect. This concept was initially described by Forrester in 1958 as "demand amplification" (Forrester, 1958). Subsequently, the term "bullwhip effect" was coined by Lee et al. (1997) to describe the phenomenon. Lee et al. (1997) describe the bullwhip effect as the phenomenon where minor fluctuations in customer demand result in significant variations in upstream actors' orders. As one moves upstream from the retailer to the manufacturer, these fluctuations amplify. This phenomenon leads to inefficiencies, excess inventory, stockouts, and increased costs throughout the supply chain (Towill et al., 1992).

The bullwhip effect has been extensively studied in the field of supply chain management due to its complexity and significant impact on supply chain performance. According to Holweg and Disney (2005), the demand amplification problem still persists after years of study in multi-echelon supply chains. It is driven by both operational factors such as order batching, price fluctuations, lead times, and demand forecasting inaccuracies and behavioral factors including rational decision-making, overreaction to backlogs, miscommunication, and risk aversion. Hussain and Drake (2011) found that order batching in multi-echelon supply chains significantly amplifies demand variability, exacerbating the bullwhip effect, and suggested that more frequent, smaller order batches can mitigate this

issue. Blinder (1982) demonstrated that price fluctuations and promotions cause customers to purchase in larger quantities than needed, leading to irregular demand patterns and contributing to inventory instability. Chen et al. (2000) quantified the bullwhip effect in supply chains and found that longer lead times and inaccurate demand forecasting significantly increase demand variability, thereby intensifying the bullwhip effect. Supply chain actors make decisions based on their own perspectives and objectives, often without full visibility of the entire chain. Sterman (1989) showed that managerial misperceptions of feedback and suboptimal decision-making in dynamic environments lead to significant inefficiencies and contribute to the amplification of demand variability in supply chains. Lee et al. (1997) highlight that overreaction to backlogs, miscommunication, and risk aversion lead to exaggerated order fluctuations, inefficiencies, and increased costs, emphasizing the need for better communication and risk management strategies to stabilize supply chain operations.

Wikner et al. (1991) explore various strategies to improve supply chain performance using the Forrester production-distribution model, focusing on methods such as fine-tuning decision rules, reducing system delays, removing the distribution echelon, changing individual echelon decision rules, and enhancing information flow to reduce demand amplification. The study finds that integrating accurate and timely information flow throughout the supply chain significantly mitigates the bullwhip effect and improves overall supply chain stability.

The Beer Distribution Game is a multi-player simulation game developed by MIT in the 1960s, which holds significant importance in the field of system dynamics and supply chain literature. It serves as a powerful tool for illustrating the complexities and challenges inherent in supply chain management while allowing participants to experience firsthand the dynamics of inventory management, and order fulfillment. The Beer Distribution Game emphasizes how human behavior, such as overlooking time delays and supply lines, leads to oscillations in inventory levels and how the supply chain responds to external shocks in demand as a whole (Sterman, 2000).

Building on the insights from studies such as Wikner et al. (1991) and the experiential learning facilitated by the Beer Distribution Game (Sterman, 2000), it becomes evident that

demand amplification is a recurring challenge in supply chain management. Lee et al. (1997) identified various factors contributing to the bullwhip effect, including demand forecast updating, order batching policies, lead time variability, price fluctuations, information delays, rationing and shortage gaming, and behavioral factors. According to Houlihan (1987), strategic gaming in the supply chain may lead to several negative consequences, including inflated orders, distorted demand signals, and increased variability in demand. These behaviors may result in excess inventory, inefficient allocation of resources, and ultimately, reduced supply chain performance and profitability. Chen et al. (1998) attribute the bullwhip effect partly to the necessity of forecasting demand. Building on this, Wu et al. (2006) suggested that insufficient coordination between supply chain partners can exacerbate the bullwhip effect, emphasizing the importance of collaborative decision-making and information sharing to align forecasts and prevent order amplifications. This interconnected perspective underscores the need for coordinated efforts among supply chain actors to mitigate the bullwhip effect and improve overall supply chain performance. Barlas and Gunduz (2011), and Jaksic and Rusjan (2007) both highlight the role of demand variability and the lack of communication in amplifying the bullwhip effect. Barlas and Gunduz (2011) specifically identify isolated demand forecasting as a major structural cause. They emphasize the importance of accurate demand forecasting and collaborative information sharing among supply chain actors to minimize inventory variability and improve overall supply chain performance.

Numerous studies have investigated the impact of information sharing which underscores its importance in mitigating the bullwhip effect and improving overall supply chain performance. According to Xu et al. (2001), sharing demand and forecast information proves effective in decreasing order fluctuations and minimizing safety stock levels. Gavirneni et al (1999) compare the outcomes of scenarios with no information sharing against those with information-sharing strategies employed by the retailer. Their findings highlight the significant value of information in mitigating supply chain disruptions and contributing to overall supply chain effectiveness in a basic one-retailer-one-supplier supply chain setting. Cheng and Wu (2005) investigate the effects of information sharing in a two-level supply chain with multiple retailers. By analyzing different scenarios and information-sharing strategies, the study provides insights into the potential benefits of information-sharing in reducing inventory costs, improving coordination between supply chain actors,

and enhancing overall efficiency. Dejonckheere et al. (2004) highlighted that although information sharing can significantly mitigate the bullwhip effect, it cannot eliminate it entirely.

Disney and Towill (2003) primarily focus on the performance of different ordering policies in terms of their impact on the bullwhip effect and inventory variance. The best policy in terms of minimizing the bullwhip effect depends on various factors such as demand variability, production lead times, and cost considerations. Gino et al. (2007) highlight the role of inventory durability, transit lags, and individual decision biases in creating the bullwhip effect in a single-echelon supply chain. The results suggest that decision makers' inventory ordering decisions deviate from optimality, leading to overordering when inventory levels are already high and underordering when levels are low, with transit lags exacerbating these tendencies.

In dynamic systems, decision-makers often underestimate the time it takes for actions to produce outcomes due to inherent delays in feedback loops, leading to a misunderstanding of system behavior. Additionally, decision-makers sometimes fail to notice or respond promptly to the slow buildup of inventory or delays that occur over time. This oversight leads to inertia, where they hesitate or delay in adapting to changes in the environment (Sterman, 1989). Reducing the bullwhip effect in supply chains can be achieved through strategies such as minimizing production lead times, optimizing order quantities, improving forecasting accuracy, and enhancing information sharing and coordination among supply chain partners (Disney and Towill, 2003). Xun (2012) stated that longer inventory adjustment times can increase oscillations and system instability, highlighting the importance of timely inventory adjustments to mitigate disruptions.

Demand amplification arises from internal factors or events within the system rather than external influences. While customer demand may exhibit high volatility, the exacerbation of the situation is primarily self-induced, stemming from mechanisms or events within the system itself. This internal volatility often leads to distorted signals throughout the supply chain, causing inefficiencies in inventory management, production planning, and distribution. Consequently, addressing demand amplification necessitates a comprehensive understanding of these internal mechanisms. In this research, a model will be constructed

and simulated to explore the dynamics of a supply chain. By simulating various scenarios and exploring parameters such as inventory adjustment times, shipment delays, and learning delays, insights into the complexities of supply chain dynamics will be investigated. The emphasis lies in understanding the internal dynamics of the supply chain, including the interactions between actors and their inventory management styles. This research will contribute to understanding how specific operational parameters affect supply chain performance and differ from the existing literature in several key aspects. Firstly, while previous studies have primarily focused on investigating the bullwhip effect and its drivers in supply chains, this research extends this by specifically examining the impact of inventory adjustment times, lead times, and shipment delays on supply chain performance and responsiveness. By systematically varying these parameters in a simulation model, a comprehensive understanding of how different inventory management practices influence system behavior and performance will be provided. The effects will also be analyzed in an echelon-specific manner, considering different actor behaviors. The research will identify scenarios where the retailer benefits most or the manufacturer experiences the worst outcomes. By examining these nuances, the study aims to provide a detailed understanding of how specific dynamics impact each echelon's performance within the supply chain. Additionally, learning delays and sudden changes in customer demand, which may significantly affect supply chain dynamics, but have received limited attention in previous studies, are emphasized.

3. RESEARCH OBJECTIVES AND METHODOLOGY

In the preceding section, the problem is defined, highlighting the complexity of supply chains as intricate systems with internal dynamics that are hard to comprehend. This section will further elaborate on the specific objectives of this study and the methodology employed, aiming to shed light on how different inventory management styles influence these complex supply chain dynamics.

3.1. Research Objectives

Several important factors in a supply chain affect its internal dynamics, including inventory management practices, communication, lead times, and coordination among supply chain actors (Chopra and Meindl, 2016). This study aims to examine how the behaviors of supply chain actors affect overall supply chain performance under various conditions. This research will closely examine the internal dynamics of the supply chain, the interactions between actors, how their inventory management styles influence responses to sudden changes in customer demand, and how these responses affect overall supply chain performance. By focusing on the interactions between retailers, manufacturers, and potentially distributors, the research will explore how their decisions regarding inventory management influence the stability and responsiveness of the supply chain.

In this study, the focus will be on examining how the behavior of supply chain actors in response to a sudden increase in customer demand impacts overall supply chain performance. The behavior of supply chain actors is characterized by three key factors. First, the time it takes for actors to recognize new information and update their expectations is referred to as learning delay. This highlights the importance of how quickly and accurately information is updated. Second, how fast or impulsive an actor is in responding to changes in perceived demand, known as inventory adjustment times. Third, the time lag between when an actor places an order and when the order is received is referred to as shipment delay. These three inventory management parameters shape the internal dynamics and performance of the supply chain, and they can differ for each actor. By examining different combinations

of these parameters, the research aims to understand how various actor behaviors impact overall supply chain performance, particularly in terms of responsiveness, the ability to fulfill orders in a timely manner, and the fluctuations in inventory levels. The study will analyze different configurations of inventory management parameters for each actor within the supply chain to determine which behaviors enhance or hinder supply chain efficiency and stability.

The investigation will involve simulating scenarios where the behavior and performance of supply chain actors will be observed by varying inventory management parameters mentioned above i.e. inventory adjustment times, shipment delays, and learning delays. The impact of these parameters on supply chain performance will be closely examined, with a particular emphasis on inventory levels and backlogs. This will involve investigating the average demand backlog over time and determining the depletion time of backlogs. These metrics will provide insights into how effectively the supply chain responds to changes in customer demand and manages inventory levels to meet demand fluctuations. Furthermore, the study will assess inventory variations for each actor by analyzing their deviation from target levels. This analysis is crucial as it allows for the examination of how closely actors maintain their inventory levels to the desired state. By observing deviations from target behavior, particularly when inventories do not stabilize immediately and instead show fluctuations, the study can better understand the dynamics of inventory management within the supply chain. Through this analysis, the study aims to provide insights into the dynamics of supply chain inventory management and its impact on overall system performance.

3.2. Methodology

In this study, the System Dynamics (SD) approach will be used to investigate the complex long-term dynamics of a supply chain. System Dynamics is a simulation-based approach that enables researchers to observe the dynamics over time and understand unexpected behaviors of the system. Supply chains are complex systems comprising multiple actors interacting with each other. These actors may include manufacturers, suppliers, distributors, retailers, and customers, each operating individually, adjusting their inventories based on their own goals and constraints. The interactions between actors and

the decentralized nature of the supply chain lead to behaviors that are hard to comprehend and predict. Retailers place orders to downstream actors based on their inventory needs and demand forecasts, with each actor adjusting their orders and production accordingly. This upstream flow of orders initiates a chain reaction, where distributors and manufacturers adjust their production schedules and inventory levels based on the incoming orders. These interactions highlight the interconnected nature of the supply chain, where the actions of one actor can significantly impact the operations of others.

System Dynamics approach provides a valuable framework for understanding these dynamics and enables researchers to gain insights into underlying mechanisms driving the supply chain. SD methodology provides a structured approach to analyze how changes in one part of the system affect the overall behavior of the supply chain over time. The main reason the system dynamics approach is suitable for this research is its ability to effectively capture and analyze the internal feedback loops and delays inherent in supply chains. Supply chains involve complex interactions among multiple actors, each influencing the other and reacting to changes in inventory levels, orders, and production schedules in their own way. These interactions often result in non-linear behaviors and time delays, which can significantly impact overall supply chain performance. System dynamics allows for the modeling of these dynamic relationships, providing a comprehensive understanding of how small changes can propagate through the system. This makes it an ideal methodology for studying the performance of supply chains. While the dynamic nature of the problem makes it suitable for system dynamics, more importantly, this approach allows for the analysis of behavior over time, providing a deeper understanding of how supply chain performance evolves and responds to various changes in the long run.

Causal Loop Diagrams (CLDs) are widely used in system dynamics modeling to illustrate the causal relationships between variables. CLDs provide a clear visual representation of the feedback structure of a system. Variables are connected by causal links and assigned a polarity. Positive arrows indicate an increase in the cause leads to an increase in the effect, while negative arrows signify that an increase in the independent variable results in a decrease in the dependent variable. A simplified Casual Loop Diagram is presented in Figure 3.2 to illustrate the causal relationships within the Retailer's dynamics, providing insights into how adjustments in the Retailer Inventory are made and how various

factors influence one another. It summarizes the decision rule used by the Retailer to control the acquisition of new products.

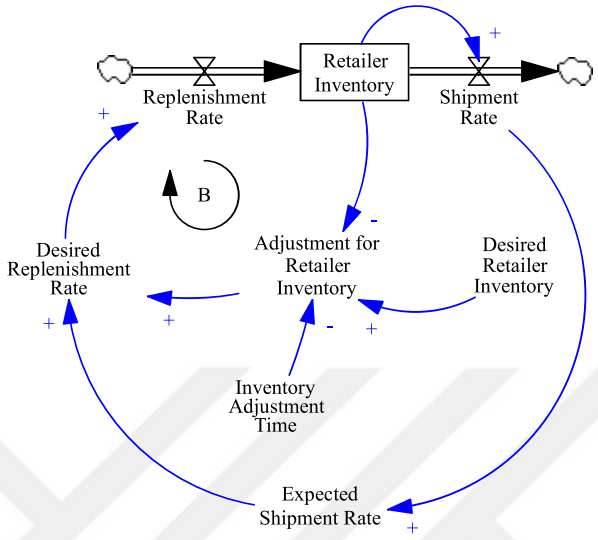

Figure 3.2. Simplified causal loop diagram.

There is a balancing loop in Figure 3.2 representing the feedback mechanism responsible for stabilizing inventory levels over time. In response to the increases or decreases in inventory level, the balancing loop kicks in to bring it back to the desired level. The *Desired Retailer Inventory* represents the target level that the retailer aims to maintain in stock at all times. When the *Retailer Inventory* level falls below this desired level, it triggers an adjustment mechanism within the balancing loop. This adjustment mechanism accelerates the replenishment rate of inventory, meaning it speeds up the flow of goods into the retailer's inventory. By doing so, it aims to prevent potential stockouts and ensure that the retailer maintains adequate levels of inventory to meet customer demand. The feedback loop operates dynamically, continuously monitoring inventory levels and making real-time decisions to align supply with demand. This reduces variability and improves overall supply chain performance.

A system dynamics model consists of three main components: stocks, flows, and converters. Stocks represent accumulations in the system, define the system's state, and play a vital role in shaping the internal dynamics. They can only change over time by their inflows and outflows. Flows represent the rate at which stocks are accumulated or depleted. Inflows

increase the stock level while outflows decrease it. For instance, a manufacturing firm's inventory is a stock accumulating with production inflow and depleting with shipment outflow. The net flow into a stock represents the rate of change of that stock (Sterman, 2000). The rate of change of a stock over time is expressed as

$$\frac{d(Stock)}{dt} = Inflow(t) - Outflow(t). \tag{3.1}$$

Converters, also known as auxiliary variables, are intermediate variables used for defining the relationships between stocks and flows. They can be constants or dynamic variables defined by an equation or a graph. Stocks are represented by rectangles while flows are depicted with arrows and converters are represented with only their names. A simplified version of a supply chain model is presented in Figure 3.1 as a Stock-Flow Diagram. The figure illustrates the fundamental components of a model. Inventories representing the stock of products at various stages of the supply chain are depicted in rectangular shapes. The flows encompass manufacturing rate, replenishment rate, and sales whereas delay times are represented as auxiliary variables. Together, these elements form the basis of the system dynamics model, allowing for the examination of different scenarios with simulation.

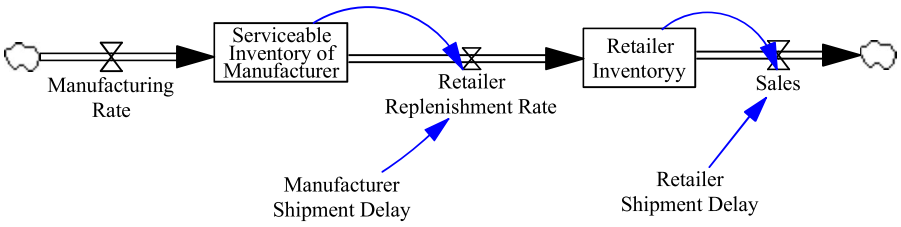

Figure 3.1. Simplified 2-echelon stock-flow diagram.

The structure of an SD model consists of a set of relations between model variables. The relations are represented as differential equations for continuous systems and difference equations for discrete models. Differential equations capture the relationships between different variables and their rates of change. For example, the change in the *Serviceable Inventory* of a manufacturer over time can be described by

$$\frac{d(Serviceable\ Inventory)}{dt} = Manufacturing\ Rate(t) - Retailer\ Replenishment\ Rate(t). \quad (3.2)$$

The *Serviceable Inventory* increases when new items are manufactured and decreases when the products are shipped to the Retailer. The rate at which the *Retailer Inventory* is replenished depends on the amount of *Serviceable Inventory* available at the manufacturer and the time delay associated with shipping these items. *Retailer Replenishment Rate* is expressed as

$$Retailer\ Replenishment\ Rate = \frac{Serviceable\ Inventory\ of\ Manufacturer}{Manufacturer\ Shipment\ Delay}. \quad (3.3)$$

Similar to Eq. 3.2, the *Retailer Inventory* increases as it receives new products from the manufacturer and decreases as products are sold to customers. The change in the *Retailer Inventory* over time is described by

$$\frac{d(Retailer\ Inventory)}{dt} = Retailer\ Replenishment\ Rate(t) - Shipments\ to\ Customers(t). \quad (3.4)$$

Vensim will be used for this analysis as a system dynamics modeling software. The model will be simulated under different scenarios and the influence of the system's internal structure will be observed rather than exogenous factors.

SD approach is particularly well-suited for investigating complex systems characterized by nonlinear relationships, time delays, and feedback loops. The problem addressed in this study is dynamic in nature featuring feedback loops and nonlinear relationships. Therefore, SD methodology will be employed in this research to analyze supply chain dynamics. Initially, the study will focus on a 2-echelon supply chain, consisting of a retailer and a manufacturer, to understand the internal dynamics of the supply chain, the interactions between actors, and how their inventory management styles influence the overall system. Additionally, this analysis will provide insights into how inventory levels, order rates, and production schedules are influenced by dynamic feedback loops. Subsequently, the research will expand to investigate a 3-echelon supply chain by incorporating a distributor into the model. The research will begin by establishing the system at equilibrium, where every stock has its equilibrium value, and inflows and outflows are

balanced representing a stable phase in the supply chain. Subsequently, a sudden step increase in customer demand will be introduced to disrupt the equilibrium state, triggering dynamic responses from the actors within the supply chain. This new demand level requires new inventory levels and adjustments in ordering and production rates. The focus will be on understanding how each stock and flow responds to the change and the time it takes for the system to adjust to its new equilibrium.

4. MODEL DESCRIPTION

The base model in this research consists of two primary echelons: a manufacturer and a retailer, both interacting to manage the supply chain for a single product under constant daily demand. The model is designed with a single player at each stage of the supply chain. The retailer is responsible for fulfilling customer orders. It processes orders based on perceived demand and places subsequent orders to the upstream echelon. The retailer should also consider the supply line while ordering to ensure accurate inventory management and prevent disruptions in supply chain operations. The supply line refers to the goods that have been ordered by the retailer but have not yet been received. When an agent does not consider the supply line while ordering, it can lead to overordering or stockouts due to a lack of accurate inventory information (Sterman, 2000). This neglect results in inefficiencies, such as increased backlogs and amplified supply chain variability, ultimately disrupting the balance of supply and demand. The manufacturer produces goods according to received orders, considering production lead times and inventory levels. The manufacturer processes the orders received from the retailer, converting raw materials into finished goods. During this production period, the goods are in a work-in-progress (WIP) state, meaning they are not yet completed and ready for shipment but are actively being manufactured. There is a manufacturing delay during the transition of goods from the WIP state to becoming part of the manufacturer's available inventory. Subsequently, there is a shipment delay, which accounts for the time it takes for the finished goods to be transported from the manufacturer to the retailer.

Each stage in the supply chain is represented by similar agents, where each agent places orders only with its upstream counterpart and ships goods immediately if sufficient inventory is available. Shipped goods arrive after a constant transit lead time, and order cancellations are not considered. If an agent cannot fully meet an order due to insufficient inventory, the unfulfilled portion is backlogged, ensuring that the order is not lost. Overall, the model captures the essential dynamics of a simple supply chain system, including customer demand, order fulfillment, inventory management, and production processes.

In the extended model, a third echelon, the distributor, will be introduced to the existing framework. The distributor will act as an intermediary between the manufacturer and the retailer, receiving orders from the retailer, processing them and subsequently placing orders with the upstream echelon based on perceived demand, which, in this case, is the manufacturer. Additionally, like the retailer, the distributor will need to consider the supply line when placing orders to maintain accurate inventory levels and prevent disruptions in the supply chain. The addition of the distributor introduces another layer of complexity to the model, requiring careful consideration of the interactions between all three echelons. However, the fundamental principles of order processing and inventory management will remain consistent across all stages.

The model is constructed using system dynamics principles, incorporating stocks, flows, and internal feedback loops to capture the complex interactions within the supply chain. The internal dynamics, the behavior of actors, how each stock and flow responds to the change, and the time it takes to adjust will be closely investigated by using the SD approach. Systematic experiments will manipulate shipment delays, inventory adjustment times, and learning delays to evaluate their impact on supply chain performance and responsiveness. SD methodology will be utilized to investigate the underlying causes of oscillations and amplifications within the system.

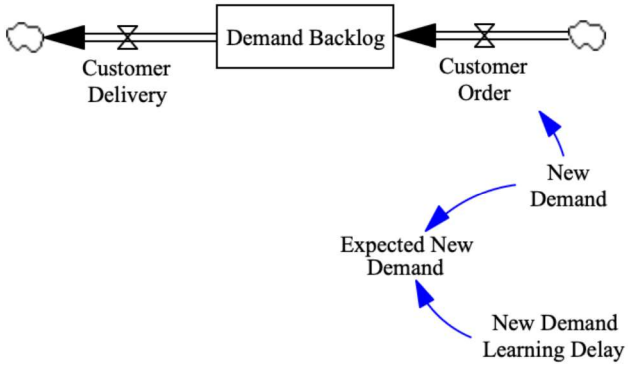

Figure 4.1. Demand backlog stock-flow diagram.

The constructed model will now be explained, with detailed explanations provided for all model variables, stock flows, and parameters. *New Demand* in Figure 4.1. is defined as the daily end-user demand for the product being studied. Specifically, it represents the quantity of items that customers are expected to request each day. In this particular scenario,

the *New Demand* is set at a constant rate of 100 items per day at the beginning of the simulation. The time unit in this model is measured in days, indicating that each time step or increment represents one day. Additionally, the model is run for a total of 1000 days, allowing for the examination of the supply chain dynamics over an extended period. *Customer Order* adjusts in response to changes in *New Demand*. If the *New Demand* increases or decreases on a particular day, the *Customer Order* for that day will reflect the corresponding change.

Demand Backlog in Figure 4.1. can be defined as the aggregate amount of orders that are placed by customers but not fulfilled yet by the retailer due to insufficient stock on hand or orders that are in transit. When there are enough goods in the inventory, orders are fulfilled and the demand backlog is depleted by customer delivery flow which is equal to the sales. The rate of change of the demand backlog over time in the model is expressed as

$$\frac{d(Demand\ Backlog)}{dt} = Customer\ Order(t) - Customer\ Delivery(t). \tag{4.1}$$

Figure 4.2. specifically represents the inventory and flow dynamics associated with the retailer, focusing on the retailer-related parts of the stock-flow system. This includes the processing of customer orders, the placement of replenishment orders to the manufacturer, and the movement of goods from the retailer to the customers, detailing how the retailer manages its inventory and responds to customer demand within the supply chain.

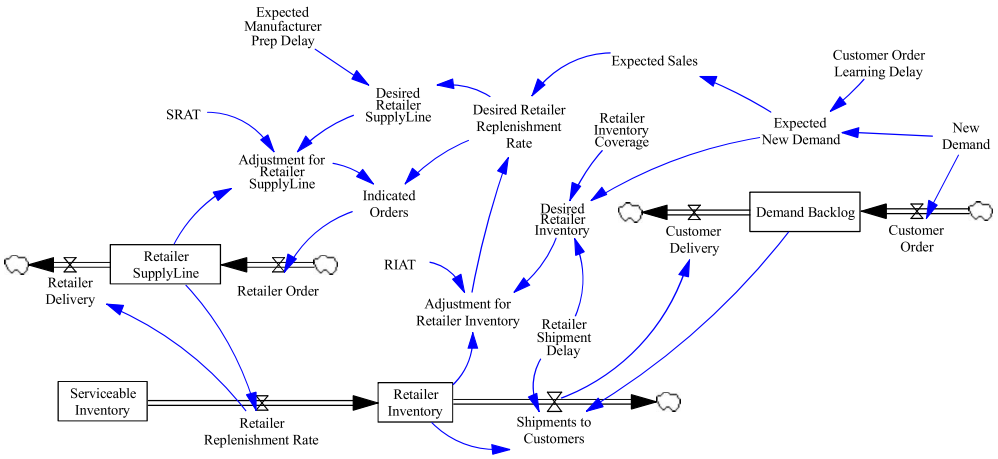

Figure 4.2. Retailer stock-flow diagram.

Learning delay refers to the time it takes for actors to recognize and process new information about demand changes and update their expectations accordingly. *Expected New Demand* is derived from the current *New Demand*, but there is a learning delay—meaning there is a lag between when the demand change occurs and when this information is processed and used. This information is used for the determination of the *Desired Retailer Inventory*. *Desired Retailer Inventory* is the target level of goods that the retailer wants to have in inventory at any time. It depends on *Expected New Demand*, *Retailer Shipment Delay*, and *Retailer Inventory Coverage*. *Desired RI* is expressed as

$$Desired\ RI = Expected\ New\ Demand\ x\ Retailer\ Shipment\ Delay\ x\ RI\ Coverage. \quad (4.2)$$

Retailers should keep more goods in the inventory than customer demand due to shipment delays and sudden fluctuations. Inventory coverage indicates how many days' worth of stock the retailer is keeping based on average demand. *Adjustment for Retailer Inventory* is the discrepancy between the desired level and actual level of retailer inventory, divided by the retailer inventory adjustment time, as expressed by

$$Adjustment\ for\ Retailer\ Inventory = \frac{Desired\ Retailer\ Inventory - Retailer\ Inventory}{RIAT}. \quad (4.3)$$

Stock adjustment creates a negative feedback loop. When the *Retailer Inventory* level falls below this desired level, the adjustment mechanism accelerates the replenishment rate of inventory, meaning it speeds up the flow of goods into the retailer's inventory. *Retailer Inventory Adjustment Time (RIAT)* represents how fast the retailer responds to changes in the discrepancy between actual and target inventory levels. The retailer anticipates that the number of products sold within a certain period will match the daily customer demand for that period. Therefore, *Expected Sales* is assumed to be equal to *Expected New Demand*. This implies that the retailer's forecast for the number of products it will sell is directly based on the anticipated daily demand from customers.

Desired Retailer Replenishment Rate represents the rate at which the retailer receives items from the downstream actor. *Desired Retailer Replenishment Rate* takes two things into account. First, it considers expected sales since retailer should replace the losses from

inventory. Second, adjustment for inventory since the retailer should reduce the discrepancy between the desired and actual inventory level. The Retailer should acquire less than expected sales if there are more goods in inventory than desired and more than if there is a shortage. *Desired Retailer Replenishment Rate* can be expressed mathematically as

$$Desired\ Retailer\ Replenishment\ Rate = Expected\ Sales + Adjustment\ for\ RI. \quad (4.4)$$

Retailer Supply Line can be defined as the total amount of orders that are placed by the retailer but not fulfilled by the manufacturer yet. This represents the number of goods that are currently in the pipeline, being processed or shipped by the manufacturer, as well as orders that the manufacturer has not yet fulfilled due to insufficient stock on hand. The supply line is a crucial component in inventory management as it helps the retailer anticipate future inventory levels and plan for upcoming demand. By monitoring the supply line, the retailer can make informed decisions about when to place new orders and how to manage current stock levels to ensure a continuous supply of products to meet customer demand without experiencing stockouts or overstock situations. *Retailer Supply Line* is depleted by *Retailer Delivery*, which is equal to *the Retailer Replenishment Rate*, and it is increased by *Retailer Order*, as expressed by

$$\frac{d(Retailer\ Supply\ Line)}{dt} = Retailer\ Order(t) - Retailer\ Delivery(t). \quad (4.5)$$

Desired Retailer Supply Line is the target supply line level that the retailer aims to maintain in the supply chain. It represents the optimal amount of stock that the retailer should have on hand or in the pipeline to meet anticipated customer demand without overstocking. This target level depends on the *Desired Retailer Replenishment Rate* and *Expected Manufacturer Prep Delay. Expected Manufacturer Prep Delay* represents the retailer's current belief or estimation about the length of time required for the manufacturer to prepare and ship the goods before they are ready. *Desired Retailer Supply Line* is expressed as

$$Desired\ Retailer\ Supply\ Line = Desired\ Retailer\ Replenishment\ Rate\ x\ Expected\ Manufacturer\ Prep\ Delay. \quad (4.6)$$

Indicated Orders is formulated as an anchoring and adjustment process. *Desired Retailer Replenishment Rate* serves as the anchor, representing the base rate at which the retailer aims to receive shipments to maintain steady inventory. This anchor is then adjusted by *Adjustment for Retailer Supply Line* which aims to correct any discrepancies between the actual and desired levels of standing orders in the supply line. By using this method, the retailer can dynamically respond to changes in the supply chain, avoiding both overstocking and stockouts. In conclusion, *Indicated Orders* take into consideration three critical components: *Expected Sales*, *Adjustment for Retailer Inventory*, and *Adjustment for Retailer Supply Line* as expressed by

Indicated Orders = Desired Retailer Replenishment Rate + Adjustment for Retailer Supply Line. (4.7)

Adjustment for Retailer Supply Line is calculated by taking the difference between the desired level and the actual level of the supply line, and then dividing it by the *Retailer Supply Line Adjustment Time (SRAT)* as expressed by

Adjustment for Retailer Supply Line = (Desired Retailer Supply Line - Retailer Supply Line) / SRAT. (4.8)

In this model, negative orders are not allowed which indicates there are no cancellations. Therefore, MAX function in Vensim is used to ensure retailer orders do not drop below zero, as expressed by

Retailer Order = MAX (Indicated Orders, 0). (4.9)

Figure 4.3 represents the inventory and flow dynamics associated with the manufacturer, focusing on the manufacturer-related parts of the stock-flow system. This includes the production, and the shipments of goods from the manufacturer to the retailer, detailing how the manufacturer manages its inventory and responds to demand within the supply chain.

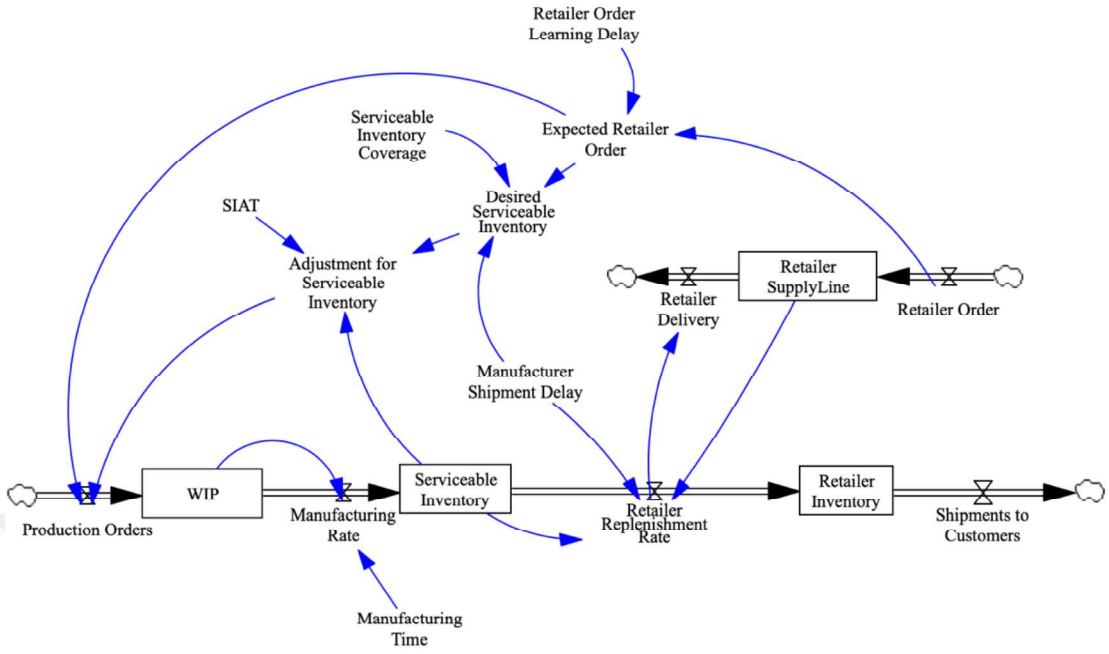

Figure 4.3. Manufacturer stock-flow diagram.

Expected Retailer Order is derived from *Retailer Order* and it is used for the determination of *Desired Serviceable Inventory*. This means that the manufacturer anticipates future orders based on current order data but with a learning delay. There is a lag between when the retailer order changes and when this information is processed and used. This *Retailer Order Learning Delay* affects how the manufacturer calculates the amount of inventory needed to meet the retailer's demand.

Desired Serviceable Inventory is the target level of goods that a manufacturer wants to have in inventory at any time to meet the retailer's demand. It depends on *Expected Retailer Order*, *Manufacturer Shipment Delay*, and *Serviceable Inventory Coverage*. Manufacturers should keep more goods in the inventory than retailer demand due to shipment delays and sudden fluctuations. *Desired SI* is expressed as

$$\textit{Desired SI} = \textit{Expected Retailer Order} \times \textit{Manufacturer Shipment Delay} \times \textit{SI Coverage}. \quad (4.10)$$

Adjustment for Serviceable Inventory is the discrepancy between the desired level and actual level of manufacturer inventory on hand divided by serviceable inventory adjustment

time. *Serviceable Inventory Adjustment Time (SIAT)* represents how quickly the manufacturer responds to changes in demand. This creates a negative feedback loop just like in the retailer's case. When the *Serviceable Inventory* level falls below the desired level, the adjustment mechanism accelerates the production rate. By making this adjustment, the goal is to ensure inventory levels are optimal while meeting customer demand and preventing both overstocking and stock shortages at the same time. *Adjustment for Serviceable Inventory* is expressed as

$$\textit{Adjustment for Serviceable Inventory} = (\textit{Desired Serviceable Inventory} - \textit{Serviceable Inventory}) / \textit{SIAT}. \quad (4.11)$$

Production Orders represent the initiation of the manufacturing process where raw materials are converted into finished goods. It can be considered as the ideal rate at which the manufacturer wishes to produce and replenish its inventory. It is determined by the sum of the *Expected Retailer Order* and the *Adjustment for Serviceable Inventory* meaning that the manufacturer adjusts its production based on the anticipated orders from the retailer, while also considering the current inventory levels. If the inventory is below the desired level, the manufacturer will increase the production rate, producing more than the expected retailer order to replenish the inventory. *Production Orders* is expressed as

$$\textit{Production Orders} = \textit{Expected Retailer Order} + \textit{Adjustment for Serviceable Inventory}. \quad (4.12)$$

Work-in-progress (WIP) refers to the items that are currently in various stages of production but are not yet completed as finished goods. WIP stock is increased by *Production Orders*, which initiate the conversion of raw materials into products and decreased by the *Manufacturing Rate*, which represents the rate at which these items are completed and moved into the final inventory of finished products. The rate of change of *WIP* over time in the model is expressed as

$$\frac{d(WIP)}{dt} = \textit{Production Order}(t) - \textit{Manufacturing Rate}(t). \quad (4.13)$$

Manufacturing Rate refers to the rate at which items are produced, representing the volume of finished goods that are completed and ready to be moved out of the *Work-In-Progress (WIP)* inventory into the *Serviceable Inventory.* *Manufacturing Time* refers to the total time required to convert raw materials into finished products within the production process. The *Manufacturing Rate* is calculated by dividing the amount of WIP by the *Manufacturing Time*. This means that the rate at which finished goods are produced depends on the quantity of items in production (*WIP*) and the time it takes to complete the manufacturing process, as expressed by

$$Manufacturing\ Rate = \frac{WIP}{Manufacturing\ Time}. \tag{4.14}$$

Serviceable Inventory, on the other hand, represents the inventory of finished goods that are ready for distribution and usable for fulfilling the retailer's demand. It is increased by the *Manufacturing Rate* and depleted by the *Retailer Replenishment Rate* as expressed as

$$\frac{d(Serviceable\ Inventory)}{dt} = Manufacturing\ Rate(t) - Retailer\ Replenishment\ Rate(t). \tag{4.15}$$

Retailer Replenishment Rate refers to the rate at which the retailer receives goods from the manufacturer to replenish its inventory, occurring with a time delay. This rate is determined by considering both the available stock in the manufacturer's inventory and the retailer's needs. *Retailer Replenishment Rate* is formulated as the minimum of *Serviceable Inventory* divided by *Manufacturer Shipment Delay,* which represents the maximum possible shipments to the retailer, and *Retailer Supply Line*. If this maximum is smaller than the retailer supply line, it indicates that there are not enough goods in the manufacturer's inventory to meet the current retailer demand, showing that the manufacturer's inventory is being depleted faster than new goods are produced. This situation leads to a buildup in the retailer supply line. Conversely, if the retailer supply line is smaller than the maximum possible shipments, it means that there are enough goods in the manufacturer's inventory to fulfill the retailer's demand, and in this scenario, the shipments are limited by the retailer supply line. This relationship is expressed as

$$Retailer\ Replenishment\ Rate = MIN\left(\frac{Serviceable\ Inventory}{Manufacturer\ Shipment\ Delay}, Retailer\ Supply\ Line\right). \quad (4.16)$$

Initially, the strict minimum function in Eq. 4.16 was used to calculate the *Retailer Replenishment Rate*, but it led to sharp, abrupt changes in response to variations in inputs. To address these issues, a fuzzy minimum approach was introduced which smooths the transition between the two limiting factors, providing a more stable and gradual change in replenishment rate. In the final model, the *Retailer Replenishment Rate* is calculated by using a fuzzy minimum (smooth) function as expressed by

$$Retailer\ Replenishment\ Rate = Effof\ Max\ Possible\ RI\ Shipments \times Retailer\ Supply\ Line. \quad (4.17)$$

The *Retailer Replenishment Rate is* calculated by considering the effect of the maximum possible shipments from the manufacturer to the retailer and then multiplying this by the retailer's supply line as can be seen from Eq. 4.17. The impact of maximum shipments is determined by a function that evaluates the ratio between the maximum possible shipments to the retailer and the retailer's supply line, as described by

$$Effof\ Max\ Possible\ RI\ Shipments = f\ (Max\ Possible\ RI\ Shipments / Retailer\ Supply\ Line). \quad (4.18)$$

The graph in Figure 4.4 illustrates the relationship between the input, Retailer Supply Line, and the output, Maximum Possible Shipments to the Retailer. The x-axis represents the ratio of the maximum possible shipments to the retailer's supply line while the y-axis represents the effect of the maximum possible shipments. The function is essentially a unity function until about 0.9. This means as the ratio increases from 0 to around 0.90, Effect of Max Possible Shipments follows a linear unity function (y=x), indicating that the replenishment rate directly matches the maximum possible shipments. When the ratio is below 1, it indicates that the supply line exceeds the maximum possible shipments. Consequently, the *Retailer Replenishment Rate* is limited by the maximum possible shipments, resulting in a rate proportional to this limit.

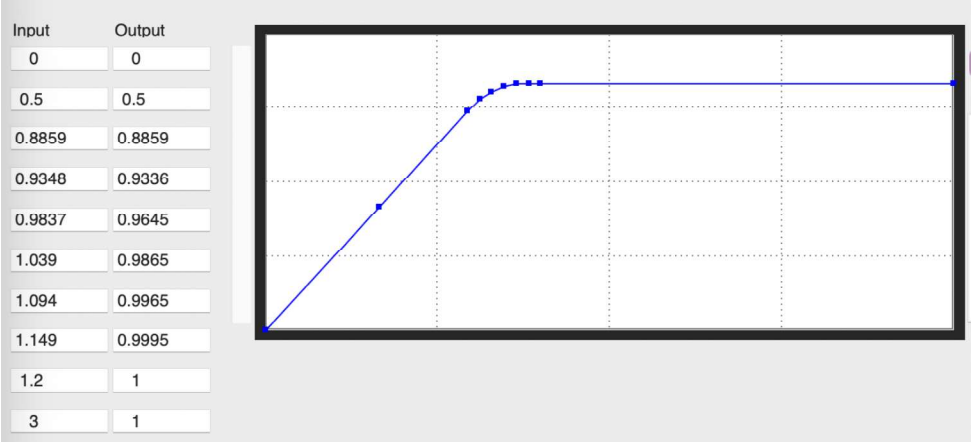

Figure 4.4. Effect of maximum possible shipments to the retailer.

Beyond x=0.9, the function begins to deviate from the linear unity relationship. The output Effect of Max Possible Shipments increases at a diminishing rate and eventually approaches a maximum value of 1. This behavior suggests a saturation effect where, after a certain point, increases in x result in smaller increments in y, until y stabilizes at 1. When the ratio exceeds 1, it suggests that the maximum possible shipments surpass the supply line, thus the replenishment rate is dictated by the supply line. Once the ratio surpasses 1, the effect of the maximum possible shipments remains constant at 1. This indicates that regardless of how much the ratio exceeds 1, the *Retailer Replenishment Rate* is always constrained by the supply line.

Retailer Inventory represents the available and usable stock of goods held by the retailer at a certain time to fulfill customer demand. It is increased by the *Retailer Replenishment Rate* and depleted by *Shipments to Customers* as expressed by

$$\frac{d(\textit{Retailer Inventory})}{dt} = \textit{Retailer Replenishment Rate}(t) - \textit{Shipments to Customers}(t). \quad (4.19)$$

Shipments to Customers refers to the rate at which goods are delivered from the retailer's inventory to the customers, accounting for a time delay. This rate is determined by considering both the available stock in the retailer's inventory and the customers' needs. It is formulated as the minimum of *Retailer Inventory* divided by *Retailer Shipment Delay,* which represents the maximum possible shipments to the customers, and *Demand Backlog.* If this maximum is smaller than the demand backlog, it indicates that the retailer's inventory

is insufficient to meet the current customer demand, implying that the inventory is being depleted faster than new shipments are arriving. This situation leads to a buildup in the demand backlog. Conversely, if the demand backlog is smaller than the maximum possible shipments, it means there are enough goods in the retailer's inventory to fulfill the demand. In this case, potential sales are limited by the demand backlog, ensuring that shipments do not exceed actual customer demand. This relationship is expressed as

$$Shipments\ to\ Customers=\left(\frac{Retailer\ Inventory}{Retailer\ Shipment\ Delay},Demand\ Backlog\right). \quad (4.20)$$

Similar to the *Retailer Replenishment Rate*, *Shipments to Customers* was initially calculated using a strict minimum function, leading to sharp, abrupt changes. To address these issues, the same approach of using a fuzzy minimum (smooth) function is applied to calculate the *Shipments to Customers*, as described by

$$Shipments\ to\ Customers = Effof\ Max\ Possible\ Customer\ Shipments\ x\ Demand\ Backlog. \quad (4.21)$$

The *Shipments to Customers is* calculated by considering the effect of the maximum possible customer shipments from the retailer and then multiplying this by the demand backlog as can be seen from Eq. 4.21. The impact of maximum shipments is determined by a function that evaluates the ratio between the maximum possible shipments to the customers and the demand backlog, as described by

$$Effof\ Max\ Possible\ Customer\ Shipments = f\ (Max\ Possible\ Customer\ Shipments\ /\ Demand\ Backlog). \quad (4.22)$$

The same graph as in Figure 4.4 is employed to illustrate the relationship for calculating *Shipments to Customers*. When the ratio between the maximum possible shipments and the demand backlog is below 1, it indicates that the demand backlog exceeds the maximum possible shipments. In this scenario, the effect of the maximum possible shipments is directly proportional to this ratio meaning that the customer shipments are limited by the maximum possible shipments. When the ratio exceeds 1, it implies that the

maximum possible shipments surpass the demand backlog, and the effect of the maximum possible shipments remains constant at 1, indicating that the customer shipments are always constrained by the demand backlog.

The initial two-echelon model, comprising a manufacturer and a retailer, has been explained, highlighting the flow of goods and inventory management between these two entities. Building on this, a three-echelon model introduces a distributor as an intermediary between the manufacturer and the retailer. In this expanded model, the manufacturer produces goods and ships them to the distributor. The distributor, in turn, manages its own inventory and processes orders from the retailer, ensuring timely delivery of goods to the retailer's inventory. Formulations for the distributor follow the same principles as those for the manufacturer and retailer, managing its inventory using an anchor and adjustment mechanism. This addition creates an additional layer of supply chain management, where the distributor acts to buffer the variability in demand and supply between the manufacturer and retailer. The distributor must balance the shipments received from the manufacturer with the demands of the retailer.

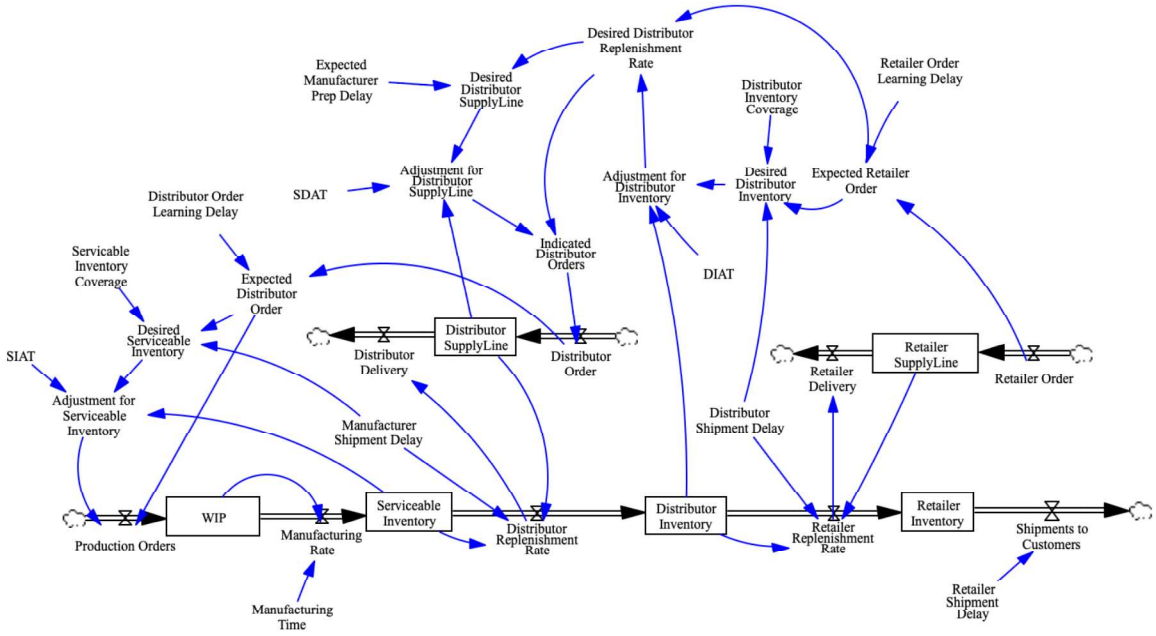

Figure 4.5. Distributor stock-flow diagram.

Figure 4.5 represents the inventory and flow dynamics associated with the distributor, focusing on the distributor-related parts of the stock-flow system. This includes the

shipments of goods from the manufacturer to the distributor and from distributor to retailer detailing how the distributor manages its inventory and responds to demand within the supply chain.

Desired Distributor Inventory is the target level of goods that a distributor wants to have in inventory at any time to meet the retailer's demand. It depends on *Expected Retailer Order*, *Distributor Shipment Delay*, and *Distributor Inventory Coverage*. Distributors should keep more goods in the inventory than retailer demand due to shipment delays and sudden fluctuations. *Desired DI* is expressed as

$$\textit{Desired DI} = \textit{Expected Retailer Order} \times \textit{Distributor Shipment Delay} \times \textit{DI Coverage}. \quad (4.23)$$

Adjustment for Distributor Inventory is the discrepancy between the desired level and actual level of distributor inventory on hand divided by distributor inventory adjustment time. *Distributor Inventory Adjustment Time (DIAT)* represents how quickly the distributor responds to changes in demand. This creates a negative feedback loop just like in the retailer and manufacturer's case. When the *Distributor Inventory* level falls below the desired level, the adjustment mechanism accelerates the replenishment process to bring inventory back in line with targets. *Adjustment for Distributor Inventory* is expressed as

$$\textit{Adjustment for Distributor Inventory} = (\textit{Desired Distributor Inventory} - \textit{Distributor Inventory}) / \textit{DIAT}. \quad (4.24)$$

Desired Distributor Replenishment Rate represents the rate at which the distributor receives items from the manufacturer. *Desired Retailer Distributor Rate* takes two things into account. First, it considers expected retailer orders since the distributor should replace the losses from inventory. Second, adjustment for inventory since the distributor should reduce the discrepancy between the desired and actual inventory level. The distributor should acquire less than expected retailer order if there are more goods in inventory than desired and more than if there is a shortage. This can be expressed mathematically as

Desired Distributor Replenishment Rate = Expected Retailer Orders x Adjustment for DI. (4.25)

Distributor Supply Line can be defined as the total amount of orders that are placed by the distributor but not fulfilled by the manufacturer yet. This represents the number of goods that are currently in the pipeline, being processed or shipped by the manufacturer, as well as orders that the manufacturer has not yet fulfilled due to insufficient stock on hand. *Distributor Supply Line* is depleted by *Distributor Delivery* which is equal to *Distributor Replenishment Rate* whereas it is increased by *Distributor Order*, as expressed by

$$\frac{d(\textit{Distributor Supply Line})}{dt} = \textit{Distributor Order}(t) - \textit{Distributor Delivery}(t). \quad (4.26)$$

Desired Distributor Supply Line is the target supply line level that the distributor aims to maintain in the supply chain. It represents the optimal amount of stock that the distributor should have on hand or in the pipeline to meet anticipated retailer demand without overstocking. This target level depends on the *Desired Distributor Replenishment Rate* and *Expected Manufacturer Prep Delay. Expected Manufacturer Prep Delay* represents the distributor's current belief or estimation about the length of time required for the manufacturer to prepare and ship the goods before they are ready. *Desired Distributor Supply Line* is expressed as

Desired Distributor Supply Line = Desired Distributor Replenishment Rate x Expected Manufacturer Prep Delay. (4.27)

Indicated Distributor Orders is formulated as an anchoring and adjustment process. *Desired Distributor Replenishment Rate* serves as the anchor, representing the base rate at which the distributor aims to receive shipments to maintain a steady inventory. This anchor is then adjusted by *Adjustment for Distributor Supply Line* which aims to correct any discrepancies between the actual and desired levels of standing orders in the supply line. By using this method, the distributor can dynamically respond to changes in the supply chain, avoiding both overstocking and stockouts. In conclusion, *Indicated Distributor Orders* take

into consideration three critical components: *Expected Retailer Orders*, *Adjustment for Distributor Inventory*, and *Adjustment for Distributor Supply Line* as expressed by

$$\textit{Indicated Distributor Orders} = \textit{Desired Distributor Replenishment Rate} + \textit{Adjustment for Distributor Supply Line.} \quad (4.28)$$

Adjustment for Distributor Supply Line is calculated by taking the difference between the desired level and the actual level of the supply line, and then dividing it by the *Distributor Supply Line Adjustment Time (SDAT)* as expressed by

$$\textit{Adjustment for Distributor Supply Line} = (\textit{Desired Distributor Supply Line} - \textit{Distributor Supply Line}) / \textit{SDAT.} \quad (4.29)$$

Since negative orders are not allowed in this model, there are no cancellations. Therefore, MAX function in Vensim is used to ensure distributor orders do not drop below zero, as expressed by

$$\textit{Distributor Order} = \textit{MAX (Indicated Distributor Orders, 0).} \quad (4.30)$$

Distributor Replenishment Rate refers to the rate at which the distributor receives goods from the manufacturer to replenish its inventory, occurring with a time delay. This rate is determined by considering both the available stock in the manufacturer's inventory and the distributor's needs. A fuzzy minimum approach was used for the formulation of the *Distributor Replenishment Rate* similar to the retailer and the manufacturer, as expressed by

$$\textit{Distributor Replenishment Rate} = \textit{Effof Max Possible DI Shipments} \times \textit{Distributor Supply Line.} \quad (4.31)$$

The *Distributor Replenishment Rate is* calculated by considering the effect of the maximum possible shipments from the manufacturer to the distributor and then multiplying this by the distributor's supply line as can be seen from Eq. 4.31. The impact of maximum shipments is determined by a function that evaluates the ratio between the maximum possible shipments to the distributor and the distributor's supply line, as described by

$$Effof\ Max\ Possible\ DI\ Shipments = f\ (Max\ Possible\ DI\ Shipments\ /\ Distributor\ Supply\ Line). \quad (4.32)$$

The same graph as in Figure 4.4 is employed to illustrate the relationship for calculating the *Distributor Replenishment Rate*. When the ratio between the maximum possible shipments and the distributor's supply line is below 1, it indicates that the supply line exceeds the maximum possible shipments. In this scenario, the effect of the maximum possible shipments is directly proportional to this ratio meaning that the replenishment rate is limited by the maximum possible shipments. When the ratio exceeds 1, it implies that the maximum possible shipments surpass the supply line, and the effect of the maximum possible shipments remains constant at 1, indicating that the replenishment rate is always constrained by the supply line.

Distributor Inventory represents the available and usable stock of goods held by the distributor at a certain time to fulfill retailer demand. It is increased by the *Distributor Replenishment Rate* and depleted by the *Retailer Replenishment Rate* as expressed by

$$\frac{d(Distributor\ Inventory)}{dt} = Distributor\ Replenishment\ Rate(t) - Retailer\ Replenishment\ Rate(t). \quad (4.33)$$

Retailer Replenishment Rate refers to the rate at which goods are delivered from the distributor's inventory to the retailer, accounting for a time delay. This rate is determined by considering both the available stock in the distributor's inventory and the retailer's needs. A fuzzy minimum approach was used for the formulation of the *Retailer Replenishment Rate,* as described by

$$Retailer\ Replenishment\ Rate = Effof\ Max\ Possible\ RI\ Shipments\ x\ Retailer\ Supply\ Line. \quad (4.34)$$

The *Retailer Replenishment Rate is* calculated by considering the effect of the maximum possible shipments from the distributor to the retailer and then multiplying this by the retailer supply line as can be seen from Eq. 4.34. The impact of maximum shipments

is determined by a function that evaluates the ratio between the maximum possible shipments to the retailer and the supply line, as described by

$$Effof\ Max\ Possible\ RI\ Shipments = f\ (Max\ Possible\ RI\ Shipments\ /\ Retailer\ Supply\ Line). \quad (4.35)$$

The same graph as in Figure 4.4 is employed to illustrate the relationship for calculating the *Retailer Replenishment Rate*. When the ratio between the maximum possible shipments and the retailer's supply line is below 1, it indicates that the supply line exceeds the maximum possible shipments. In this scenario, the effect of the maximum possible shipments is directly proportional to this ratio meaning that the replenishment rate is limited by the maximum possible shipments. When the ratio exceeds 1, it implies that the maximum possible shipments surpass the supply line, and the effect of the maximum possible shipments remains constant at 1, indicating that the replenishment rate is always constrained by the supply line.

5. EXPERIMENTATION

This section will thoroughly examine how supply chain actors, each with varying adjustment times, shipment delays, and learning delays, propagate a sudden increase in demand based on their unique behaviors. The model starts at the equilibrium, every stock has its equilibrium value, and inflows and outflows are equal to each other. This means that the rate at which items are received and shipped out is equal, ensuring that inventories remain stable and do not accumulate or deplete over time. Then, a sudden step change occurs in customer demand. The internal dynamics, the behavior of actors, how each stock and flow responds to the change, and the time it takes to adjust will be closely investigated as the system seeks its new equilibrium. Since the sudden change disrupts the equilibrium state, it will lead to different dynamic responses, and the actors will behave in various ways to adapt to the new circumstances. The impact of shipment delays, inventory adjustment times, and learning delays on supply chain performance will be explored, with a focus on inventory levels and backlogs. Examining how these factors influence system stability and responsiveness will provide insights into the internal dynamics of supply chain operations.

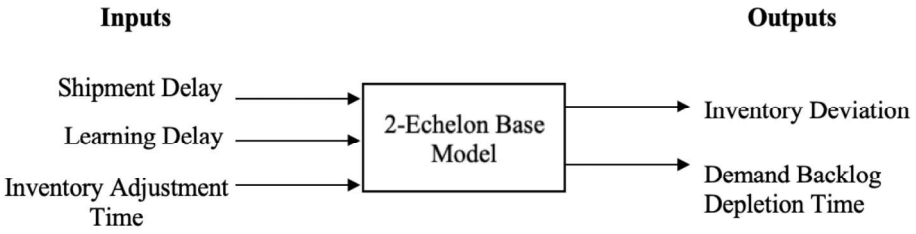

Figure 5.1. 2-echelon base model system diagram.

In Figure 5.1, the system diagram for the 2-echelon Base Model is depicted, showing the key components and their interactions. The central rectangular box represents the core model. The inputs to this model are shipment delay, learning delay, and inventory adjustment time, which serve as experimental variables that can be adjusted to study their effects. These inputs impact the system's dynamics and are manipulated to observe how changes influence the model's behavior. The outputs of the model, which are the key metrics used to evaluate

the system's performance and responsiveness, include demand backlog depletion time and inventory deviation.

The experiments will involve simulating scenarios where the outcomes of the actors' behaviors will be observed by varying inventory management parameters such as inventory adjustment times, shipment delays, and learning delays. Actors first learn about changes in demand through learning delays, reflecting the time taken to recognize and update expectations. Once informed, actors respond with their specific inventory adjustment times, indicating how swiftly they react to the new demand. Finally, the actual products arrive with a shipment delay, representing the lag between placing and receiving orders. These inventory management parameters fundamentally shape how supply chain actors operate and perform. Through exploring diverse combinations of these parameters, the research seeks to explain their impact on supply chain performance.

Firstly, several simulations will be conducted with short, medium, and long shipment delays to assess their impact on inventory levels, order fulfillment rates, backlogs, and overall supply chain performance. Secondly, inventory adjustment times will be examined to understand their influence on supply chain dynamics. Every actor in the model has its own inventory adjustment time which is an indicator of the decentralized nature of the supply chain. Each actor adjusts its inventory independently and reacts to changes at different speeds. This will cause coordination problems in the supply chain. Examining different adjustment times for different actors will give insights into how the overall dynamics of the system are affected. Finally, the effect of learning delay will be observed which denotes the time it takes for an actor to recognize new information. Internal dynamics of the system and overall supply chain performance will be observed with varying learning delays.

In summary, a series of experiments will be conducted systematically by changing the duration of shipment delays, inventory adjustment times, and learning delays to gain insights into the best configuration of these parameters for different actors. Two key metrics will be utilized to assess the system's performance and responsiveness. The first metric encompasses both the average demand backlog and demand backlog depletion time, which serve as separate but related indicators of responsiveness within the supply chain. These metrics measure how quickly the supply chain can fulfill customer demand when it experiences

sudden increases. The average demand backlog provides insight into the typical backlog of customer demand orders experienced over a defined period, reflecting the overall responsiveness of the system. The demand backlog depletion time specifically evaluates the time it takes for the backlog to be cleared, reflecting the system's ability to adapt and respond efficiently to fluctuating demand. The second metric is inventory deviation, which serves as an indicator of supply chain performance. As demand increases unexpectedly, desired inventory levels also rise, but the system may not smoothly reach its new equilibrium. To quantify this deviation from target inventory levels, a formulation is utilized, penalizing deviations using a squared term to assign a higher penalty to oscillations. By monitoring inventory deviations, the effectiveness of inventory management practices and the system's ability to maintain stable inventory levels during demand fluctuations can be evaluated comprehensively.

5.1. Case 1: 2-Echelon Base Model

A simplified stock-flow diagram of the base model was demonstrated in Figure 5.2, depicting the ordering behaviors of the retailer and manufacturer, and illustrating the inventory management parameters—inventory adjustment times, shipment delays, and learning delays.

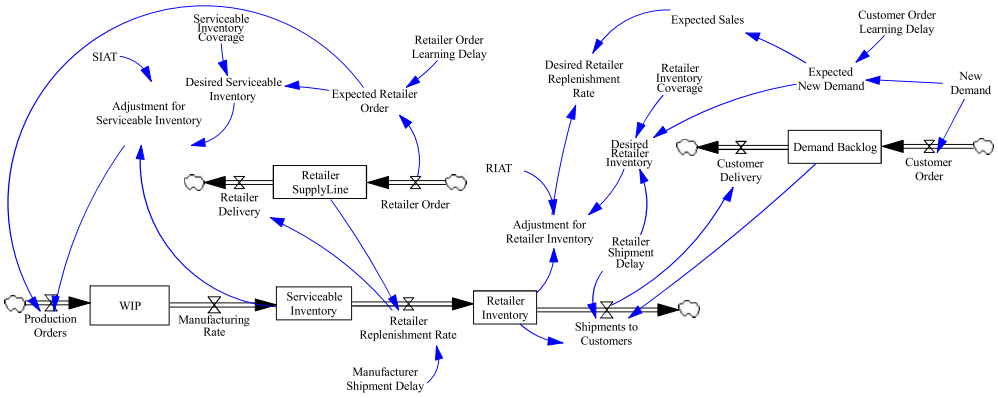

Figure 5.2. 2-echelon base model.

At the beginning of the simulation, the system is in a state of equilibrium. The equilibrium values of parameters are summarized in Table 5.1, providing a baseline for comparison with other scenarios that will be introduced in the subsequent sections.

Table 5.1. 2-echelon base model parameter values.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days

Under these conditions, the initial values of the stocks are set to match the equilibrium values, ensuring a stable starting point for the simulation. The *Retailer Inventory* begins at 300 items while the *Serviceable Inventory* stands at 375 items representing the stock available for fulfilling customer demand under equilibrium conditions. *Work-in-Progress (WIP)* is recorded 500 items initially indicating there are goods within the manufacturing process. *Demand Backlog* and *Retailer Supply Line* start at 100 items signifying there are orders to be fulfilled. These initial values represent the equilibrium state, laying the groundwork for observing how the system evolves over time.

At t=150 days into the simulation, there is a step increase in customer demand as illustrated in Figure 5.3. Before this time point, the customer demand is 100 units per day. At 150 days, demand suddenly increases to 250 units per day.

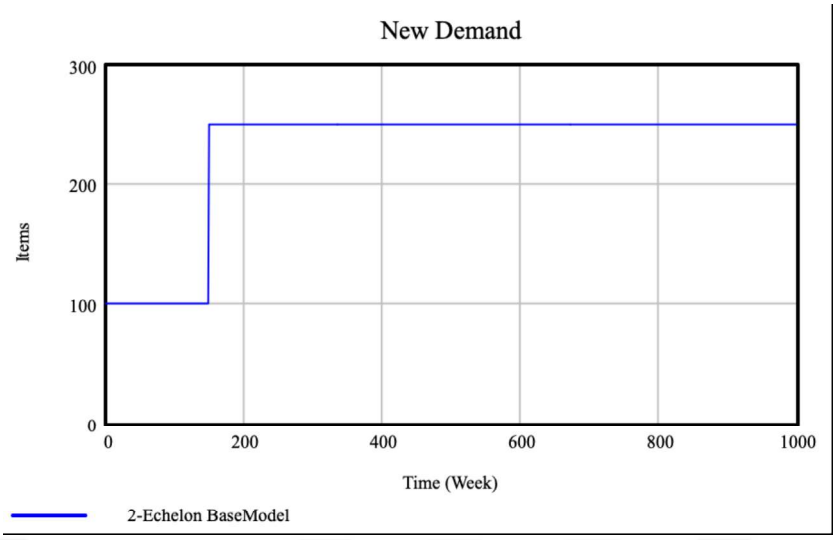

Figure 5.3. 2-echelon base run step increase in customer demand.

First, a base run is conducted with the specified equilibrium conditions. How the base model instance responds to the sudden increase in customer demand will be analyzed in this section. This will establish a baseline for understanding the performance of the supply chain and provide valuable insights into the system's initial responsiveness and efficiency in meeting the elevated demand. Variations in shipment delays, adjustment times, and learning delays will be applied to the base model in the following sections. Each parameter will be modified individually, allowing for an isolated examination of its impact on the system. While these changes are implemented, the remaining parameters will retain their initial values. This one-factor-at-a-time approach will facilitate a comprehensive analysis of how alterations to specific variables influence the overall performance and efficiency of the supply chain system in response to the step increase in customer demand.

In Figure 5.4. the behavior of the *Demand Backlog* is illustrated for the Base Model with the initial configuration. When customer demand suddenly increases from 100 to 250 at t=150, *Demand Backlog* experiences a sharp increase due to insufficient stock. Figure 5.13 illustrates that the retailer is unable to meet the new demand immediately and this causes unfulfilled orders to accumulate in the backlog.

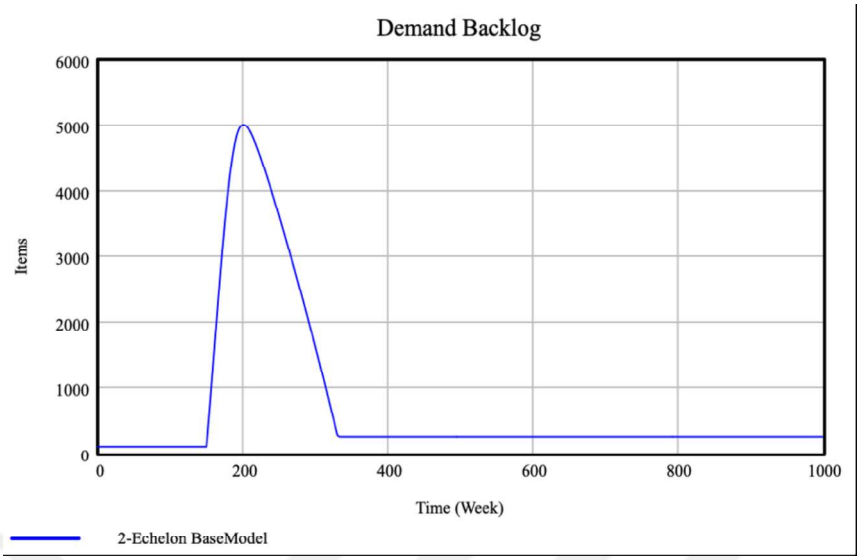

Figure 5.4. 2-echelon base run demand backlog.

When the demand backlog increases, the retailer adjusts its new *Desired Inventory* accordingly and places additional orders to the manufacturer to replenish its inventory. Then, the *Demand Backlog* starts to decrease gradually as the additional products are received from the manufacturer and the retailer can fulfill the outstanding orders. Average Demand Backlog is calculated as 823.51 items/day for the base run. It is calculated by integrating the demand backlog over time and dividing it by the total number of days to provide insight into the typical backlog of customer demand orders experienced over a defined period, reflecting the overall responsiveness of the system

The Demand Backlog Depletion Time indicates the time it takes for the backlog of customer demand to be completely fulfilled. It serves as an indicator of responsiveness in the supply chain. A shorter depletion time suggests a more responsive supply chain, as it indicates that the system can quickly recover from increased demand and fulfill customer orders within a shorter timeframe. Conversely, longer depletion times imply that the system takes more days to fulfill the backlog of customer demand, indicating potential delays in responding to fluctuations in demand. The Demand Backlog is depleted in 341.41 days in the base run, serving as a reference point for comparison with other scenarios. By varying inventory adjustment times, shipment delays, and learning delays in subsequent sections, the impact of changes in supply chain dynamics on the responsiveness indicated by the Demand Backlog Depletion Time can be assessed.

When customer demand increases at t=150, *Retailer Inventory* experiences a sharp decline due to the rapid depletion of available stock. The initial decrease at t=150 days in Figure 5.5 can be referred to as the Retailer's Stock Shortage Crisis Phase. The sudden increase in customer demand outpaces the rate at which the retailer can replenish its inventory. Customer demand cannot be met on time due to shortages in the inventory. This will lead to unfulfilled orders and demand backlogs accumulated over time. When the retailer recognizes that the inventory on hand is insufficient to meet customer demand, it places additional orders to the manufacturer. Following that, the *Retailer Inventory* starts to increase gradually as new products are received from the manufacturer. Then the inventory level stabilizes and remains relatively constant for a while.

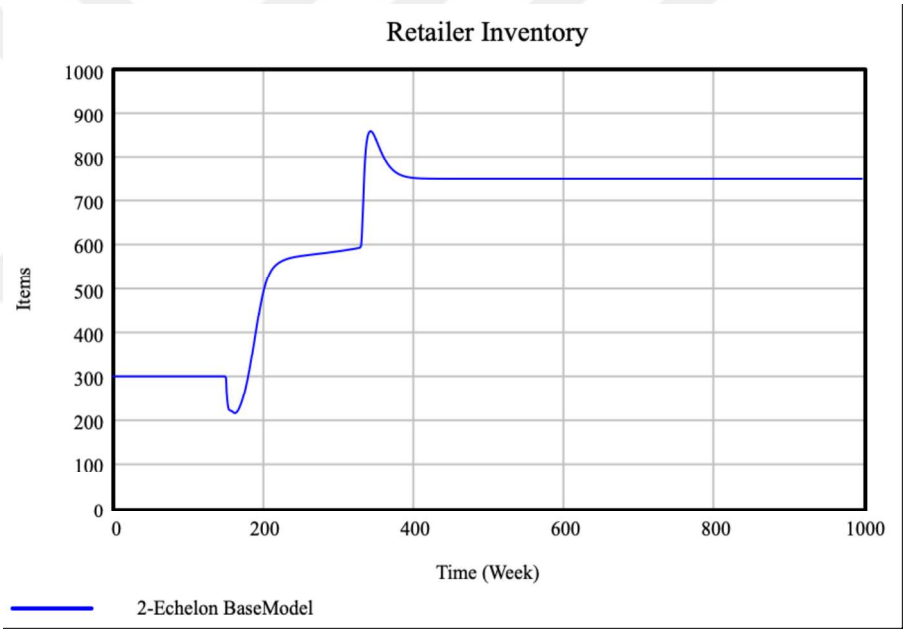

Figure 5.5. 2-echelon base run retailer inventory.

The phase where the inventory remains mostly flat between 200 and 330 days, depicted as a horizontal line in Figure 5.5, is referred to as the Stable Inventory Phase. The retailer sends products to the customer by considering the maximum possible shipments and demand backlog. When the demand backlog exceeds the maximum possible shipments, it indicates that there are more pending customer orders waiting to be fulfilled than the retailer can handle within a given timeframe. The reason the inventory level remains relatively constant for a period is that the replenishment rate is equal to the shipments to customers. The retailer adjusts its *Desired Inventory* and places additional orders to the manufacturer to

replenish its inventory. Then it sends as many products as it can from its inventory to customers until the backlog is depleted.

The phase where there is a sudden increase in inventory at t=330 days followed by reaching the equilibrium in Figure 5.5, is referred to as the Back-to-normal phase. When backlogs are fulfilled, it starts shipping products equal to the daily demand. The point where there is a sudden increase in *Retailer Inventory* is the time when the demand backlog is finally fulfilled and the products sent to the customers decrease. When the retailer has successfully met all customer demands and there are no pending orders, it has more products in inventory than required to fulfill daily demand leading to an increase in *Retailer Inventory*. In response to this, the retailer adjusts its ordering behavior accordingly and reduces its orders to prevent overstocking. As a consequence, *Retailer Inventory* experiences a decrease over time since it receives fewer products from the manufacturer than it sends to customers. Eventually, the *Retailer Inventory* stabilizes and reaches a new equilibrium aligned with the daily demand.

When customer demand increases at t=150, *Serviceable Inventory* experiences a sharp decline like *Retailer Inventory* due to the rapid depletion of available stock. The initial decrease in Figure 5.6 can be referred to as the Manufacturer's Stock Shortage Crisis Phase. When the retailer recognizes that the inventory on hand is insufficient to meet customer demand, it places additional orders to the manufacturer. This caused a decrease in the *Serviceable Inventory* at first since the manufacturer sent all its extra stock. Then, the manufacturer starts to produce new goods to meet the retailer's new demand leading to a gradual increase in its inventory. Then the inventory level stabilizes and remains relatively constant for a while.

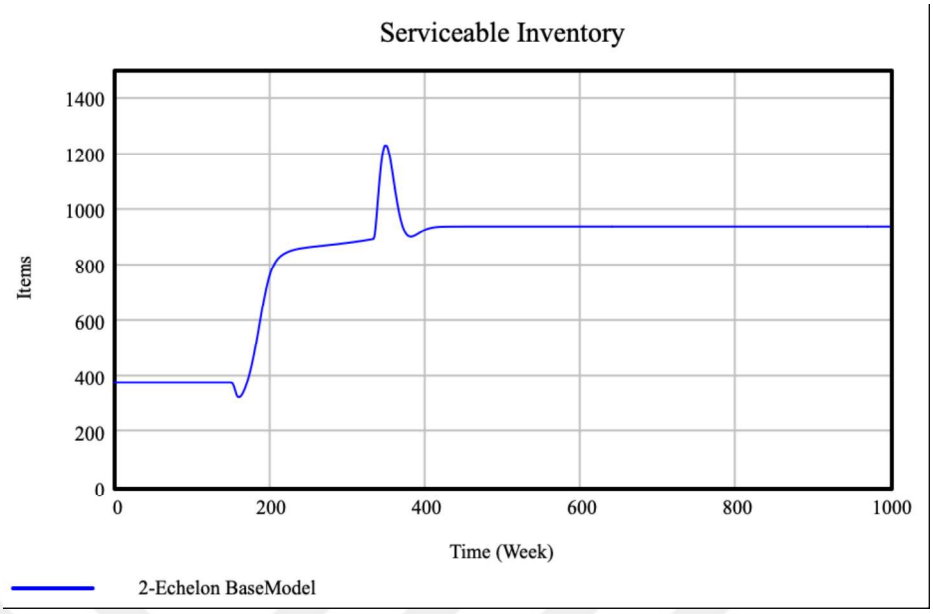

Figure 5.6. 2-echelon base run serviceable inventory.

The phase where the inventory remains relatively constant between 200 and 335 days, depicted as a horizontal line in Figure 5.6, is referred to as the Stable Inventory Phase. The reason the *Serviceable Inventory* remains relatively constant for a while is that the *Manufacturing Rate* is equal to the *Retailer Replenishment Rate*. Similar to the retailer, the manufacturer manages its inventory by considering the maximum possible shipments and the retailer's supply line. When the retailer's supply line exceeds the manufacturer's production rate, it indicates that there are more pending orders from the retailer than the manufacturer can fulfill within a given timeframe. Consequently, the *Serviceable Inventory* level remains relatively constant for a period, as the manufacturing rate matches the retailer's replenishment rate. The manufacturer adjusts its production schedule and aims to meet the retailer's demand by replenishing its inventory accordingly. As a result, the manufacturer sends as many products as it can to the retailer until the retailer's supply line is depleted.

The phase where there is a sudden increase in inventory at t=335 days, followed by reaching the equilibrium in Figure 5.6, is referred to as the Back-to-normal phase. Similar to the retailer, the manufacturer's inventory experiences a sudden increase when the retailer's supply line is finally fulfilled, and the shipment rate to the retailer decreases. As the retailer adjusts its ordering behavior to prevent overstocking, it reduces the frequency and quantity of orders. Consequently, the manufacturer reduces production, leading to a sharp increase in

Serviceable Inventory, creating extra inventory. Once this extra inventory is utilized and becomes insufficient, the manufacturer increases production again, eventually reaching equilibrium.

Inventory deviation will be used as an indicator of supply chain performance. It serves as a metric to evaluate the system's ability to maintain stable inventory levels during fluctuations in demand. Essentially, inventory deviation measures how closely the inventory levels align with the desired targets. Higher deviations indicate that the inventory levels are fluctuating significantly from the intended targets, which can lead to inefficiencies in the supply chain, such as stockouts or overstocking. The deviation is calculated as the squared difference between the actual inventory level and the target inventory level. By squaring the difference, the formulation emphasizes both positive and negative deviations from the target, without considering the direction. This helps penalize deviations equally regardless of whether they result in excess or insufficient inventory. Additionally, the squared term amplifies the impact of deviations, penalizing larger discrepancies more severely than smaller ones, thereby providing a comprehensive assessment of inventory performance. The Retailer Inventory deviation, recorded at 14.72 M, and the Serviceable Inventory deviation, at 13.96 M, serve as benchmarks for comparison against other scenarios. These values, on their own, may not provide significant insights but are crucial for evaluating the relative performance of different supply chain scenarios.

5.1.1. Case 1.1: Inventory Adjustment Time Scenarios

Inventory adjustment time refers to the time it takes for supply chain actors to react to new conditions. During the simulation, a discrepancy between desired and actual inventory levels occurs due to sudden demand change. Inventory adjustment times represent the lag between recognizing the discrepancy and implementing the necessary changes. It reflects how fast actors respond to changes in inventory levels. On one hand, if the adjustment time is long, the size of the correction will be small for any discrepancy. The adjustments tend to be more gradual and occur at a slower speed. This will reduce amplification and result in a more stable behavior. On the other hand, the time required to close the discrepancy between desired and actual inventory levels and reach the goal will be longer. Conversely, shorter adjustment times lead to larger changes in response to discrepancies and may cause

overreaction where the adjustments may be disproportionate to the actual changes. However, the time required to close the discrepancy will be shorter since the responses are more immediate. In summary, there is a trade-off between the time it takes to reach the new equilibrium level and the stability of the system. The equilibrium values of all parameters are tabulated in Table 5.2. Only inventory adjustment times will be changed in this section with values of 5, 10, and 20 and they are highlighted in bold.

Table 5.2. 2-echelon model parameter values at inventory adjustment time scenarios.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	**5,10,20 days**
Retailer Inventory Adjustment Time	**5,10,20 days**
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days

The actors in the supply chain have different inventory adjustment times. It indicates that each actor acts in its own way and reacts to changes at its own speed. One actor might prefer high responsiveness, adapting quickly to changes with a short adjustment time while another actor might prioritize stability and consistency with a longer adjustment time. This diversity may cause complexities and unexpected dynamics in the supply chain while affecting the overall performance. In this section, several simulations will be conducted with various scenarios, subjecting both the manufacturer and the retailer to short, medium, and long adjustment times, leading to a range of possibilities in terms of responsiveness and performance. Table 5.3. illustrates the different combinations of adjustment times for both *Retailer Inventory* and *Serviceable Inventory.* The letters "R" and "S" correspond to Retailer Inventory and Serviceable Inventory, respectively, while the numbers denote the adjustment times in days. For instance, in the case of "R5S20," the *Retailer Inventory Adjustment Time* is 5 days, and the *Serviceable Inventory Adjustment Time* is 20 days.

Table 5.3. 2-echelon model retailer and serviceable inventory adjustment times (days).

	Retailer Inventory Adjustment Time (days)	Serviceable Inventory Adjustment Time (days)
R5S5	5	5
R5S20	5	20
R10S10	10	10
R20S5	20	5
R20S20	20	20

The behavior of the *Demand Backlog* follows a similar pattern in general across different cases as can be seen from Figure 5.7. When customer demand suddenly increases from 100 to 250 at t=150, *Demand Backlog* experiences a sharp increase in all cases due to insufficient stock. However, the extent of the increase and the peak varies depending on the behavior of the retailer and the manufacturer.

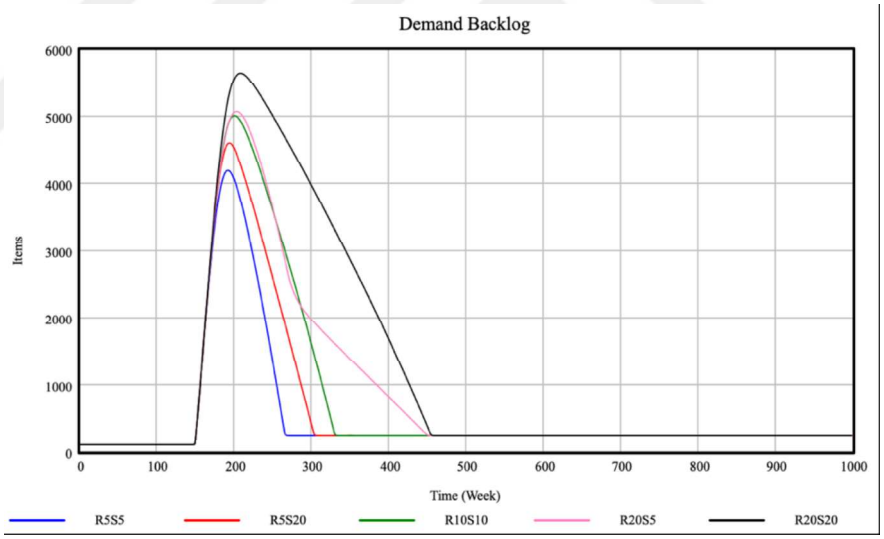

Figure 5.7. 2-echelon model demand backlog with inventory adjustment time scenarios.

The blue line represents the case where they both have short inventory adjustment times indicating that both the retailer and the manufacturer behave highly responsive to changes (R5S5). The red line represents the case where the retailer behaves highly responsive but the manufacturer is much slower to respond (R5S20). The green line depicts a scenario where both the retailer and the manufacturer have medium adjustment times (R10S10). In the case represented by the pink line, the retailer slowly responds to changes

while the manufacturer is highly responsive (R20S5). Finally, the black line represents the case where they both prefer longer inventory adjustment times and act slowly (R20S20).

The minimum peak in *Demand Backlog* occurs when both the retailer and the manufacturer have short inventory adjustment times (R5S5). Since both actors are highly responsive to changes, they adjust their inventory levels more quickly compared to other cases. Also, this is the fastest case to reach the new equilibrium since they are both highly responsive (see Figure 5.7.) The accumulation of demand backlog is a bit more when the manufacturer responds slower compared to the first case. When they both have medium inventory adjustment times, the behavior lies between the extreme cases indicating moderate unfulfilled demand. It is higher compared to the case of short adjustment times but lower than long adjustment times. The case where the retailer slowly responds to changes while the manufacturer is highly responsive is very similar to the case when they both have medium inventory adjustment times at first. However, as time progresses, the pace at which the demand backlog is depleted slows down. This slowdown occurs because the retailer supply line is depleted before the demand backlog is fully addressed. As a result, the retailer runs out of incoming shipments while still having outstanding customer orders to fulfill. This situation leads to stockouts and unfulfilled customer demand, pressuring the retailer to place urgent orders to replenish stock quickly.

When both the retailer and the manufacturer have longer inventory adjustment times, the response to demand change is slower. Consequently, the highest accumulation of *Demand Backlog* and peak occurs in this case due to slow adaptation. Furthermore, this case is the slowest to reach the new equilibrium state since they are both slow to respond to changes. *Demand Backlog* starts to decrease gradually as the additional products are received from the manufacturer and the retailer can fulfill the outstanding orders. The Average Demand Backlog values for various adjustment times are provided in Table 5.4. The values are calculated by integrating the demand backlog over time and dividing it by the total number of days to find an indicator for the average backlog level throughout the simulation.

Table 5.4. 2-echelon model average demand backlog with inventory adjustment time scenarios.

	Average Demand Backlog (Items/Day)
R5S5	598.46
R5S20	701.322
R10S10	823.51
R20S5	935.161
R20S20	1252.99

When inventory adjustment times are longer, the average demand backlog tends to be higher. The lowest average demand backlog is when both the retailer and the manufacturer have short inventory adjustment times and behave highly responsive to changes. This is consistent with the fact that the minimum peak in *Demand Backlog* occurs when both the retailer and the manufacturer have short inventory adjustment times and it is the fastest case to reach the new equilibrium. A small average demand backlog is beneficial for maintaining customer satisfaction, indicating that the supply chain is effectively meeting customer demand without excessive delays. The highest is when they are both slow to respond which is also the highest peak and slowest to reach the new equilibrium state.

The Demand Backlog Depletion Times are provided in Table 5.5. for various adjustment times. The Demand Backlog Depletion Time represents the time it takes for the backlog of customer demand to be completely fulfilled in each scenario.

Table 5.5. 2-echelon model demand backlog depletion times with inventory adjustment time scenarios.

	Demand Backlog Depletion Time (days)
R5S5	277.15
R5S20	314.72
R10S10	341.41
R20S5	463.53
R20S20	465.47

The results are compared with the base case R10S10 to assess the impact of inventory adjustment times on the responsiveness of the supply chain. For instance, R5S5 has the shortest depletion time of 277.15 days, indicating high responsiveness. This indicates a more responsive supply chain compared to the base case, as demand can be fulfilled quickly within a shorter timeframe. As the adjustment times for both Retailer and Serviceable Inventory increase, the depletion time also increases, suggesting a slower response to demand fluctuations.

The behavior of the *Retailer Inventory* can be observed in Figure 5.8. for different scenarios. The case R10S10 is the initial base run that is conducted with the specified equilibrium conditions. When customer demand increases at t=150, *Retailer Inventory* experiences a sharp decline in all cases due to the rapid depletion of available stock. When the retailer places additional orders to the manufacturer, the *Retailer Inventory* starts to increase gradually as new products are received. Then the inventory level stabilizes and remains relatively constant for a while. Up to this point, the behavior of *Retailer Inventory* is the same for all scenarios.

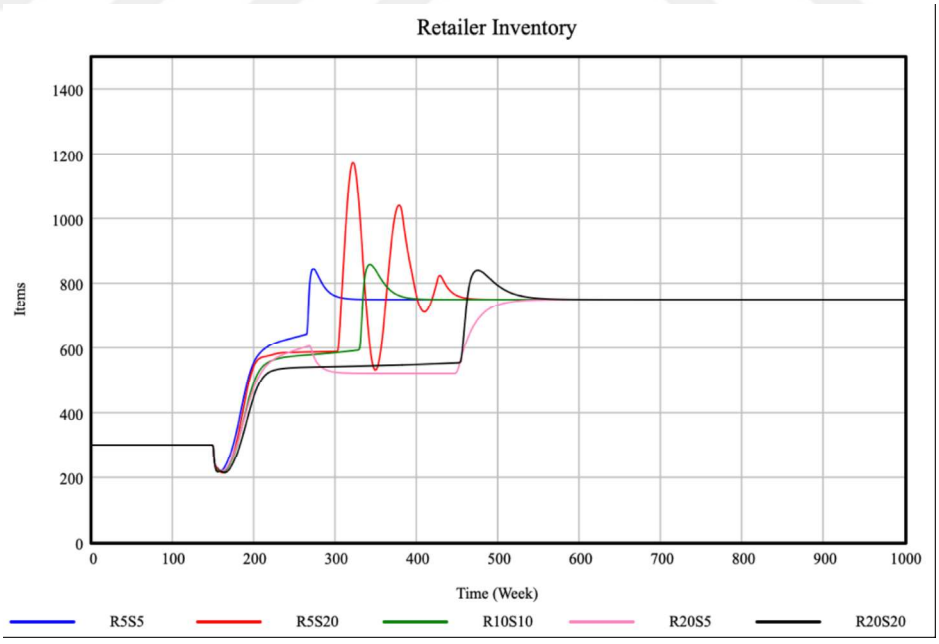

Figure 5.8. 2-echelon model retailer inventory with inventory adjustment time scenarios.

The reason the inventory level remains relatively constant for a period is that the replenishment rate is equal to the shipments. The point where there is a sudden increase in

Retailer Inventory is the time when the demand backlog is finally fulfilled and the shipments to the customers decrease. When the retailer has successfully fulfilled all past demand and reduces its orders to prevent overstocking, *Retailer Inventory* experiences a decrease over time. Eventually, the *Retailer Inventory* stabilizes and reaches a new equilibrium aligned with the daily demand. In three cases when both the retailer and the manufacturer have short, medium, or long inventory adjustment times equal to each other, the behavior of the *Retailer Inventory* follows a similar pattern. The only difference is the time it takes for the system to reach the new equilibrium.

When the retailer has long and the manufacturer has short inventory adjustment times, the behavior is similar at first. Then a different pattern emerges, characterized by a notable decrease in the *Retailer Inventory.* Furthermore, the *Retailer Inventory* does not experience a sudden increase when backlogs are depleted, it reaches the new equilibrium level more smoothly. Since the manufacturer is more responsive than the retailer, the *Retailer Inventory* is replenished more efficiently leading to the lowest *Retailer Supply Line* among all cases.

In the R20S5 scenario, the retailer benefits because its longer inventory adjustment times help stabilize inventory levels, reducing the risk of overreacting. Simultaneously, the manufacturer's fast response ensures timely replenishment, enabling the retailer to meet customer demand efficiently without fluctuations. The case where both the retailer and the manufacturer behave highly responsive to changes is the fastest one to reach the new equilibrium. Short adjustment times enable actors to quickly adapt to the rapid increase in customer demand. The case where the retailer is highly responsive while the manufacturer is much slower to respond differs from the others. The discrepancy between the adjustment times of actors causes oscillations. Since the manufacturer responds slower than the retailer, a larger gap occurs between the *Desired Retailer Inventory* and the actual *Retailer Inventory* compared to other cases. When the retailer wants to adjust its inventory quickly and the manufacturer’s response remains sluggish, the retailer cannot replenish its inventory at the desired pace leading to imbalances and overcorrection. The retailer keeps placing new orders while waiting for fulfillment leading to an accumulation in the *Retailer Supply Line*. Also, the highest peak in the *Retailer Supply Line* is in this case. Consequently, the slower the manufacturer's response, the greater the oscillations in the *Retailer Inventory* and the longer it takes to reach the new equilibrium.

The Retailer Inventory Deviation values are summarized in Table 5.6. The values are derived from a formulation that calculates the squared difference between the actual retailer inventory levels and the target inventory levels.

Table 5.6. 2-echelon model retailer inventory deviation with inventory adjustment time scenarios.

	Retailer Inventory Deviation
R5S5	10.33 M
R5S20	17.28 M
R10S10	14.72 M
R20S5	22.27 M
R20S20	22.63 M

The results illustrate that a lower deviation indicates that the actual inventory levels are closer to the target, reflecting a better supply chain performance. In this case, scenario R5S5 exhibits the lowest deviation at 10.33 M, suggesting relatively accurate inventory control when both retailer and manufacturer adjustment times are short. Specifically, longer adjustment times, such as R20S5 and R20S20, correspond to higher deviations from the target inventory level due to fluctuations and potentially greater inefficiencies in responding to changes in demand.

The behavior of the *Serviceable Inventory* can be observed in Figure 5.9. for different scenarios. When customer demand increases at t=150, *Serviceable Inventory* experiences a sharp decline like *Retailer Inventory* in all cases due to the rapid depletion of available stock. When the retailer places additional orders to the manufacturer a decrease occurs in the *Serviceable Inventory* at first since the manufacturer sent all its extra stock. Then, the manufacturer starts to produce new goods to meet the retailer's new demand leading to a gradual increase in its inventory. Then the inventory level stabilizes and remains relatively constant for a while. Up to this point, the behavior of *Serviceable Inventory* is the same for all scenarios.

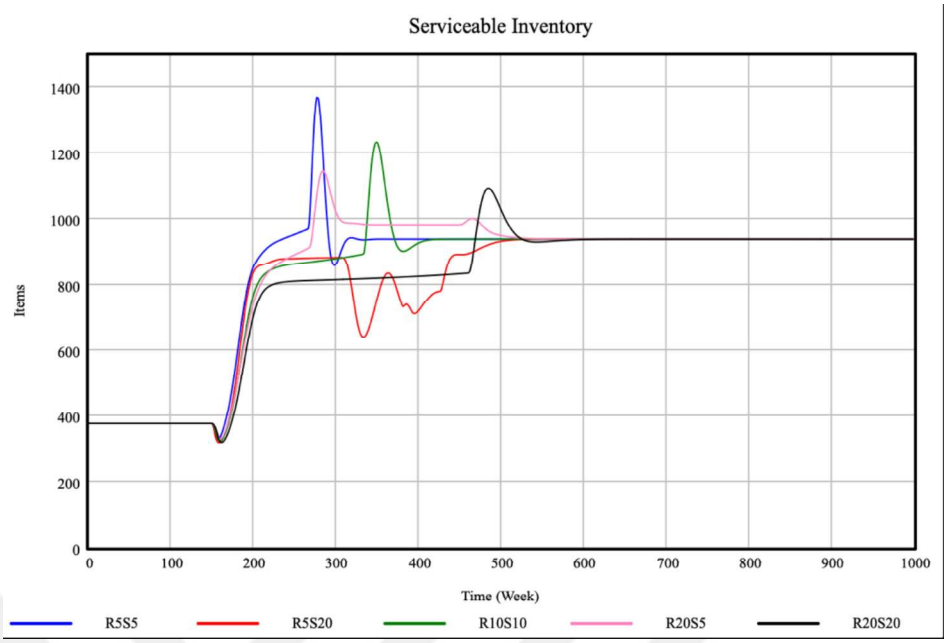

Figure 5.9. 2-echelon model serviceable inventory with inventory adjustment time scenarios.

The reason the *Serviceable Inventory* remains relatively constant for a while is that the *Manufacturing Rate* is equal to the *Retailer Replenishment Rate*. The manufacturer adjusts its production schedule and aims to meet the retailer's demand by replenishing its inventory accordingly. As a result, the manufacturer sends as many products as it can to the retailer until the retailer's supply line is depleted. The inventory suddenly increases when the retailer's supply line is fulfilled, and the shipment rate to the retailer decreases. As the retailer reduces orders to prevent overstocking, the manufacturer initially cuts production, causing a spike in *Serviceable Inventory*, which is then used up, prompting the manufacturer to increase production again until equilibrium is reached. In R20S5, the manufacturer, being highly responsive, cuts production sooner as the retailer reduces orders to prevent overstocking, leading to an earlier spike in *Serviceable Inventory*.

In three cases when both the retailer and the manufacturer have short, medium, or long inventory adjustment times equal to each other, the behavior of the *Serviceable Inventory* follows a similar pattern. They differ in terms of the time it takes for the system to reach the new equilibrium and the magnitude of the highest peak observed in the inventory level. The shorter the adjustment time, the higher the peak. However, in R20S5, there is a notable

difference compared to the other scenarios. After a stable period, the inventory oscillates below the equilibrium level before eventually reaching a new equilibrium.

In the scenario where the retailer is highly responsive while the manufacturer responds much slower (R5S20), the manufacturer's inventory experiences significant fluctuations. Since the retailer adjusts orders rapidly to meet changing demand dynamics, the manufacturer struggles to keep up with the irregularities in incoming orders and synchronize its production pace accordingly. This mismatch results in periods where the manufacturer's inventory oscillates below its equilibrium.

The Serviceable Inventory Deviation values are summarized in Table 5.7. For the *Serviceable Inventory*, scenario R5S5 exhibits the lowest deviation at 11.99 M, suggesting relatively accurate inventory control when both retailer and manufacturer adjustment times are short. Conversely, longer adjustment times, as seen in scenarios R5S20 and R20S20, correspond to higher deviations from the target inventory level, indicating potential inefficiencies in responding to changes in demand.

Table 5.7. 2-echelon model serviceable inventory deviation with inventory adjustment time scenarios.

	Serviceable Inventory Deviation
R5S5	11.99 M
R5S20	16.07 M
R10S10	13.96 M
R20S5	13.36 M
R20S20	17.68 M

5.1.2. Case 1.2: Shipment Delay Scenarios

Shipment delays refer to the time it takes for products to be transported from one actor to another in the supply chain. These delays can occur at various stages. In this model, there are 2 shipment delays to be considered, the *Retailer Shipment Delay* and the *Manufacturer Shipment Delay*. *Retailer Shipment Delay* represents the time between the products being shipped by the retailer and their arrival to the customers. It encompasses the time required

for the products to be transported from one location to another when there is enough inventory to fulfill the demand. It does not include the duration during which the retailer awaits sufficient inventory before sending out new products. Similarly, *Manufacturer Shipment Delay* is the time between the manufacturer shipping the products and their receipt by the retailer.

Shipment delay is an example of material delay which refers to the time it takes for physical products to move through the system. Shipment delays are essential factors in the supply chain dynamics as they directly affect the availability of products. Different simulations will be conducted with varying values of shipment delays in this section to understand the impact of these delays since they affect the overall responsiveness and efficiency of the system. When shipment delays are long, the risk of stockouts will be higher and actors may need to maintain larger safety stocks to account for the lead times resulting in high holding costs. Also, longer delays may cause customer dissatisfaction due to slower order fulfillment and damage the company's reputation. On the other hand, shorter shipment delays may increase transportation costs.

Shipment delays significantly influence target inventory levels within the supply chain. The time it takes for products to be shipped from one actor to another directly impacts the availability of goods for customers. Longer shipment delays result in prolonged lead times, increasing the risk of stockouts and necessitating larger safety stock levels to accommodate these delays. Also, extended shipment delays can lead to customer dissatisfaction. Conversely, shorter shipment delays reduce transit times, minimizing lead times and lowering the risk of stockouts. This reduction in lead times enables a more efficient flow of products through the supply chain, reducing the need for larger safety stock levels.

Both the manufacturer and the retailer will be subjected to short, medium, and long shipment delays leading to a range of possibilities in terms of responsiveness and stability. Exploring different scenarios will provide important insights into the overall efficiency and performance of the supply chain in meeting customer demand. The equilibrium values of all parameters are tabulated in Table 5.8. Only shipment delays will be changed in this section with values of 1, 2, 3, and 5 and they are highlighted in bold.

Table 5.8. 2-echelon model parameter values at shipment delay scenarios.

Parameters	Values
Manufacturing Time	5 days
Manufacturer Shipment Delay	**1,2,3,5 days**
Retailer Shipment Delay	**1,2,3,5 days**
Serviceable Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days

In this section, several simulations will be conducted with various scenarios. Both the manufacturer and the retailer will be subjected to short, medium, and long shipment delays leading to a range of possibilities in terms of responsiveness and performance. Table 5.9. illustrates the different combinations of shipment delays for both *Retailer Inventory* and *Serviceable Inventory*. The letters "R" and "S" correspond to Retailer Inventory and Serviceable Inventory, respectively, while the numbers denote the shipment delays in days. For instance, in the case of "R2S3," the *Retailer Shipment Delay* is 2 days, and the *Manufacturer Shipment Delay* is 3 days.

Table 5.9. 2-echelon model retailer and serviceable inventory shipment delays (days).

	Retailer Shipment Delay (days)	Manufacturer Shipment Delay (days)
R1S1	1	1
R2S3	2	3
R3S3	3	3
R3S2	3	2
R5S5	5	5

The behavior of the *Demand Backlog* follows a similar pattern in general across different cases as can be seen from Figure 5.10. When customer demand suddenly increases from 100 to 250 at t=150, *Demand Backlog* experiences a sharp increase in all cases due to insufficient stock. However, the extent of the increase and the peak varies depending on the behavior of the retailer and the manufacturer.

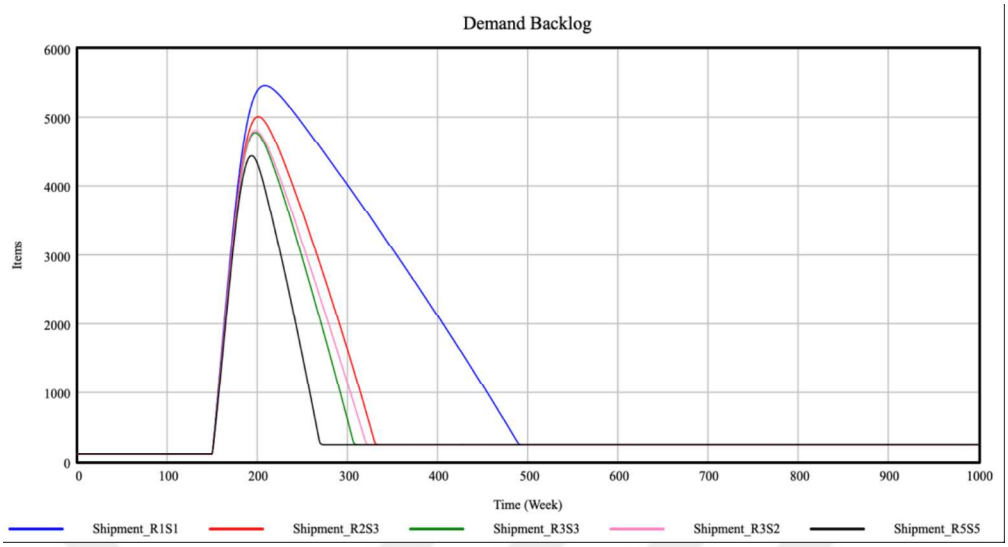

Figure 5.10. 2-echelon model demand backlog with shipment delay scenarios.

When both the retailer and the manufacturer have low shipment delays, it means that products are being transported quickly from the manufacturer to the retailer and from the retailer to the customers. In this scenario, the supply chain is optimized for rapid delivery, and there is minimal delay in fulfilling customer orders. However, despite the efficiency in transportation, the sudden increase in customer demand from 100 to 250 at t=150 exceeds the capacity of the supply chain to restock inventory promptly. With low shipment delays, the system does not have sufficient safety stock or buffer inventory to absorb such a sharp increase in demand. As a result, when the shipment delays are low, the demand backlog experiences the highest increase because the supply chain is unable to replenish inventory quickly enough to meet the surge in demand. On the other hand, the supply chain with long shipment delays is better prepared to handle the surge. The larger safety stock levels act as a cushion, allowing the system to absorb the shock of increased demand more effectively. Therefore, despite the slower transit times, the supply chain with long shipment delays experiences a lower increase in demand backlog compared to scenarios with shorter shipment delays (see Figure 5.10.).

The Average Demand Backlog values for various shipment delays are provided in Table 5.10. The values are calculated by integrating the demand backlog over time and dividing it by the total number of days just like in the previous section.

Table 5.10. 2-echelon model average demand backlog with shipment delay scenarios.

	Average Demand Backlog (Items/Day)
R1S1	1310.3
R2S3	823.51
R3S3	733.387
R3S2	766.421
R5S5	612.198

When shipment delays are shorter, the average demand backlog tends to be higher. The lowest average demand backlog is when both the retailer and the manufacturer have long shipment delays. This is consistent with the fact that the minimum peak in Demand Backlog occurs when both the retailer and the manufacturer have long shipment delays and it is the fastest case to reach the new equilibrium.

Table 5.11. 2-echelon model demand backlog depletion time with shipment delay scenarios.

	Demand Backlog Depletion Time (days)
R1S1	500.25
R2S3	341.41
R3S3	317.81
R3S2	331.44
R5S5	280.35

Demand Backlog Depletion Time serves as an indicator of responsiveness in the supply chain, with the results presented in Table 5.11. The scenario with the shortest depletion time R5S5 demonstrates the highest level of responsiveness, indicating that the supply chain can efficiently address fluctuations in demand. Conversely, scenario R1S1 exhibits a longer demand backlog depletion time, suggesting lower responsiveness in the supply chain. With low shipment delays, the system lacks sufficient safety stock or buffer inventory to absorb sharp demand increases, resulting in the demand backlog reaching high levels and prolonging the time required to fulfill customer orders.

The behavior of the *Retailer Inventory* can be observed in Figure 5.11. for different scenarios. The case R2S3 is the initial base run that is conducted with the specified equilibrium conditions.

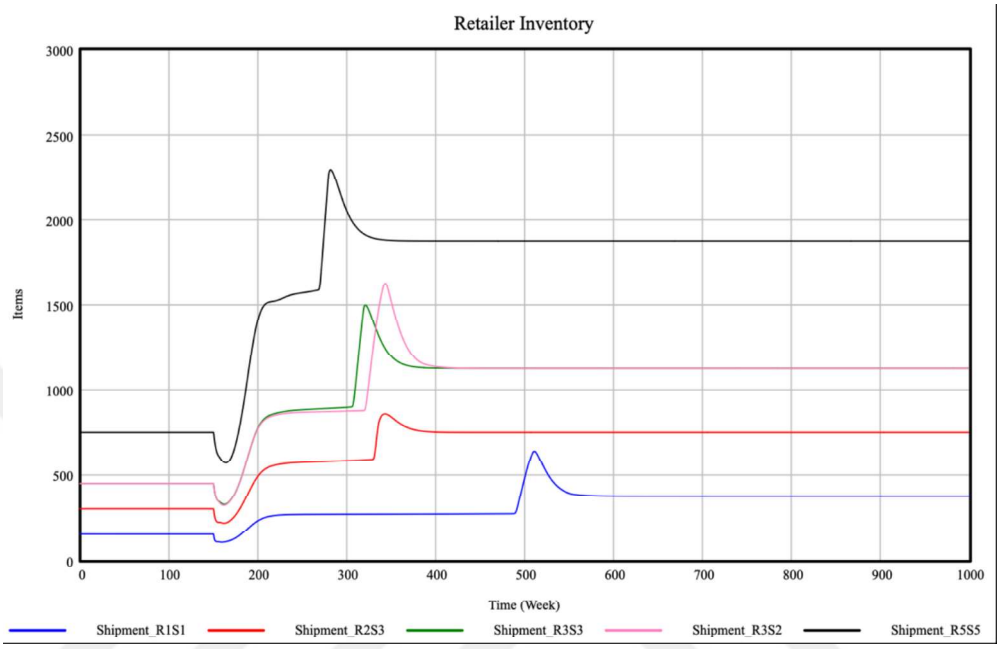

Figure 5.11. 2-echelon model retailer inventory with shipment delay scenarios.

The behavior of *Retailer Inventory* mirrors that of the base run in all scenarios, with the same dynamics observed in response to changes in customer demand and adjustments in ordering patterns. Initially, *Retailer Inventory* sharply declines as customer demand surges at t=150, but gradually increases as the retailer replenishes stock from the manufacturer, stabilizing for a period as replenishment matches shipments. Subsequently, *Retailer Inventory* experiences a sudden increase when the demand backlog is fulfilled, followed by a decrease as the retailer adjusts orders to prevent overstocking, ultimately stabilizing at a new equilibrium aligned with daily demand.

While the overall pattern of *Retailer Inventory* behavior remains consistent across all scenarios, the timing of the changes and the specific inventory levels differ across scenarios. In scenarios with long shipment delays, the *Retailer Inventory* peaks are highest due to the prolonged lead times, allowing for higher desired inventory levels and the accumulation of extra stock. Conversely, in scenarios with short shipment delays, the *Retailer Inventory* levels are lower due to reduced transit times and less buffer stock. Despite similarities in the

timing of phase changes across scenarios, in the R1S1 scenario, the peak occurs later due to the depletion of the demand backlog happening notably later compared to others.

Table 5.12. 2-echelon model retailer inventory deviation with shipment delay scenarios.

	Retailer Inventory Deviation
R1S1	6.21 M
R2S3	14.72 M
R3S3	31.38 M
R3S2	35.62 M
R5S5	68.98 M

The results in Table 5.12. shows that as the shipment delays increase, the deviation of the *Retailer Inventory* from the target also increases. This indicates that longer shipment delays lead to greater deviations from the desired inventory level. Among the scenarios, R5S5 exhibits the highest deviation, suggesting that the longest shipment delays result in the most significant inventory fluctuations. Conversely, R1S1 shows the lowest deviation, indicating that shorter shipment delays result in relatively smoother inventory management.

The behavior of the *Serviceable Inventory* can be observed in Figure 5.12. for different scenarios. The behavior of *Serviceable Inventory* mirrors that of the base run in all scenarios, with the same dynamics observed in response to changes in customer demand and adjustments in ordering patterns. When customer demand spikes at t=150, *Serviceable Inventory* mirrors Retailer Inventory's sharp decline due to rapid stock depletion. The retailer's additional orders prompt a decline in Serviceable Inventory initially as the manufacturer dispatches extra stock. As the manufacturer increases production to meet the new demand, *Serviceable Inventory* gradually increases, stabilizing thereafter. The equilibrium is maintained as the manufacturing rate aligns with the retailer's replenishment rate, ensuring a steady state of inventory over time.

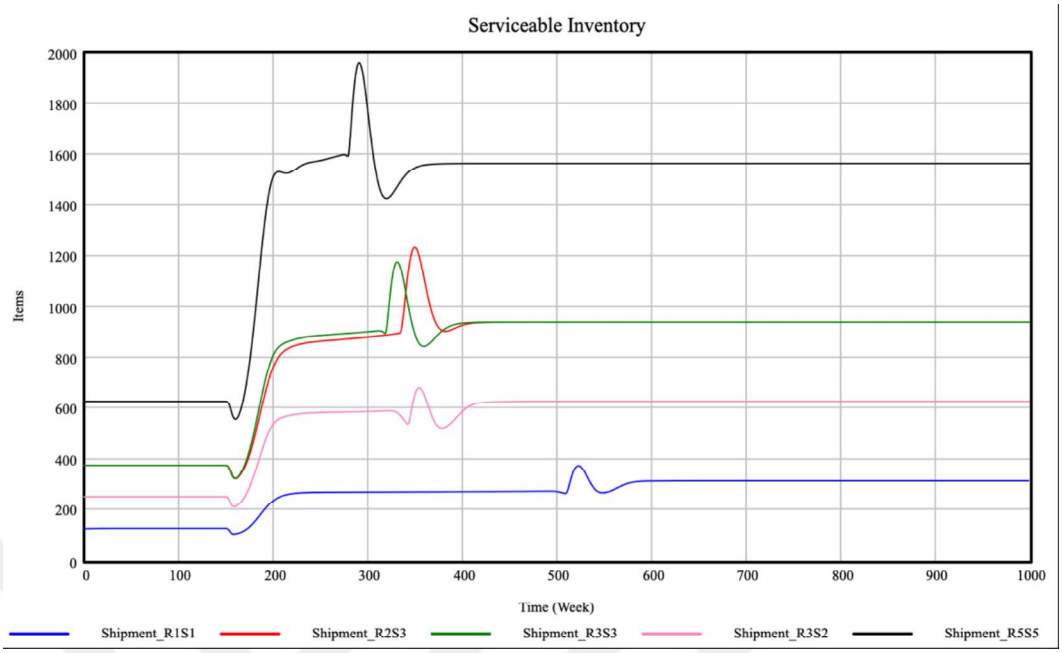

Figure 5.12. 2-echelon model serviceable inventory with shipment delay scenarios.

While the general trend remains consistent across all scenarios, variations in the timing and specific inventory levels are observed just like in *Retailer Inventory*. In instances with long shipment delays, the peaks in *Serviceable Inventory* are notably higher compared to short delays. Despite similarities in the timing of transitional phases across scenarios, the R1S1 scenario exhibits a delayed peak due to the later depletion of the demand backlog compared to others.

Table 5.13. 2-echelon model serviceable inventory deviation with shipment delay scenarios.

	Serviceable Inventory Deviation
R1S1	8.32 M
R2S3	13.95 M
R3S3	12.38 M
R3S2	5.65 M
R5S5	29.75 M

The results in Table 5.13. indicate that the deviation of the *Serviceable Inventory* from the target varies across different scenarios. Interestingly, R3S2 exhibits the lowest deviation, suggesting that moderate shipment delays for both the retailer and manufacturer lead to

relatively stable serviceable inventory levels. On the other hand, R5S5 demonstrates the highest deviation, indicating that longer shipment delays result in more significant fluctuations in *Serviceable Inventory*.

5.1.3. Case 1.3: Learning Delay Scenarios

Learning delay refers to the time it takes for supply chain actors to recognize new information and update their expectations. During the simulation, there is a step increase in customer demand at t=150 days. *New Demand* represents the actual shift in demand reflecting the needs of customers while *Expected New Demand* signifies the Retailer's comprehension of the change in demand as can be seen from Figure 5.13. While customer demand undergoes an abrupt and steep change, the Retailer updates its expectations more gradually and smoothly.

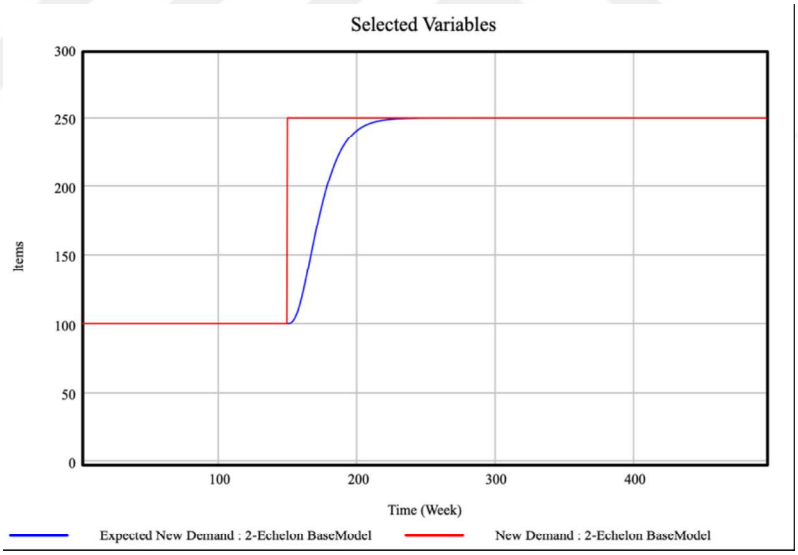

Figure 5.13. 2-echelon model actual vs expected new demand.

Material delay refers to the time it takes for physical products to move through the system while information delay refers to the time it takes for information to propagate through the supply chain. Manufacturing times, shipment, and distribution delays in this system are examples of material delays. The learning delay for the Retailer to understand the change in customer demand and the delay for the Manufacturer to comprehend the Retailer's new orders are the information delays in this supply chain. Information delay may

affect the dynamics and the performance of the system. Third-order exponential smoothing is applied by using the SMOOTH3 function in Vensim. In this section, the effect of learning delays on the supply chain will be investigated to gain insights into the system's responsiveness and overall performance in meeting customer demand. When there is a sudden increase in customer demand, it may take some time for the Retailer to update its expectations due to the learning delay. Similarly, the Manufacturer may also encounter a delay in grasping the change in *Retailer Orders*. Once they are convinced about the change, they adjust their Desired Inventory levels accordingly. These delays might affect actors' ability to respond promptly and effectively due to the lag between the actual change and their conviction about the alteration.

On one hand, if the learning delay is long, actors' expectation update will be delayed leading to a slower response. This delayed conviction may cause inefficiencies or potential stockouts. On the other hand, shorter delays may lead to instability within the system due to instant expectation updates and quick responses. Excessively short delays may result in overreaction that leads to oscillations between overstocking and understocking. In summary, there is a trade-off between the system's stability and responsiveness within the supply chain. The equilibrium values of all parameters are tabulated in Table 5.14. Only learning delays will be changed in this section with values of 5, 9, and 25 and they are highlighted in bold.

Table 5.14. 2-echelon model parameter values at learning delay scenarios.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	**5,9,25 days**
Retailer Orders Learning Delay	**5,9,25 days**

How learning delays influence backlogs, the *Retailer Inventory* and the *Serviceable Inventory* will be explored with various scenarios. Short, medium, and long delays will be considered for both *Customer Orders Learning Delay* and *Retailer Orders Learning Delay*. Different scenarios for learning delays are summarized in Table 5.15. where *Retailer Orders Learning Delay* represents the time it takes for the manufacturer to become aware of the change in retailer order and *Customer Orders Learning Delay* represents the time it takes for the retailer to fully understand the change in customer order.

Table 5.15. illustrates the different combinations of learning delays for both *Retailer Orders* and *Customer Orders.* The letters "R" and "C" correspond to Retailer Orders and Customer Orders, respectively, while the numbers denote the learning delays in days. For instance, in the case of "R9C25," the *Retailer Orders Learning Delays* is 9 days, and the *Customer Orders Learning Delays* is 25 days.

Table 5.15. 2-echelon model retailer orders and customer orders learning delays.

	Retailer Orders Learning Delay (days)	**Customer Orders Learning Delay (days)**
R5C5	5	5
R9C25	9	25
R9C9	9	9
R25C9	25	9
R25C25	25	25

Demand Backlog follows a similar pattern in general across different cases as can be seen from Figure 5.14. As explained in the previous section, when customer demand suddenly increases, the *Demand Backlog* experiences a sharp increase in all cases due to insufficient stock**.** However, the extent of the increase and the peak varies depending on the behavior of the retailer and the manufacturer. Building on the insights gained from the previous section, where the impact of inventory adjustment times was examined, the focus now shifts to the influence of learning delays. R5C5 represents the case where both the retailer and the manufacturer have short learning delays, allowing for quick adaptation to new information. R9C9 depicts the case where both have moderate learning delays while R25C25 illustrates the case where both have long learning delays. In the case of R9C25, the manufacturer learns the change in retailer order relatively quickly but there's a significant

delay for the manufacturer. Conversely in R25C9, the retailer becomes aware of the change in customer demand more quickly while the learning delay is higher for the manufacturer.

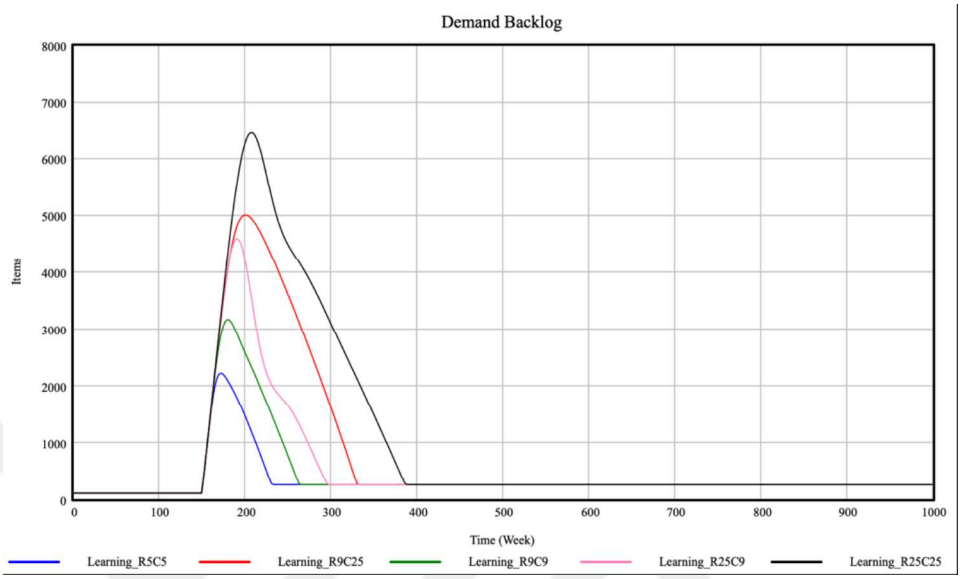

Figure 5.14. 2-echelon model demand backlog with learning delay scenarios.

Among the scenarios listed, R5C5 has the lowest demand backlog indicating that quick awareness allows for more efficient order fulfillment and reduces the accumulation of unfulfilled customer orders. Conversely, R25C25 exhibits the highest demand backlog signifying that high learning delays cause difficulties in meeting customer demand. The second-best scenario for demand backlog is R9C9 where both the retailer and the manufacturer have moderate learning delays. It is not as efficient as R5C5, but it still allows for relatively effective order management. The demand backlog is higher in the case R9C25 compared to R25C9. In R9C25, the significant delay in the retailer's awareness of the demand change leads to a high demand backlog although the manufacturer quickly adjusts to changes in retailer order. The retailer's response to the change in demand begins with the recognition of this change. If the learning delay is high, the retailer will adjust its inventory level and ordering behavior later leading to an accumulation in backlog. Even if the manufacturer adjusts quickly to changes, the retailer will give orders based on previous demand patterns, unaware of the recent change in demand due to the high learning delay.

The Average Demand Backlog values for various learning delays are provided in Table 5.16. The values are calculated by integrating the demand backlog over time to find an indicator for the average backlog level throughout the simulation.

Table 5.16. 2-echelon model average demand backlog with learning delay scenarios.

	Average Demand Backlog (Items/Day)
R5C5	419.313
R9C25	823.51
R9C9	508.997
R25C9	616.296
R25C25	1063.02

When learning delays are longer, the average demand backlog tends to be higher. The lowest average demand backlog is when both the retailer and the manufacturer demonstrate quick awareness of changes leading to faster responses. This is consistent with Figure 5.14., the minimum peak in *Demand Backlog* occurs when both the retailer and the manufacturer have short learning delays and it is the fastest case to reach the new equilibrium. The highest is when they are both slow to comprehend the changes which is also the highest peak and slowest to reach the new equilibrium state.

The results presented in Table 5.17. indicate the impact of learning delays on the responsiveness of the supply chain, as measured by the Demand Backlog Depletion Time. R5D5 exhibits the shortest depletion time at 241.81 days, indicating a relatively agile supply chain response. Conversely, longer learning delays, as observed in scenarios like R9D25 and R25D25, correspond to longer depletion times, suggesting delays in the system's ability to adapt and respond to changes in customer demand. Therefore, shorter learning delays appear to enhance supply chain responsiveness, leading to quicker fulfillment of customer orders.

Table 5.17. 2-echelon model demand backlog depletion times with learning delay scenarios.

	Demand Backlog Depletion Time (days)
R5C5	241.81
R9C25	341.41
R9C9	273.91
R25C9	306.59
R25C25	397.22

The behavior of the *Retailer Inventory* can be observed in Figure 5.15. for different scenarios. The case R9C25 is the initial base run that is conducted with the specified equilibrium conditions. As explained in the previous sections, *Retailer Inventory* experiences a sharp decline in all cases due to the rapid depletion of available stock. Then it starts to increase as new products are received from the manufacturer in response to additional orders placed by the retailer to meet customer demand. Then the inventory level stabilizes and remains relatively constant for a while in R5C5, R9C9, and R9C25. These 3 cases exhibit a similar behavior.

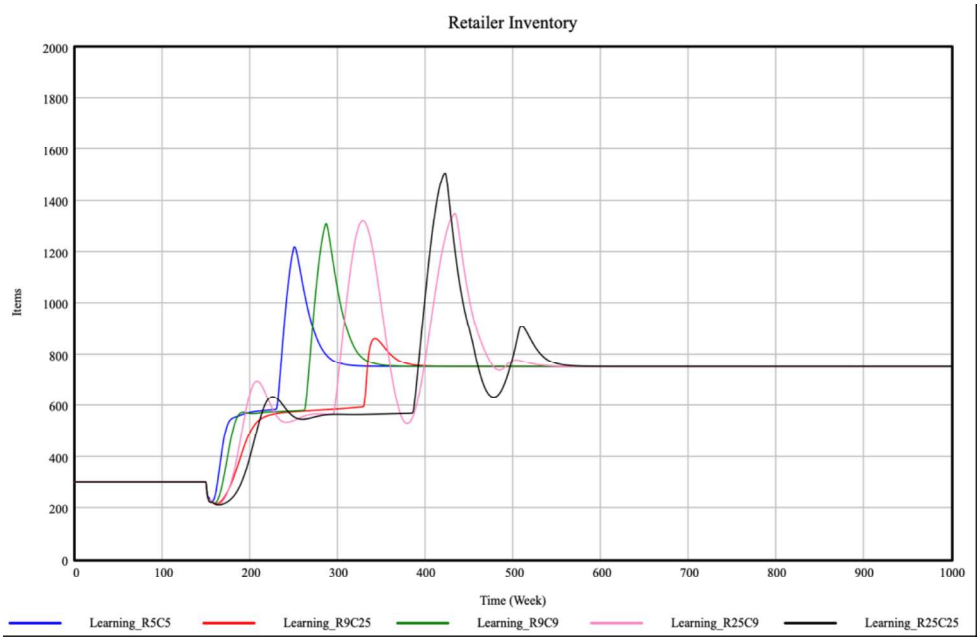

Figure 5.15. 2-echelon model retailer inventory with learning delay scenarios.

The point where there is a sudden increase in *Retailer Inventory* is the time when the demand backlog is finally fulfilled and the products sent to the customers decrease. Then, the Retailer adjusts its orders and the *Retailer Inventory* experiences a decrease over time since it receives fewer products from the manufacturer than it sends to customers. Eventually, the *Retailer Inventory* stabilizes and reaches a new equilibrium aligned with the daily demand. The best scenario for *Retailer Inventory* is when the *Customer Orders Learning Delay* is long and the *Retailer Orders Learning Delay* is short. This means that the retailer quickly becomes aware of the changes in customer demand and adjusts its desired inventory level accordingly while it takes more time for the manufacturer to recognize the changes in Retailer's orders. This scenario allows the retailer to adapt swiftly to fluctuations in demand without being hindered by delays whilst the manufacturer is not affected by the retailer's sudden decisions. This leads to better performance and lower peaks in *Retailer Inventory*. Conversely, long *Retailer Orders Learning Delay* causes high oscillations in *Retailer Inventory.* The Retailer places orders based on customer demand. However, the manufacturer becomes aware of these orders late due to high learning delay leading to discrepancies. The retailer receives either too many or too few products causing high oscillations in its inventory. Also, these cases take longer to stabilize and reach equilibrium compared to other scenarios.

The Retailer Inventory Deviation values provided in Table 5.18. offer insights into the impact of learning delays on inventory management within the supply chain. Shorter learning delays, as seen in scenario R5D5, correspond to lower deviations from the target inventory level, indicating more effective inventory control. In contrast, longer learning delays, such as those in scenarios R25D9 and R25D25, result in higher deviations from the target inventory level.

Table 5.18. 2-echelon model retailer inventory deviation with learning delay scenarios.

	Retailer Inventory Deviation
R5C5	10.41 M
R9C25	14.72 M
R9C9	15.13 M
R25C9	31.97 M
R25C25	33.89 M

Figure 5.16. illustrates the dynamics of *Serviceable Inventory* across different scenarios. When customer demand increases, *Serviceable Inventory* experiences a sharp decline like *Retailer Inventory* in all cases due to the rapid depletion of available stock as explained in previous sections. Then, the manufacturer starts to produce new goods leading to a gradual increase in its inventory. After that, the inventory level stabilizes and remains relatively constant for a while for all scenarios.

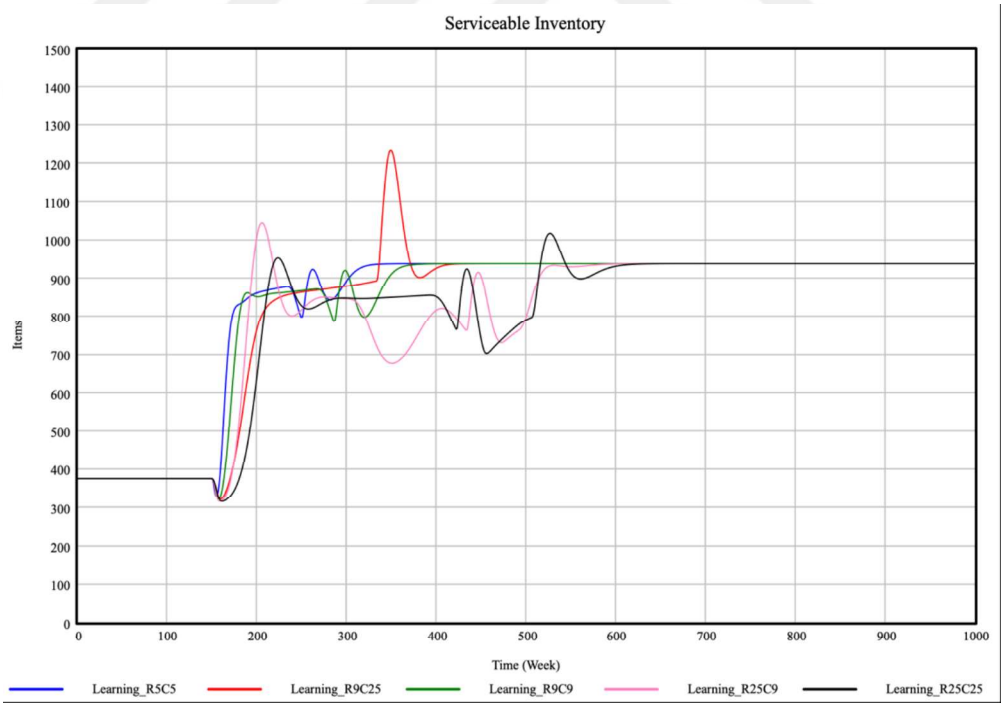

Figure 5.16. 2-echelon model serviceable inventory with learning delay scenarios.

Similar to *Retailer Inventory*, a long *Retailer Orders Learning Delay* causes high oscillations in *Serviceable Inventory*. In the base scenario, the *Serviceable Inventory* experiences a sharp increase and then reaches its new equilibrium level when the *Demand*

Learning Delay is long and the *Retailer Orders Learning Delay* is short. However, in other cases, the *Serviceable Inventory* exhibits oscillations before reaching the new equilibrium.

Table 5.19. illustrates the values of the Serviceable Inventory Deviation with varying learning delays. Shorter learning delays, as observed in scenario R5D5, correspond to lower deviations from the target inventory level, indicating more effective inventory control. Conversely, longer learning delays, such as those in scenarios R25D9 and R25D25, result in higher deviations from the target inventory level.

Table 5.19. 2-echelon model serviceable inventory deviation with learning delay scenarios.

	Serviceable Inventory Deviation
R5C5	5.75 M
R9C25	13.95 M
R9C9	8.57 M
R25C9	18.00 M
R25C25	20.01 M

5.2. Case 2: 3-Echelon Base Run

A simplified stock-flow diagram of the 3-echelon base model was demonstrated in Figure 5.17, depicting the ordering behaviors of the retailer, distributor, and manufacturer, and illustrating the inventory management parameters—inventory adjustment times, shipment delays, and learning delays. In the case of the 3-echelon supply chain, an additional stock comes into play to represent the expanded structure. A distributor is introduced as an intermediary between the manufacturer and the retailer, adding another layer to the distribution network. While the basic principles remain consistent with the 2-echelon case, where the manufacturer supplies the retailer directly, the distributor now plays a crucial role in managing inventory and facilitating the flow of goods. At the beginning of the simulation, the system is in a state of equilibrium just like the 2-echelon case.

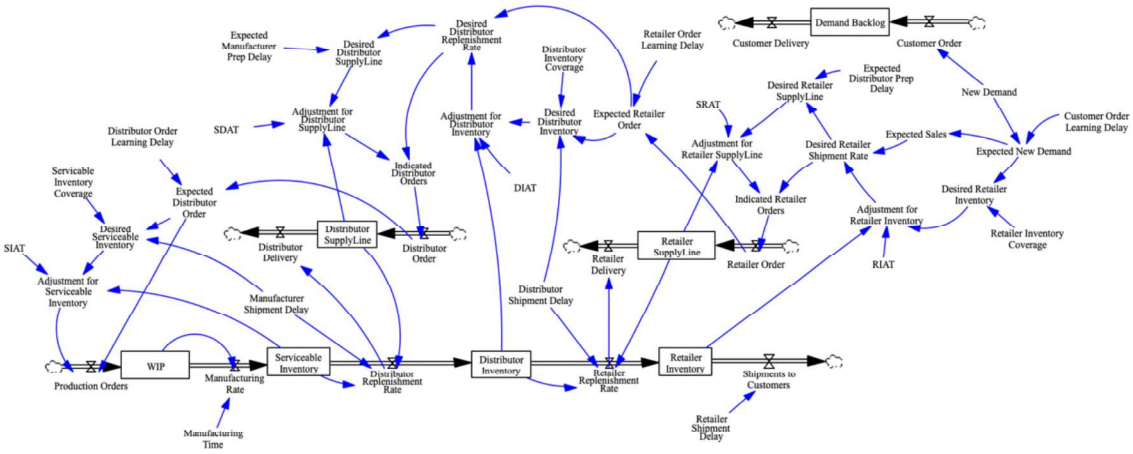

Figure 5.17. 2-echelon model serviceable inventory with learning delay scenarios.

The *Distributor Inventory* starts at 450 items, reflecting the stock available at the distribution level and the *Distributor Supply Line* starts at 100 items signifying there are orders to be fulfilled. All other stocks have the same equilibrium values as the 2-echelon model. The equilibrium values of parameters for the 3-Echelon case are summarized in Table 5.20, providing a baseline for comparison with other scenarios that will be introduced in subsequent sections.

Table 5.20. 3-echelon base model parameter values.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Distributor Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	10 days
Distributor Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days
Distributor Orders Learning Delay	9 days

In the 3-echelon case, a similar approach will be taken to assess the system's response to the sudden increase in customer demand. At t=150 days in the simulation, the demand is expected to experience a step increase from 100 to 250 units per day. Just like in the 2-echelon case, an initial base run will be conducted using the specified equilibrium conditions. This base run will serve as a reference point for evaluating the performance of the supply chain and understanding its initial responsiveness to the increased demand. Subsequent sections will then introduce variations in adjustment times, shipment delays, and learning delays to observe their effects on the system's dynamics. Through this comparative analysis, insights will be gained into how the additional echelon of distribution impacts the supply chain's behavior and efficiency in managing increased customer demand.

In Figure 5.18. the behavior of the *Demand Backlog* is illustrated for the 3-echelon Base Model with the initial configuration. A similar behavior is observed with the 2-echelon case when customer demand undergoes a sudden surge from 100 to 250 units at t=150. As with the 2-echelon case, the Retailer struggles to promptly fulfill the increased demand, resulting in the accumulation of unmet orders in the backlog. However, in the 3-echelon case, the peak point of the backlog is notably higher, indicating a more pronounced accumulation of unmet orders before the system stabilizes.

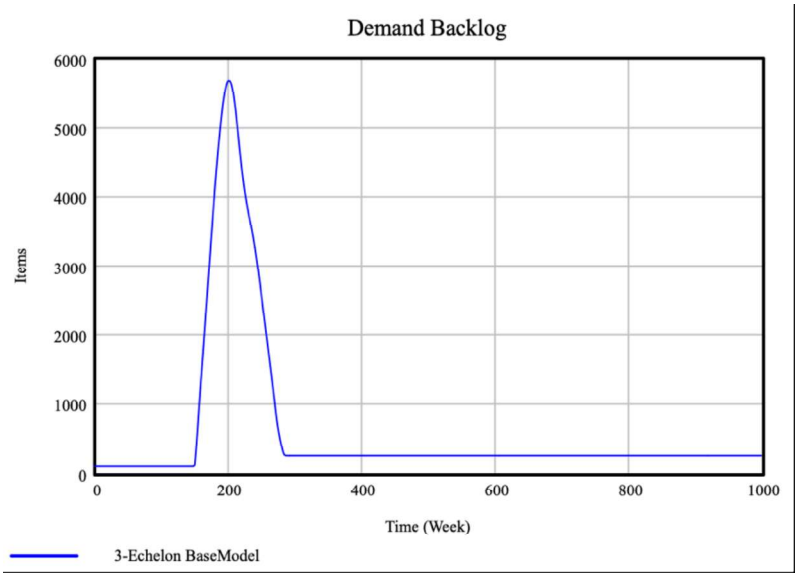

Figure 5.18. 3-echelon base run demand backlog.

In the 3-echelon case, when the demand backlog increases, the retailer adjusts its new *Desired Inventory* accordingly and places additional orders to the distributor, rather than directly to the manufacturer, to replenish its inventory. Subsequently, the Distributor, upon receiving these orders, adjusts its own inventory levels and places additional orders with the manufacturer to fulfill the increased demand. As a result, the Demand Backlog begins to gradually decrease as the additional products flow through the supply chain from the manufacturer to the distributor and finally to the retailer, enabling the fulfillment of outstanding orders at each level.

The average demand backlog is calculated to be 712.58 items per day, which represents the typical backlog of customer demand orders experienced over a defined period. This metric provides insight into the overall responsiveness of the system to fluctuations in demand. The Demand Backlog Depletion Time in the 3-echelon setup is observed to be 294 days, indicating the time it takes for the backlog of customer demand to be completely fulfilled. These metrics serve as reference points for comparison with other scenarios, allowing for the assessment of how changes in inventory adjustment times, shipment delays, and learning delays impact the responsiveness of the supply chain. Together, these metrics offer a comprehensive understanding of the system's ability to manage demand variations efficiently, which is crucial for evaluating its responsiveness and performance in meeting customer needs over time.

In Figure 5.19, the impact of increased customer demand on the *Retailer Inventory* is illustrated. In the 3-echelon case, similar to the 2-echelon scenario, the *Retailer Inventory* experiences a sharp decline due to the rapid depletion of available stock when customer demands increase. Similar to the 2-echelon case, the initial decrease at t=150 days in Figure 5.18 can be referred to as the Retailer's Stock Shortage Crisis Phase.

However, in this more complex setup, the inventory oscillates before gradually increasing. Initially, the distributor ships its available stock to the retailer. As the distributor typically maintains more stock than the daily demand, it ships additional products to the retailer, leading to a slight increase in the *Retailer Inventory*. However, this increase is insufficient to fulfill the demand, resulting in a subsequent decrease in inventory levels and creating minor oscillations. Recognizing the ongoing insufficiency in inventory levels, the

retailer places additional orders with the distributor. Subsequently, the *Retailer Inventory* starts to increase gradually as new products are received from the distributor.

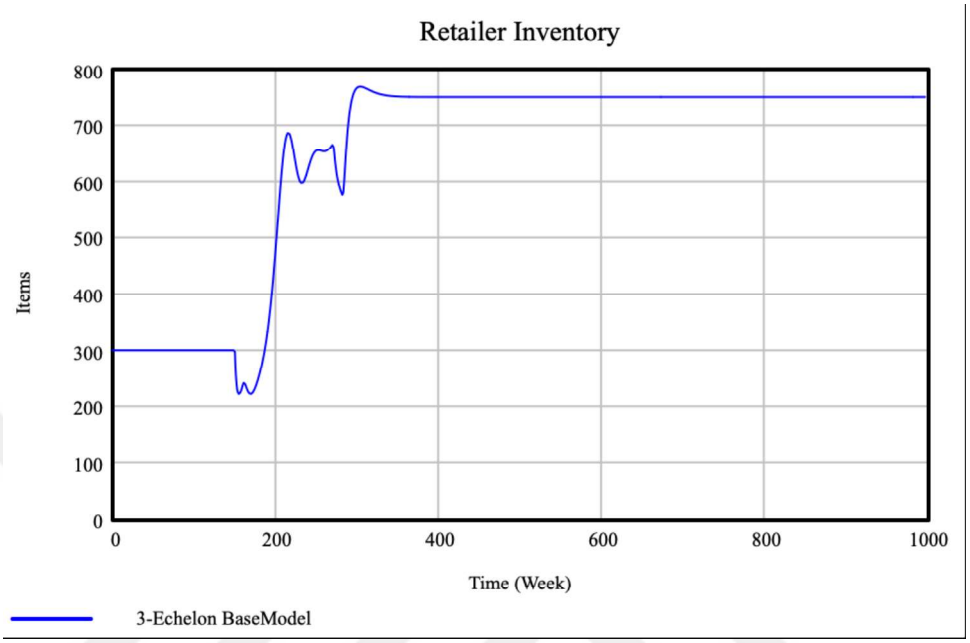

Figure 5.19. 3-echelon base run retailer inventory.

In the 2-echelon setup, the inventory remains stable for a while after the sudden increase. However, in the 3-echelon case, *Retailer Inventory* experiences oscillations after the increase between 200 and 300 days due to instabilities in distributor and manufacturer inventories. Similar to the 2-echelon scenario, the retailer considers the maximum possible shipments and demand backlog when sending products to customers. As the *Retailer Inventory* increases to a higher level, the retailer adjusts its orders downward, prompting a similar response from the distributor. Consequently, manufacturing activities decrease, affecting the first serviceable inventory, followed by the distributor and finally the retailer. However, as the retailer's inventory declines to insufficient levels, it increases its orders once again, initiating a cycle of oscillations.

The final increase in *Retailer Inventory* occurs when the backlogs are fulfilled at t=300, and shipments to customers decrease accordingly. This is referred to as the Back-to-normal phase. A similar pattern emerges as in the 2-echelon case as backlogs are fulfilled and the retailer adjusts its shipments to match daily demand. As the retailer successfully fulfills customer demands, its inventory surpasses the necessary levels, prompting it to

reduce orders to avoid overstocking. Consequently, *Retailer Inventory* experiences slight decreases over time as fewer products are received from the distributor that are sent to customers, eventually stabilizing at a new equilibrium aligned with daily demand. Once the retailer achieves its new equilibrium, it maintains this balanced state without further adjustments.

A sharp decline in the *Distributor Inventory* is observed at t=150 days in Figure 5.20 due to the rapid depletion of available stock when faced with increased retailer demand. Since the manufacturer typically does not maintain significantly more stock than the daily demand, the *Distributor Inventory* does not increase and oscillate as observed with the retailer's inventory. Instead, the distributor gives orders to the manufacturer to address the need for replenishment. Consequently, the *Distributor Inventory* begins to increase steadily as new products are received from the manufacturer.

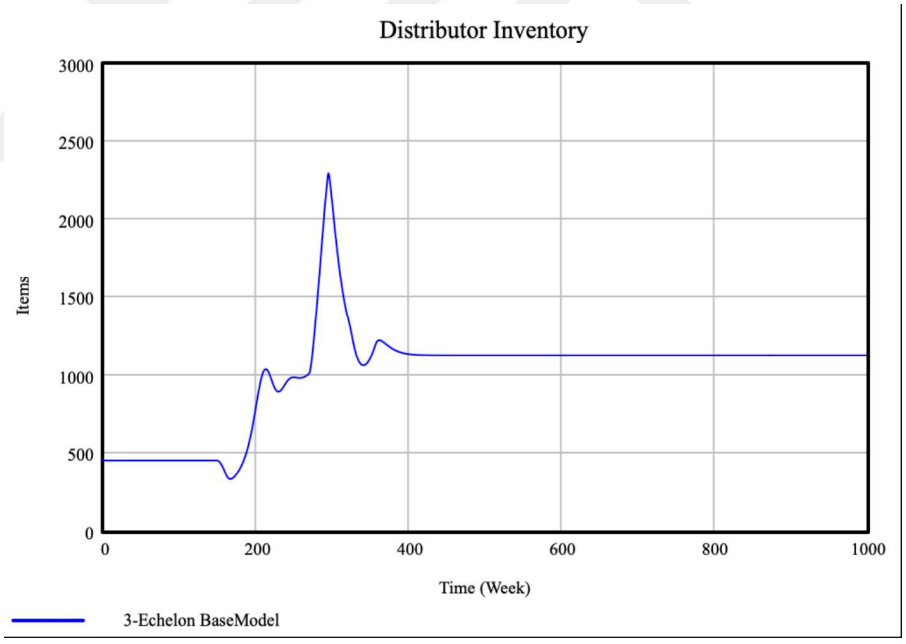

Figure 5.20. 3-echelon base run distributor inventory.

The distributor considers the maximum possible shipments and retailer supply line when sending products to the retailer. In parallel with the retailer's actions, the distributor also adjusts its orders and shipments accordingly, leading to oscillations in the *Distributor Inventory* as it responds to fluctuations in retailer demand. The highest increase in *Distributor Inventory* occurs when the retailer supply line is fulfilled, leading to a decrease

in shipments to the retailer while shipments from the manufacturer to the distributor remain constant. As the distributor successfully fulfills the retailer demand, its inventory surpasses the necessary levels, prompting adjustments to orders to avoid overstocking. Consequently, distributor inventory experiences slight decreases over time as fewer products are received from the manufacturer that are sent to the retailer, eventually stabilizing at a new equilibrium aligned with retailer demand. The distributor's inventory level reaches significantly higher points compared to those of the retailer and manufacturer.

Similarly, a sharp decline in the *Serviceable Inventory* is depicted at t=150 days in Figure 5.21, resulting from the rapid depletion of available stock in response to increased distributor demand. The manufacturer initiates production orders to address the surge in demand. As newly manufactured products are added to the inventory, the *Serviceable Inventory* begins to increase ensuring a consistent supply to meet distributor requirements.

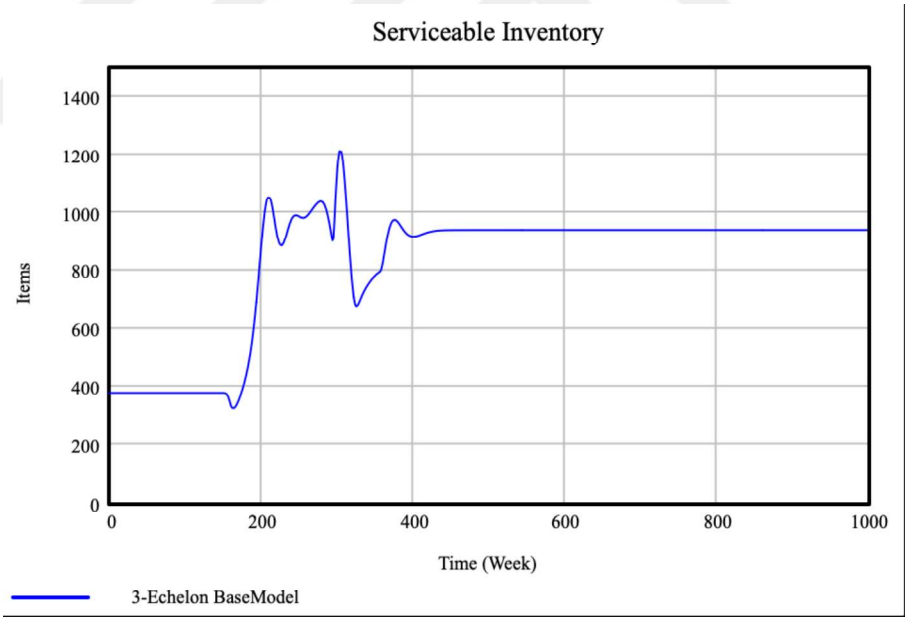

Figure 5.21. 3-echelon base run serviceable inventory.

The manufacturer considers the maximum possible shipments and distributor supply line when sending products to the distributor. In parallel with the distributor's actions, the manufacturer also adjusts its orders and shipments accordingly, leading to oscillations in the *Serviceable Inventory* as it responds to fluctuations in distributor demand.

After the oscillation period, the *Serviceable Inventory* experiences its final increase when the distributor supply line is fulfilled, leading to a decrease in shipments to the distributor. As the manufacturer effectively meets distributor demands, its inventory surpasses the necessary levels, prompting adjustments to production to prevent overstocking. Consequently, the *Serviceable Inventory* undergoes slight decreases over time as fewer products are produced that are sent to distributors, ultimately stabilizing at a new equilibrium aligned with distributor demand.

For the 3-echelon case, the Retailer Inventory deviation, recorded at 12.82 M, the Distributor Inventory deviation, at 49.53 M, and the Serviceable Inventory deviation, at 15.42 M, serve as benchmarks for comparison against other scenarios. These values, on their own, may not provide significant insights but are crucial for evaluating the relative performance of different supply chain scenarios.

5.2.1. Case 2.1: Inventory Adjustment Time Scenarios

In this section, the impact of inventory adjustment times will be observed, similar to Case 1.1 in the 2-echelon model.

Table 5.21. 3-echelon model parameter values at inventory adjustment time scenarios.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Distributor Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	**5,10,20 days**
Distributor Inventory Adjustment Time	**5,10,20 days**
Retailer Inventory Adjustment Time	**5,10,20 days**
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days
Distributor Orders Learning Delay	9 days

The equilibrium values of all parameters are tabulated in Table 5.21., with only inventory adjustment times being altered, featuring values of 5, 10, and 20 highlighted in bold. Through several simulations, how different scenarios affect the manufacturer, distributor, and retailer will be investigated with each subjected to short, medium, and long adjustment times.

Table 5.22. illustrates the different combinations of adjustment times for Retailer, Distributor, and Manufacturer inventories. The letters "R", “D”, and "S" correspond to Retailer Inventory, Distributor Inventory, and Serviceable Inventory, respectively, while the numbers denote the adjustment times in days. For instance, in the case of "R5D10S20," the Retailer Inventory Adjustment Time is 5 days, the Distributor Inventory Adjustment Time is 10 days, and the Serviceable Inventory Adjustment Time is 20 days.

Table 5.22. 3-echelon model retailer, distributor, and serviceable inventory adjustment times (days).

	Retailer Inventory Adjustment Time (days)	**Distributor Inventory Adjustment Time (days)**	**Serviceable Inventory Adjustment Time (days)**
R5D5S5	5	5	5
R5D10S20	5	10	20
R10D10S10	10	10	10
R20D10S5	20	10	5
R20D20S20	20	20	20

In the 3-echelon model, the behavior of the *Demand Backlog* closely mirrors the 2-echelon case, as observed in Figure 5.22. When customer demand undergoes a sudden surge from 100 to 250 at t=150, the *Demand Backlog* experiences a sharp increase across all scenarios due to inadequate stock levels. However, similar to the 2-echelon case, the extent of the increase and the peak varies depending on the behaviors of the retailer, distributor, and manufacturer.

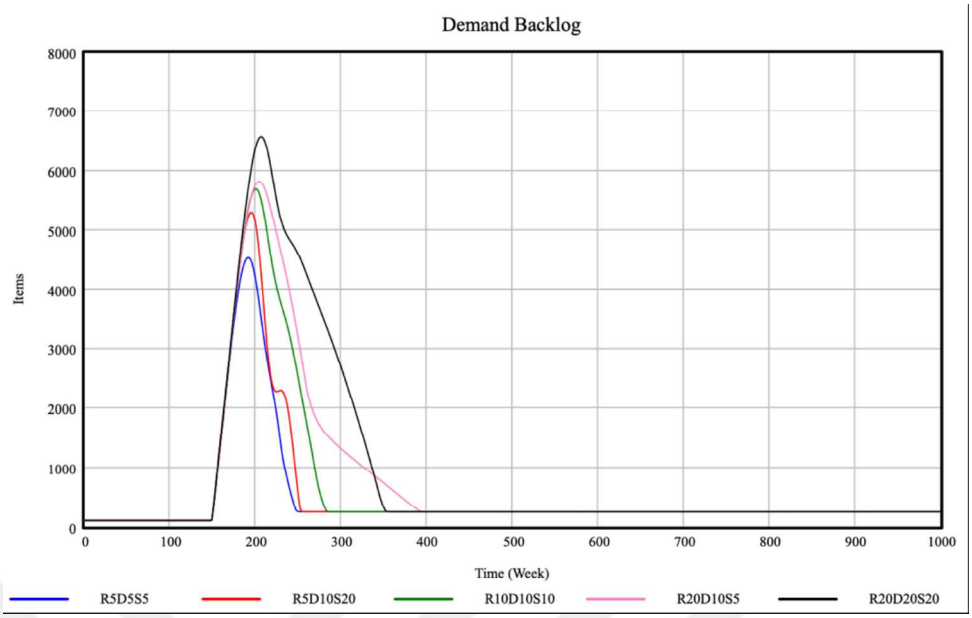

Figure 5.22. 3-echelon model demand backlog with inventory adjustment time scenarios.

The minimum peak in the *Demand Backlog* is observed when all actors have short inventory adjustment times just like the 2-echelon case. This scenario highlights the high responsiveness of all actors to changes in inventory levels, resulting in rapid adjustments. As a consequence, this case reaches the new equilibrium faster compared to others. When all actors have longer inventory adjustment times, the response to demand change is slower. Consequently, the highest accumulation of *Demand Backlog* and peak occurs in this case due to slow adaptation. However, unlike the 2-echelon case, this isn't the slowest scenario to reach the new equilibrium state. The slowest scenario in this regard is R20D10S5 – Rapid Retailer, Delayed Distributor, and Sluggish Manufacturer. *Demand Backlog* starts to decrease gradually as additional products are received from the manufacturer and the retailer can fulfill the outstanding orders.

The Average Demand Backlog values for various adjustment times are provided in Table 5.23. Compared to the 2-echelon setup, all cases in the 3-echelon model reach equilibrium more rapidly. Consequently, the average demand backlogs across these scenarios are smaller.

Table 5.23. 3-echelon model average demand backlog with inventory adjustment time scenarios.

	Average Demand Backlog (Items/Day)
R5D5S5	550.294
R5D10S20	598.357
R10D10S10	712.583
R20D10S5	842.211
R20D20S20	992.886

When inventory adjustment times are longer, the average demand backlog tends to be higher. The lowest average demand backlog is when all actors have short inventory adjustment times and behave highly responsive to changes. A small average demand backlog is beneficial for maintaining customer satisfaction, indicating that the supply chain is effectively meeting customer demand without excessive delays. The highest is when they are both slow to respond which is also the highest peak.

The Demand Backlog Depletion Times are provided in Table 5.24. for various adjustment times. The Demand Backlog Depletion Time represents the time it takes for the backlog of customer demand to be completely fulfilled in each scenario.

Table 5.24. 3-echelon model demand backlog depletion times with inventory adjustment time scenarios.

	Demand Backlog Depletion Time (days)
R5D5S5	259.09
R5D10S20	264.59
R10D10S10	294
R20D10S5	406.15
R20D20S20	363.18

The results are compared with the base case R10D10S10 to assess the impact of inventory adjustment times on the responsiveness of the supply chain. For instance, R5D5S5 has the shortest depletion time of 259.09 days, indicating high responsiveness. This indicates a more responsive supply chain compared to the base case, as demand can be fulfilled

quickly within a shorter timeframe. As the adjustment times for all actors increase, the depletion time also increases, suggesting a slower response to demand fluctuations.

The behavior of the *Retailer Inventory* can be observed in Figure 5.23. for different scenarios. The case R10D10S10 is the initial base run that is conducted with the specified equilibrium conditions. In scenarios R5D5S5 and R20D20S20, the behavior of the *Retailer Inventory* closely mirrors that of R10D10S10. The main difference is the time it takes for each scenario to reach equilibrium. With shorter adjustment times in R5D5S5, equilibrium is achieved more rapidly, while in R20D20S20, characterized by longer adjustment times, the process of reaching equilibrium is comparatively slower. Despite these differences in adjustment times, the fundamental behavior of the *Retailer Inventory* remains the same across these scenarios.

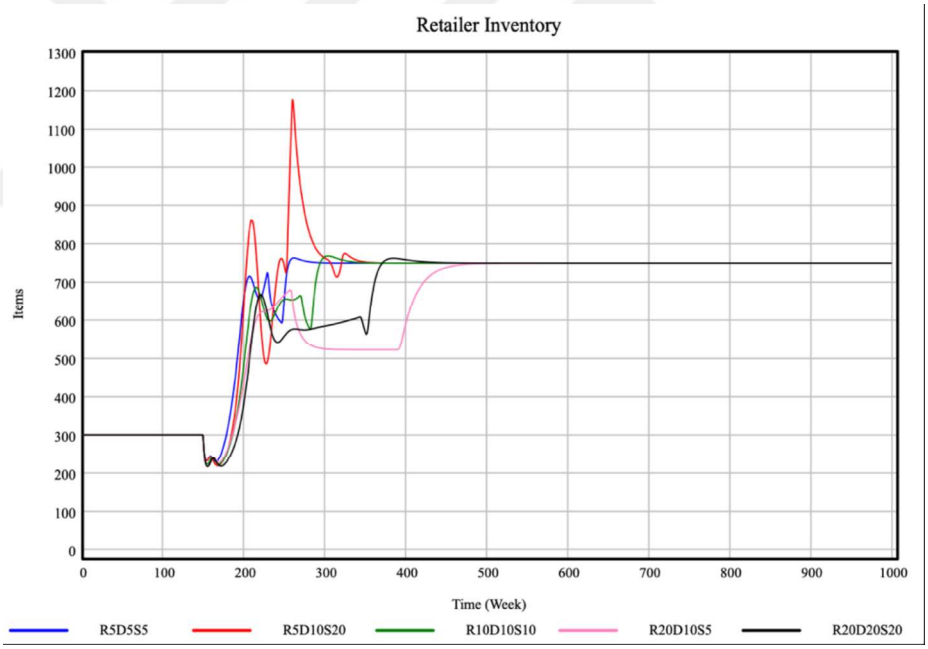

Figure 5.23. 3-echelon model retailer inventory with inventory adjustment time scenarios.

When the retailer has a long inventory adjustment time, the behavior is similar at first. Then a different pattern emerges, characterized by a notable decrease in the *Retailer Inventory.* Furthermore, the *Retailer Inventory* does not experience a sudden increase when backlogs are depleted, it reaches the new equilibrium level more smoothly. Since the upstream echelons are more responsive than the retailer, the *Retailer Inventory* is replenished more efficiently, leading to a steadier transition to the new equilibrium level.

In R5D10S20, the behavior of the *Retailer Inventory* is different from other scenarios. High oscillations can be observed in Figure 5.22. When the retailer rapidly adjusts its orders based on fluctuating demand, but upstream actors are slow to respond, it creates an imbalance within the supply chain. The rapid adjustments made by the retailer can lead to fluctuations in inventory levels further upstream. However, since the upstream actors have longer adjustment times, they cannot immediately adapt to these changes. As a result, the supply chain experiences disruptions, as it tries to reconcile the mismatch between demand and supply.

The Retailer Inventory Deviation values are summarized in Table 5.25. R5D5S5 exhibits the lowest deviation at 9.87 M, suggesting relatively accurate inventory control when all actors have short adjustment times. Specifically, longer adjustment times, such as R20D10S5 and R20D20S20, correspond to higher deviations from the target inventory level due to fluctuations.

Table 5.25. 3-echelon model retailer inventory deviation with inventory adjustment time scenarios.

	Retailer Inventory Deviation
R5D5S5	9.87 M
R5D10S20	13.45 M
R10D10S10	12.82 M
R20D10S5	19.71 M
R20D20S20	17.37 M

The behavior of the *Distributor Inventory* can be observed in Figure 5.24. for different scenarios. In scenarios except for R5D10S20, the behavior of the *Distributor Inventory* closely mirrors that of the base run. When adjustment times are longer, as seen in R20D20S20, the process of reaching equilibrium tends to be slower compared to scenarios with shorter adjustment times. However, in the case of R5D10S20, the behavior is different from the typical pattern observed in the base run, and high oscillations are observed just like in the *Retailer Inventory.*

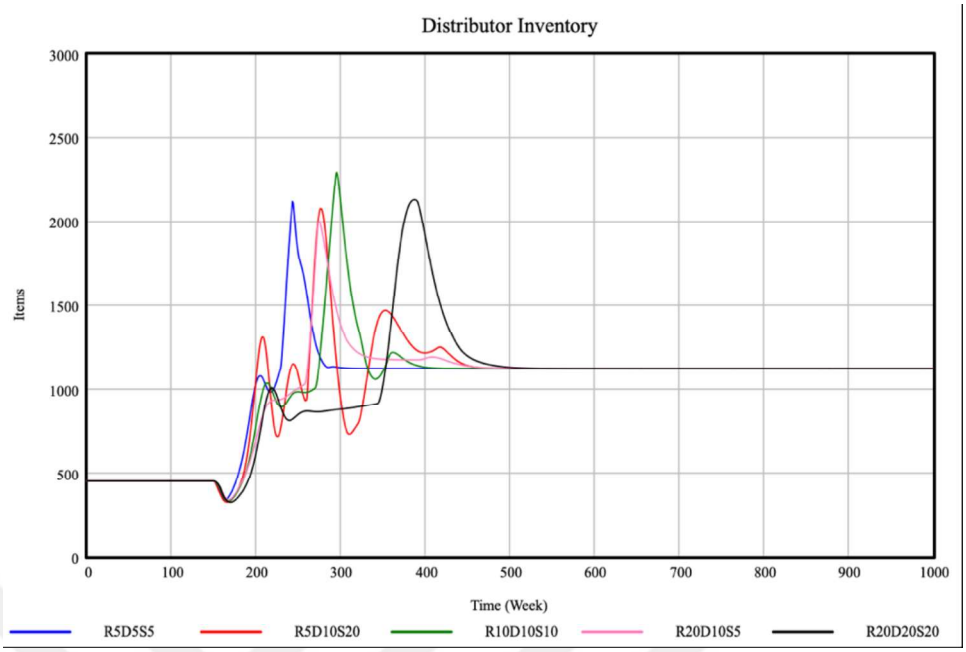

Figure 5.24. 3-echelon model distributor inventory with inventory adjustment time scenarios.

The Distributor Inventory Deviation values are outlined in Table 5.26. indicate varying degrees of deviation from the target inventory level across different scenarios. For instance, R5D5S5 exhibits the lowest deviation at 33.75 M, suggesting relatively accurate inventory control when all actors have short adjustment times. Conversely, longer adjustment times, such as R20D20S20, correspond to higher deviations from the target inventory level due to fluctuations. The Distributor Inventory Deviation values are generally higher compared to the Retailer Inventory Deviation values. This suggests that distributors experience more significant fluctuations in inventory levels compared to retailers.

Table 5.26. 3-echelon model distributor inventory deviation with inventory adjustment time scenarios.

	Distributor Inventory Deviation
R5D5S5	33.75 M
R5D10S20	45.79 M
R10D10S10	49.53 M
R20D10S5	40.04 M
R20D20S20	72.13 M

The behavior of the *Serviceable Inventory* can be observed in Figure 5.25. for different scenarios. In scenarios except for R5D10S20, the behavior of the *Serviceable Inventory* closely mirrors that of the base run. While oscillations are present in the base run, they are more pronounced in the R5D10S20 scenario.

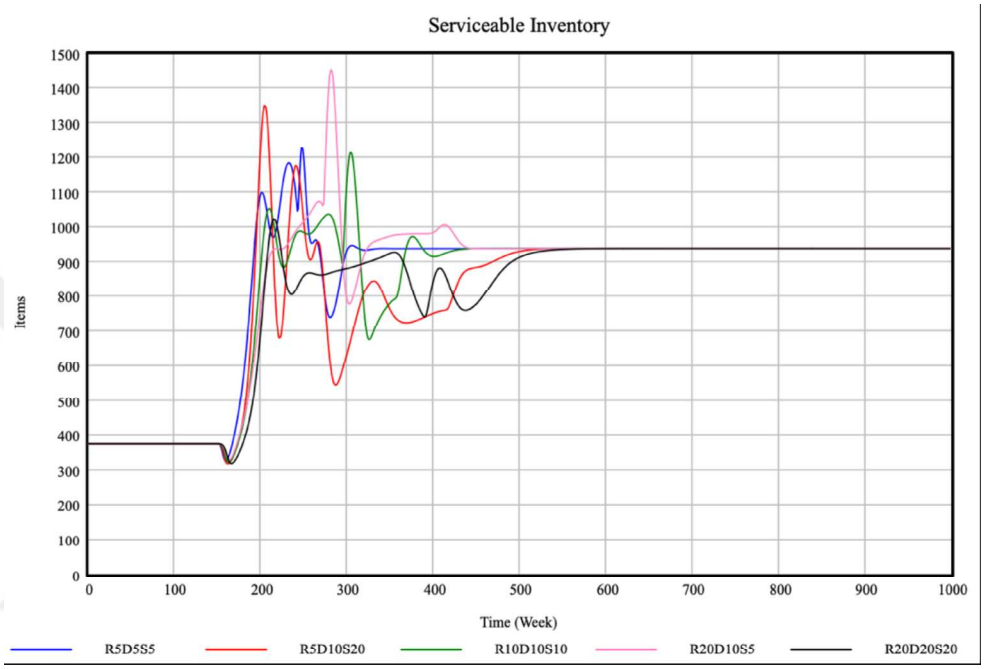

Figure 5.25. 3-echelon model serviceable inventory with inventory adjustment time scenarios.

The Serviceable Inventory Deviation values are summarized in Table 5.27. R5D5S5 exhibits the lowest deviation at 9.87 M while longer adjustment times, such as correspond to higher deviations from the target inventory level due to fluctuations. In comparison to both Retailer Inventory and Distributor Inventory Deviation values, Serviceable Inventory Deviation values generally fall within an intermediate range.

Table 5.27. 3-echelon model serviceable inventory deviation with inventory adjustment time scenarios.

	Serviceable Inventory Deviation
R5D5S5	12.13 M
R5D10S20	22.02 M
R10D10S10	15.42 M
R20D10S5	16.46 M
R20D20S20	17.54 M

5.2.2. Case 2.2: Shipment Delay Scenarios

The impact of learning delays will be observed in this section, similar to Case 1.2 in the 2-echelon model. The equilibrium values of all parameters are tabulated in Table 5.28., with only shipment delays being altered, featuring values of 1, 2, 3, and 5 highlighted in bold. How different scenarios affect the manufacturer, distributor, and retailer will be investigated through several simulations. Short, medium, and long shipment delays will be considered for *Manufacturer Shipment Delay, Distributor Shipment Delay, and Retailer Shipment Delay*.

Table 5.28. 3-echelon model parameter values at shipment delay scenarios.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	**1,2,3,5 days**
Distributor Shipment Delay	**1,2,3,5 days**
Retailer Shipment Delay	**1,2,3,5 days**
Serviceable Inventory Adjustment Time	10 days
Distributor Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	25 days
Retailer Orders Learning Delay	9 days
Distributor Orders Learning Delay	9 days

Different combinations of shipment delays for *Manufacturer Shipment Delay, Distributor Shipment Delay, and Retailer Shipment Delay* are illustrated in Table 5.29. The letters "R", "D", and "S" correspond to Retailer Shipment Delay, Distributor Shipment Delay, and Manufacturer Shipment Delay, respectively, while the numbers denote the shipment delays in days. For instance, in the case of "R3D3S2," the *Retailer Shipment Delay* is 3 days, the *Distributor Shipment Delay* is 3 days, and the Manufacturer Shipment Delay is 2 days.

Table 5.29. 3-echelon model retailer, distributor, and serviceable inventory shipment delays (days).

	Retailer Shipment Delay (days)	**Distributor Shipment Delay (days)**	**Manufacturer Shipment Delay (days)**
R1D1S1	1	1	1
R2D3S3	2	3	3
R3D3S3	3	3	3
R3D3S2	3	3	2
R5D5S5	5	5	5

The behavior of the *Demand Backlog* follows a consistent pattern across different cases, as depicted in Figure 5.26. The behavior in 3-echelon closely mirrors that of 2-echelon scenarios. When customer demand suddenly rises from 100 to 250 at t=150, the *Demand Backlog* sharply increases across all cases due to insufficient stock. However, variations in the extent of the increase and the peak occur based on the behavior of the retailer, distributor, and manufacturer.

The dynamics described for scenarios with low and long shipment delays in 2-echelon supply chains are also applicable to 3-echelon configurations. In both cases, low shipment delays facilitate rapid transportation of products from manufacturers to retailers. However, when faced with a sudden surge in demand, the supply chain struggles to restock inventory swiftly, resulting in a notable increase in demand backlog as can be seen in Figure 5.26. Conversely, longer shipment delays provide the supply chain with a greater buffer in the form of larger safety stock levels, enabling it to absorb the shock of increased demand more effectively. Consequently, despite the longer transit times associated with long shipment

delays, 3-echelon supply chains experience a lower surge in demand backlog compared to scenarios with shorter shipment delays.

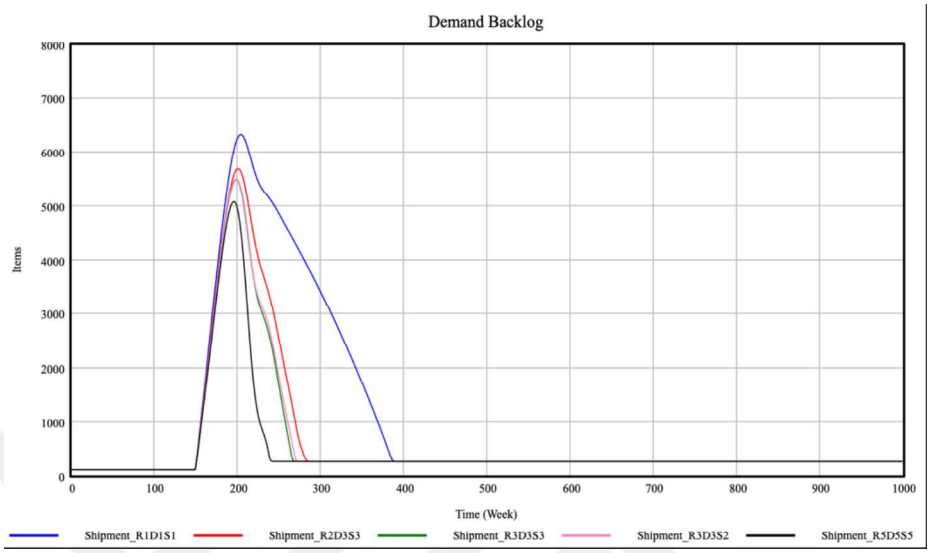

Figure 5.26. 3-echelon model demand backlog with shipment delay scenarios.

The Average Demand Backlog values for various shipment delays are provided in Table 5.30. The values are calculated by integrating the demand backlog over time and dividing it by the total number of days just like in the 2-echelon case.

Table 5.30. 3-echelon model average demand backlog with shipment delay scenarios.

	Average Demand Backlog (Items/Day)
R1D1S1	1098.27
R2D3S3	712.583
R3D3S3	653.284
R3D3S2	661.056
R5D5S5	546.376

In 3-echelon supply chain configurations, a similar trend is observed regarding the impact of shipment delays on the average demand backlog. When shipment delays are shorter, the average demand backlog tends to be higher. Conversely, the lowest average demand backlog is when all actors have long shipment delays. This observation aligns with

the finding that the minimum peak in *Demand Backlog* occurs when all actors have long shipment delays and it is the fastest case to reach the new equilibrium.

Table 5.31. 3-echelon model demand backlog depletion time with shipment delay scenarios.

	Demand Backlog Depletion Time (days)
R1D1S1	397.34
R2D3S3	294
R3D3S3	277.93
R3D3S2	281.68
R5D5S5	250.93

Demand Backlog Depletion Times are demonstrated in Table 5.31. In the 3-echelon scenario, shorter depletion times correspond to increased responsiveness, exemplified by the R5D5S5 configuration with the shortest depletion time of 250.93 days. Conversely, the R1D1S1 setup exhibits a longer depletion time of 397.34 days, implying lower responsiveness. Similar to the 2-echelon case, shorter shipment delays contribute to higher demand backlog levels, prolonging the time needed to fulfill customer orders in three-echelon supply chains.

The behavior of the *Retailer Inventory* can be observed in Figure 5.27. for different scenarios. The case R2D3S3 is the initial base run that is conducted with the specified equilibrium conditions. In the 3-echelon setup, the behavior of the *Retailer Inventory* diverges slightly from the 2-echelon case. While the dynamics largely mirror those of the base run, with similar responses to demand fluctuations and ordering adjustments, there is a notable difference in the stable period. Following a surge in customer demand at t=150, *Retailer Inventory* experiences a sharp decline, followed by a gradual increase as the retailer replenishes stock. After that, the *Retailer Inventory* stabilizes for a period as replenishment matches shipments until the demand backlog is met in the 2-echelon case. Unlike the 2-echelon scenario, the *Retailer Inventory* oscillates in that period in the 3-echelon configuration. However, it's important to note that in the R1D1S1 case, oscillations are absent, aligning more closely with the behavior observed in the 2-echelon setup. Subsequently, Retailer Inventory undergoes a sudden increase when the demand backlog is

fulfilled, prompting the retailer to adjust orders to prevent overstocking. This leads to a decrease, ultimately stabilizing at a new equilibrium aligned with daily demand.

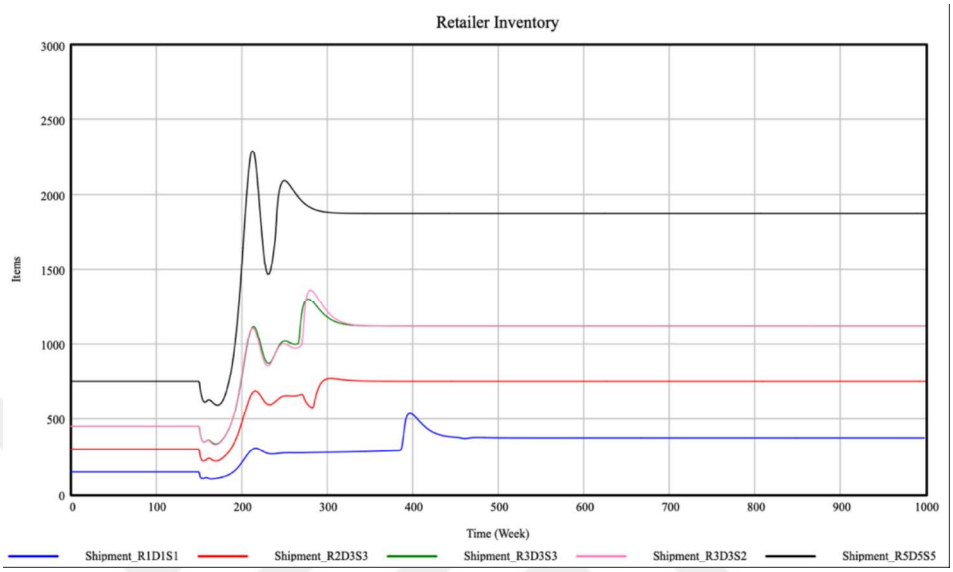

Figure 5.27. 3-echelon model retailer inventory with shipment delay scenarios.

Similar to the 2-echelon case, in scenarios with long shipment delays, the *Retailer Inventory* peaks higher due to extended lead times, allowing for increased desired inventory levels and surplus stock accumulation. Conversely, shorter shipment delays result in lower *Retailer Inventory* levels due to reduced transit times and diminished buffer stock. In the R1D1S1 scenario, the peak occurs later compared to others, signifying a delayed depletion of the demand backlog.

Table 5.32. 3-echelon model retailer inventory deviation with shipment delay scenarios.

	Retailer Inventory Deviation
R1D1S1	5.17 M
R2D3S3	12.82 M
R3D3S3	27.25 M
R3D3S2	28.04 M
R5D5S5	68.78 M

The Retailer Inventory Deviation values provided in Table 5.32. for the 3-echelon case reveals a similar trend to the 2-echelon scenarios. Specifically, longer shipment delays

correspond to higher deviations from the target inventory level due to fluctuations. R5D5S5 exhibits the highest deviation, indicating substantial inventory variability attributed to extended shipment delays. Conversely, R1D1S1 shows the lowest deviation, implying more consistent inventory management with shorter delays.

The behavior of the *Distributor Inventory* follows a similar trajectory to that of both the Retailer and Manufacturer Inventory in response to changes in customer demand as can be seen in Figure 5.28. Initially, it experiences a sharp decline as demand surges, mirroring the rapid depletion seen in other inventory levels. As the distributor receives additional products from the manufacturer to replenish stock, its inventory begins to increase gradually. However, the *Distributor Inventory* exhibits higher oscillations as it increases to very high levels. These oscillations are more pronounced compared to other actors in the supply chain. Distributor Inventory undergoes a sudden increase when the retailer's supply line is fulfilled, prompting adjustments in orders to prevent overstocking. This leads to a subsequent decrease, eventually stabilizing at a new equilibrium aligned with daily demand.

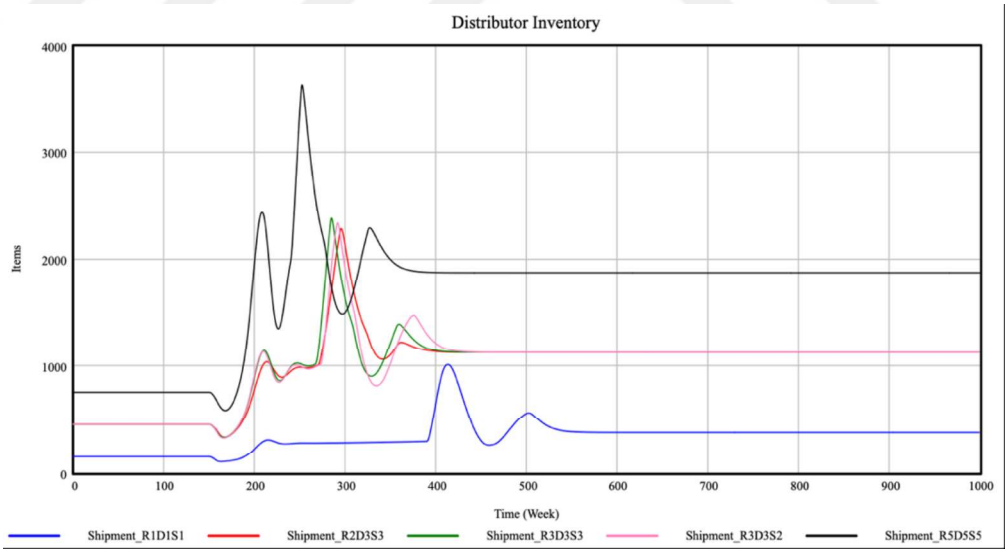

Figure 5.28. 3-echelon model distributor inventory with shipment delay scenarios.

Just as Retailer Inventory peaks higher due to extended lead times, allowing for increased desired inventory levels and surplus stock accumulation, Distributor Inventory experiences similar dynamics. Conversely, shorter shipment delays result in lower levels of Distributor Inventory due to reduced transit times and diminished buffer stock. In R1D1S1,

the peak occurs later compared to others, indicating a delayed depletion of the demand backlog.

The Distributor Inventory Deviation values are provided in Table 5.33. for the 3-echelon. Specifically, longer shipment delays correspond to higher deviations from the target inventory level due to fluctuations. R5D5S5 exhibits the highest deviation. Conversely, R1D1S1 shows the lowest deviation, implying more consistent inventory management with shorter delays.

Table 5.33. 3-echelon model distributor inventory deviation with shipment delay scenarios.

	Distributor Inventory Deviation
R1D1S1	14.33 M
R2D3S3	49.52 M
R3D3S3	48.45 M
R3D3S2	51.08 M
R5D5S5	108.86 M

The behavior of the *Serviceable Inventory* in the 3-echelon configurations is depicted in Figure 5.29. and it closely resembles that of the 2-echelon scenarios. Across all cases, the *Serviceable Inventory* exhibits consistent dynamics in response to changes in customer demand. Similar to the 2-echelon setup, when customer demand surges at t=150, *Serviceable Inventory* experiences a sharp decline due to rapid stock depletion. As the manufacturer ramps up production to meet demand, *Serviceable Inventory* gradually increases. However, unlike the 2-echelon case, the Serviceable Inventory in the 3-echelon setup does not stabilize thereafter; instead, it oscillates, reflecting the added complexity introduced by the additional echelon. It's notable that in both 2-echelon and 3-echelon setups, the highest oscillations in *Serviceable Inventory* occur when shipment delays are long, reflecting the challenges posed by extended transit times.

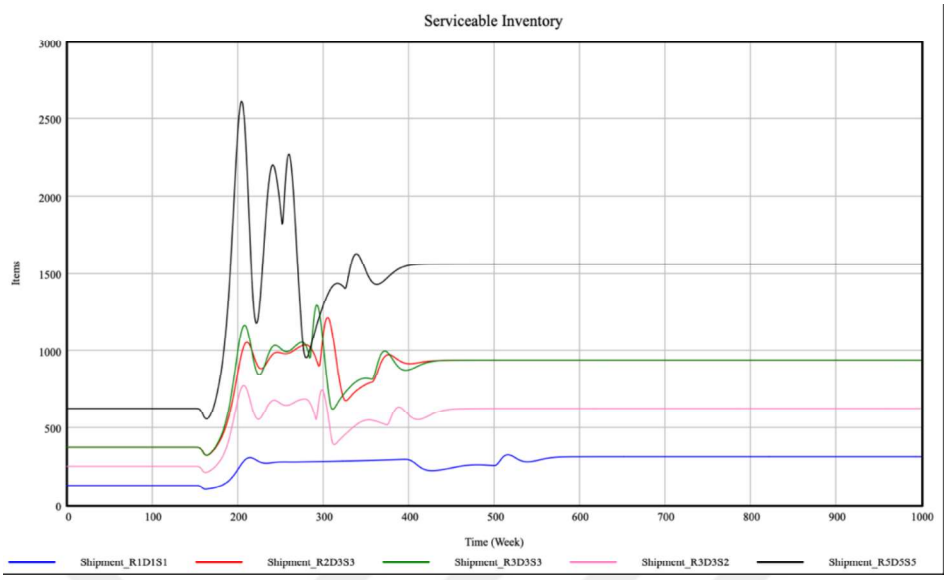

Figure 5.29. 3-echelon model serviceable inventory with shipment delay scenarios.

In instances with long shipment delays, the peaks in *Serviceable Inventory* are notably higher compared to short delays. Just like in the 2-echelon setup, *Serviceable Inventory* experiences fluctuations in response to changes in customer demand. However, the extent of these fluctuations varies across scenarios as can be seen from Figure 5.28. For instance, in scenario R1D1S1, which represents short shipment delays for all actors, *Serviceable Inventory* exhibits the lowest deviation from the target, suggesting relatively stable inventory levels. Conversely, scenario R5D5S5, characterized by long shipment delays, demonstrates the highest deviation, indicating more significant fluctuations in Serviceable Inventory.

Table 5.34. 3-echelon model serviceable inventory deviation with shipment delay scenarios.

	Serviceable Inventory Deviation
R1D1S1	2.33 M
R2D3S3	15.42 M
R3D3S3	16.32 M
R3D3S2	7.27 M
R5D5S5	59.44 M

5.2.3. Case 2.3: Learning Delay Scenarios

In this section, the impact of learning delays will be observed, similar to Case 1.3 in the 2-echelon model. The equilibrium values of all parameters are tabulated in Table 5.35., with only learning delays being altered, featuring values of 5, 9, and 25 highlighted in bold. Through several simulations, how different scenarios affect the manufacturer, distributor, and retailer will be investigated. Short, medium, and long delays will be considered for *Customer Orders Learning Delay, Retailer Orders Learning Delay, and Distributor Orders Learning Delay*.

Table 5.35. 3-echelon model parameter values at learning delay scenarios.

Parameters	**Values**
Manufacturing Time	5 days
Manufacturer Shipment Delay	3 days
Distributor Shipment Delay	3 days
Retailer Shipment Delay	2 days
Serviceable Inventory Adjustment Time	10 days
Distributor Inventory Adjustment Time	10 days
Retailer Inventory Adjustment Time	10 days
Customer Orders Learning Delay	**5,9,25 days**
Retailer Orders Learning Delay	**5,9,25 days**
Distributor Orders Learning Delay	**5,9,25 days**

Table 5.36. illustrates the different combinations of learning delays for *Customer Orders Learning Delay, Retailer Orders Learning Delay, and Distributor Orders Learning Delay.* The letters "D", "R", and "C" correspond to Distributor Orders, Retailer Orders, and Customer Orders, respectively, while the numbers denote the learning delays in days. For instance, in the case of "D9R9C25," the *Distributor Orders Learning Delays* is 9 days, the Retailer *Orders Learning Delays* is 9 days, and the *Customer Orders Learning Delays* is 25 days.

Table 5.36. 3-echelon model distributor orders, retailer orders, and customer orders learning delays.

	Distributor Orders Learning Delay (days)	Retailer Orders Learning Delay (days)	Customer Orders Learning Delay (days)
D5R5C5	5	5	5
D9R9C25	9	9	25
D9R9C9	9	9	9
D25R25C9	25	25	9
D25R25C25	25	25	25

Demand Backlog follows a similar pattern across different cases at first, as can be seen from Figure 5.30. As explained in the previous sections, when customer demand suddenly increases, the *Demand Backlog* experiences a sharp increase in all cases due to insufficient stock. When upstream echelons, such as distributors and manufacturers, have high learning delays, it takes them longer to recognize changes in demand and adjust their production and shipment schedules accordingly. This delayed response leads to oscillations in the *Demand Backlog*. Initially, there was a sharp increase in the backlog due to insufficient stock. As upstream echelons slowly update their expectations and react to the increased demand, they may overcompensate by producing and shipping too much inventory, leading to temporary surpluses. This cycle of delayed response and over-adjustment creates fluctuations in inventory levels and the *Demand Backlog*, disrupting the overall stability of the supply chain.

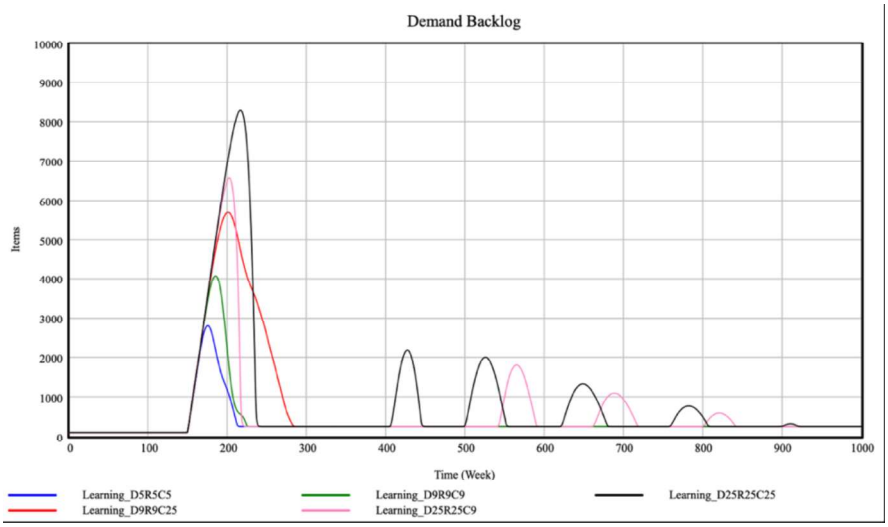

Figure 5.30. 3-echelon model demand backlog with learning delay scenarios.

In scenarios such as D5R5C5, D9R9C25, and D9R9C9, the behavior of inventory mirrors that of typical 2-echelon supply chains initially. *Retailer Inventory* undergoes a sharp decline as available stock depletes rapidly due to sudden increases in customer demand. Subsequently, it begins to increase as the retailer places new orders with the manufacturer to replenish stock. However, unlike in 2-echelon setups where equilibrium is achieved without significant oscillations, these scenarios exhibit oscillatory patterns in inventory levels. Notably, these oscillations tend to be more pronounced and reach higher peaks as adjustments move from downstream upstream echelons.

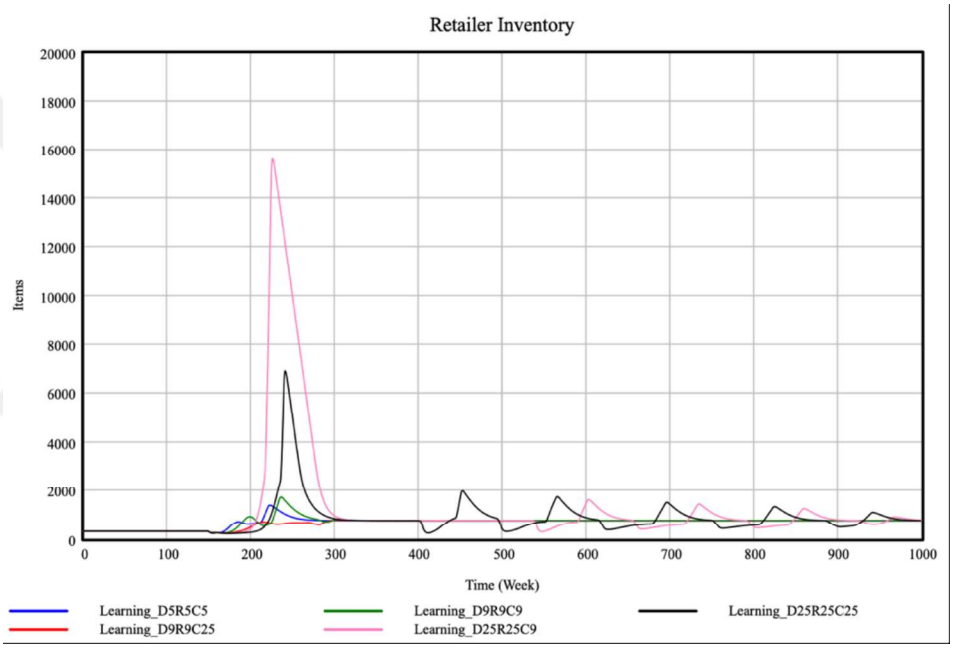

Figure 5.31. 3-echelon model retailer inventory with learning delay scenarios.

However, in scenarios like D25R25C9 and D25R25C25, where upstream echelons have extended learning delays, the supply chain dynamics exhibit intense oscillations, particularly noticeable in distributor and manufacturer inventories. These oscillations are markedly higher compared to scenarios with shorter learning delays. The prolonged learning delays mean that adjustments in ordering and production schedules lag behind changes in customer demand, leading to frequent over- and under-stocking situations. As a result, the distributor and manufacturer face greater challenges in aligning their supply with fluctuating demand patterns, causing inventory levels to swing dramatically between excess and shortage. This heightened variability underscores the critical role of timely and accurate

information flow and adaptive inventory management strategies in mitigating supply chain disruptions and stabilizing operations.

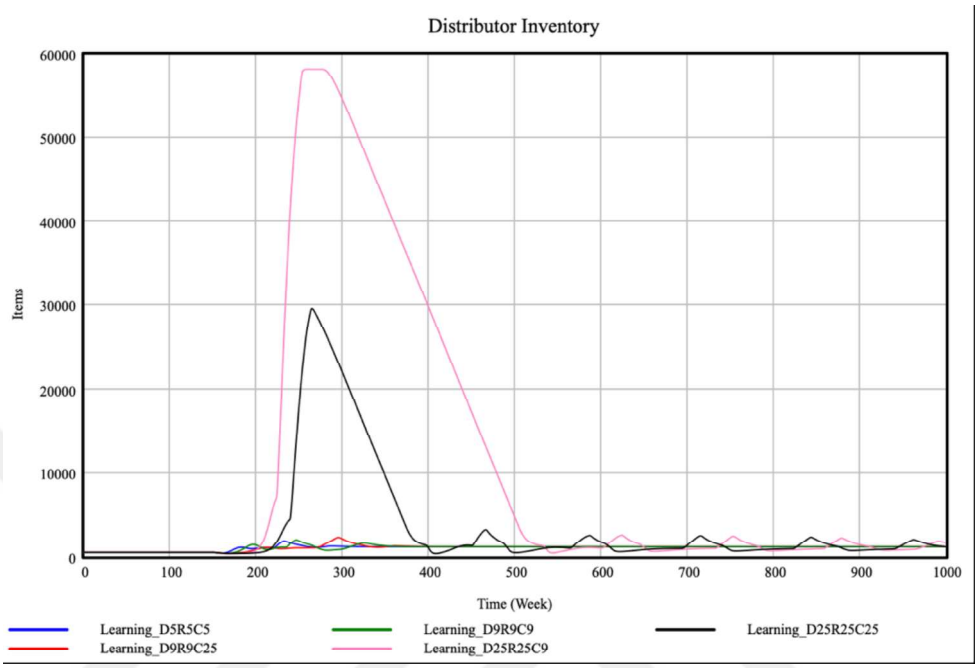

Figure 5.32. 3-echelon model distributor inventory with learning delay scenarios.

Extended learning delays, especially in upstream echelons like distributors and manufacturers, significantly disrupt supply chain dynamics, leading to erratic behavior across all stages. A 25-day delay in recognizing changes in orders is excessive in fast-paced supply chains. This delay results in inefficient responses to fluctuations in demand, causing inventory levels to oscillate widely between surplus and shortage. Such erratic behavior not only increases operational costs due to inefficient resource allocation but also compromises customer satisfaction by leading to delayed order fulfillment and potential stockouts. Therefore, reducing learning delays is crucial for enhancing supply chain responsiveness and stability, ensuring smoother operations and improved overall performance.

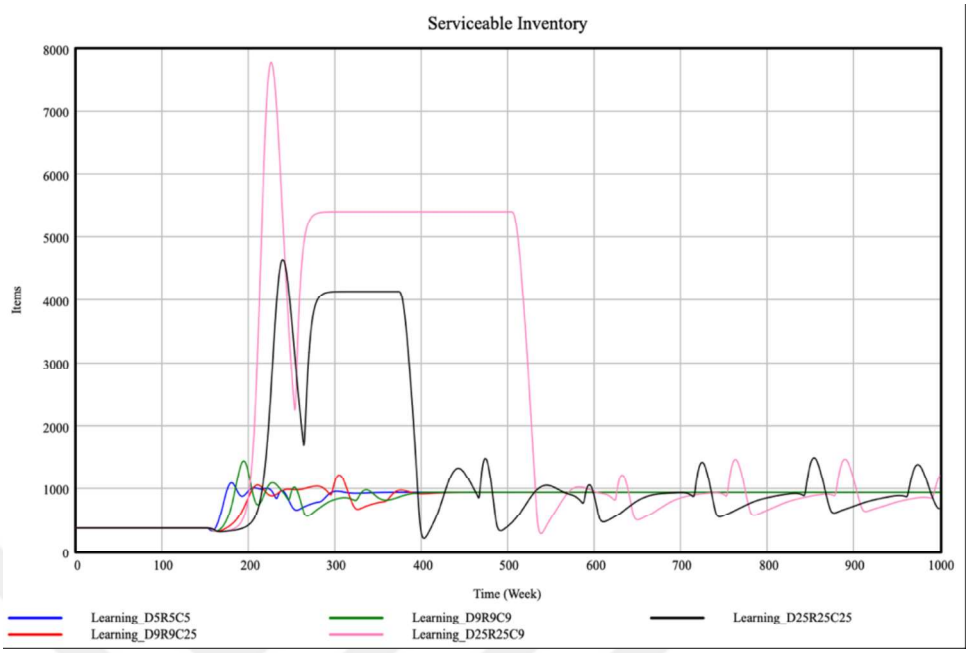

Figure 5.33. 3-echelon model serviceable inventory with learning delay scenarios.

6. DISCUSSION

In this section, the results of the simulation experiments will be discussed, with a focus on how supply chain actors' behaviors influence overall supply chain performance across different scenarios in response to a sudden increase in customer demand. The effects of three key factors—inventory adjustment time, shipment delay, and learning delay—on key supply chain performance metrics will be discussed. Two key metrics will be used to assess supply chain performance and responsiveness: the average demand backlog and backlog depletion time, which together indicate how effectively the supply chain responds to sudden increases in demand, and inventory deviation, which serves as an indicator of supply chain performance by measuring the extent to which actual inventory levels deviate from target levels.

6.1. Role of Adjustment Times

Inventory adjustment time refers to the period it takes for supply chain actors, such as the retailer and the manufacturer, to respond to discrepancies between actual and desired inventory levels, reflecting how fast or impulsive an actor is in responding to changes in perceived demand. When there is a sudden increase in demand, a longer inventory adjustment time means that actors are slower to react and make the necessary adjustments to their inventory. The findings of this research indicate that inventory adjustment times significantly impact supply chain performance metrics. When both the retailer and the manufacturer are slow to respond to changes, the study shows that the average demand backlog, which indicates the accumulation of unfulfilled orders, increases accordingly. This delay in adjusting inventory levels to meet increased demand prolongs the demand backlog depletion time, which measures how quickly these backlogs can be cleared. Consequently, the supply chain experiences reduced responsiveness in fulfilling customer orders promptly. Moreover, the findings of the research suggest that the inventory adjustment time of the retailer has a more significant impact on Demand Backlog Depletion Time compared to the manufacturer’s. The results show that whether the retailer responds quickly or slowly to changes in demand creates a significant difference in how quickly backlogs are cleared. In contrast, changes in the manufacturer’s inventory adjustment time exhibit a relatively smaller effect on depletion time. This is because the retailer is closer to the end customers

and directly manages the final stages of order fulfillment. Additionally, the retailer's slower adjustments result in immediate and noticeable delays in clearing backlogs, whereas the manufacturer's changes have a more buffered and distributed impact throughout the supply chain. When the retailer is slow to respond to changes and adjust its desired inventory levels accordingly, it delays increasing orders to the manufacturer, which further exacerbates the backlog and slows down the entire supply chain.

When the retailer is highly responsive, it effectively reduces demand backlog and improves customer satisfaction, but this adversely affects the upstream echelon, the manufacturer, regardless of whether the manufacturer responds quickly or slowly. This leads to a high peak in the manufacturer's inventory before achieving equilibrium. However, when the retailer makes more rapid decisions compared to the manufacturer, it triggers oscillations in both their inventories. This occurs because the rapid adjustments by the retailer to meet the new demand do not align with the manufacturer's production or supply capabilities, resulting in fluctuating inventory levels for both parties. The retailer orders varying quantities from the manufacturer in quick succession, causing fluctuations in its own inventory level. Simultaneously, the manufacturer also struggles to maintain a stable production schedule in response to these rapid and sometimes inconsistent retailer demands.

Inventory deviation is calculated based on the difference between actual inventory levels and the new equilibrium level that is established after the demand change. This metric considers that inventories do not reach instantaneously to new levels but rather measure how effectively and swiftly the supply chain reaches the new equilibrium. When retailer inventory adjustment time remains constant, slower manufacturer response contributes to a higher retailer inventory deviation from the target level. This occurs because the retailer relies on the manufacturer to replenish stock based on consumer demand. If the manufacturer does not promptly adjust production or supply quantities to meet the retailer’s needs, the retailer may experience shortages or surpluses relative to its desired level. Moreover, the highest retailer inventory deviation from the target level occurs when both the retailer’s and the manufacturer’s responses to change are slow, as delays in adapting to changing demand increase discrepancies.

Large deviations from target inventory levels cause stockouts and overstock situations, leading to lost sales, customer dissatisfaction, increased holding costs, and potential waste of perishable goods. Managing these deviations incurs additional costs and disrupts operations, causing scheduling issues and inefficiencies (Chopra & Meindl, 2007). While stability refers to the overall consistency and smoothness of inventory levels, inventory deviation quantifies the extent to which inventory levels diverge from the target. Although high inventory deviation often signifies poor stability, they are not exactly the same. Since deviation is calculated by penalizing discrepancies from the target using a squared term, the worst-case scenario is characterized by remaining farthest from the target level for the longest duration. Initially, the scenario with oscillations, R5S20—where the retailer makes more rapid decisions compared to the manufacturer—appears to be the worst case for both the retailer and the manufacturer in terms of inventory deviation due to high instability. However, upon closer inspection, it becomes evident that R20S20 and R20S5—where the retailer responds slowly to changes— represent the worst-case scenarios. In R20S20, both the retailer and manufacturer have slow response times, resulting in a delayed reaction to demand changes. This slow adjustment means that the inventory remains insufficient for a longer duration, exacerbating the overall deviation from the equilibrium inventory levels. The prolonged shortfall leads to a more significant cumulative penalty due to the squared discrepancies from target inventory levels, making R20S20 the worst-case scenario in terms of inventory deviation. Moreover, the extended period of insufficient inventory increases the time required to clear backlogs of unfulfilled orders.

There is a notable trade-off between inventory deviation and demand backlog depletion time. On the one hand, for the cases where the retailer responds slowly to changes, customer dissatisfaction worsens due to extended backlog depletion times, leading to delays in order fulfillment, potential lost sales, and reduced customer loyalty. On the other hand, there are no oscillations in inventory levels in these cases, so inventory costs are not excessively high due to the stable nature of inventory levels during the shortage. This highlights a trade-off where maintaining stable but insufficient inventory may mitigate cost fluctuations but can still negatively impact customer service by delaying order fulfillment and potentially compromising customer satisfaction. In contrast, for example in the R5S20 scenario—where the retailer makes more rapid decisions compared to the manufacturer—the retailer maintains high customer satisfaction by quickly clearing backlogs, though this

necessitates frequent order adjustments that result in significant fluctuations in inventory levels. This trade-off underscores the delicate balance between maximizing customer satisfaction and effectively managing inventory costs. When the retailer responds slowly, the manufacturer's impact on inventory levels is minimal. However, when the retailer responds quickly, the manufacturer's impact becomes significant, as it must rapidly adjust its production and shipments to keep up with the retailer's frequent and large order changes.

When a distributor is added to the model to simulate a 3-echelon supply chain, a similar result to a 2-echelon system is observed, where increased inventory adjustment times lead to higher average demand backlogs and prolonged depletion times. This occurs because the delay in adjusting inventory levels to meet increased demand extends the time required to clear backlogs. Among the supply chain actors, the retailer continues to have the highest effect on depletion time. Notably, in the R5D10S20 scenario—where the retailer responds quickly, the distributor responds slowly, and the supplier responds even more slowly—the backlog is depleted the last. Interestingly, although all actors are slow in the R20D20S20 scenario, this configuration depletes the backlog faster than the R5D10S20 case. In the R5D10S20 scenario, the retailer's quick response leads to frequent and large orders. However, the slower responses from the distributor and the manufacturer mean they cannot keep up with these sudden changes, creating bottlenecks and delays that ultimately slow down backlog depletion. Conversely, in the R20D20S20 scenario, all actors respond slowly, which results in a more synchronized and steady adjustment process. This coordinated slow response avoids the disruptive bottlenecks seen in the R5D10S20 scenario, allowing for more consistent progress in depleting the backlog. The R5D10S20 scenario demonstrates that a fast-responding retailer, when paired with slower upstream actors, can hinder overall supply chain performance due to the mismatch in response times, creating significant delays in backlog depletion. It also highlights the critical impact of the retailer's response time on overall supply chain performance.

Comparing the 2-echelon and 3-echelon cases, it is observed that the demand backlog is depleted faster in the 3-echelon model. The presence of a distributor in the 3-echelon case accelerates backlog depletion by buffering and distributing demand shocks across the supply chain. This intermediary role allows for more responsive adjustments in inventory levels between the retailer and manufacturer, as the distributor absorbs and smooths out

fluctuations in demand. However, this increased responsiveness comes at the cost of more fluctuations and waves in inventory levels. Nevertheless, these fluctuations do not result in larger inventory deviations. This is because the 3-echelon model achieves its desired inventory levels more quickly, even with periodic fluctuations, compared to the 2-echelon case.

The general behavior remains very similar in the 3-echelon case compared to the 2-echelon with similar responsiveness sets. In the 3-echelon setup, the R5D10S20 case where the retailer responds quickly, the distributor responds slowly, and the supplier responds slowest exhibits the most oscillations since the rapid response by the retailer to the demand change contrasts sharply with the slower responses from the distributor and supplier. This mismatch in response times creates frequent adjustments in inventory levels as each actor tries to balance supply with the rapid changes in demand. Despite having the most oscillations, the R5D10S20 case does not exhibit the largest deviation. The R20D20S20 scenario frequently maintains inventory levels significantly far from the target due to slow responses from all actors, thereby showing the largest inventory deviation from desired levels compared to other scenarios.

The manufacturer experiences the most frequent fluctuations due to its position at the end of the supply chain, followed by the distributor and then the retailer. This means that the inventory levels at the manufacturer oscillate more frequently where it must continuously adjust to the cumulative demand changes passed down from the retailer and distributor, resulting in more waves compared to the distributor and retailer. However, the highest peak in inventory levels occurs at the distributor. The distributor, situated between the retailer and manufacturer, acts both as a buffer and an amplifier. It absorbs and amplifies demand fluctuations from both ends of the supply chain, receiving varying orders from retailers and responding with larger orders to manufacturers, leading to significant inventory peaks as it balances these incoming and outgoing demands. In contrast, the retailer, being closest to the end customer, has more stable and predictable demand patterns, leading to fewer adjustments. Thus, the distributor sees the highest peaks, the manufacturer faces the most frequent fluctuations, and the retailer maintains more stable inventory levels.

6.2. Role of Shipment Delays

The target level in inventory management is influenced significantly by the shipment delay, which encompasses the time required for the products to be transported from upstream actors to downstream actors when there is enough inventory to fulfill the demand. When shipment delays are short, the target inventory level is set lower because goods arrive quickly to replenish stock. Since the inventory system is designed for consistent, rapid replenishment, it maintains lower target inventory levels during periods of short shipment delays, relying on quick arrivals to restock inventory efficiently. However, when there is a sudden increase in demand, the inventory cannot adequately cover this surge. Sudden demand spikes exceed the available inventory, causing delays in fulfilling orders and increased backlog until new stock arrives. The results demonstrate that low shipment delays directly lead to high backlogs and delayed backlog depletion due to insufficient buffer stock.

The Retailer Inventory exhibits similar behavior in all cases of shipment delays, whether long or short; only the timing and magnitude of the changes differ due to the different target levels. The Manufacturer Inventory also demonstrates a similar pattern. The findings indicate that prolonged shipment delays lead to greater inventory discrepancies. This is an expected outcome since both the retailer and the manufacturer set higher target inventory levels in response to longer delays, which in turn increases the discrepancy between the new target level and the actual inventory on hand. In contrast, lower shipment delays result in lower inventory deviations but lead to high backlogs and prolonged depletion times when there is a sudden increase in demand. This occurs because inventory levels are kept lower, assuming quick replenishment. However, if demand increases unexpectedly, the lower inventory cannot meet this surge, causing delays in order fulfillment and increased backlogs. This mismatch ultimately leads to lower customer satisfaction due to delays and stockouts. The research findings indicate that low shipment delays are advantageous for maintaining low inventory deviations under stable demand conditions. However, during sudden changes in demand, low shipment delays are associated with higher risks of inventory shortages and customer dissatisfaction due to delays in order fulfillment.

Findings in the 3-echelon case with a distributor show that low shipment delays result in high backlog and prolonged depletion times, similar to observations in the 2-echelon

setup. Moreover, varying shipment delays influence inventory deviations in both setups similarly while lower shipment delays reduce inventory deviations, they exacerbate backlog depletion times during sudden demand fluctuations.

Compared to the 2-echelon setup, the 3-echelon system experiences more fluctuations in inventory levels for both the retailer and manufacturer. In the 2-echelon system, inventory levels exhibit a single peak before stabilizing, with no oscillations. In the 3-echelon setup, the manufacturer experiences many frequent fluctuations in inventory levels due to its position at the end of the supply chain, which did not occur in the 2-echelon system. However, the highest peaks in inventory levels occur at the distributor, positioned between the retailer and manufacturer. In contrast, the retailer, being closest to the end customer, experiences more stable and predictable shipment schedules, leading to fewer, more controlled adjustments.

6.3. Role of Learning Delays

Learning delay refers to the time it takes for supply chain actors to recognize new information and update their expectations accordingly. This delay highlights the importance of how quickly information is integrated into decision-making. This research identifies two types of learning delays: customer order learning delay, which occurs when the retailer learns about changes in the customer demand, and retailer order learning delay, which happens when the manufacturer learns about changes in the retailer demand. When learning delays increase, the average demand backlog and depletion time also increase. This is because longer learning delays mean that actors take more time to recognize and respond to changes in demand, leading to slower adjustments in inventory levels. Consequently, unfulfilled orders accumulate, and it takes longer to clear these backlogs, reducing the supply chain's overall responsiveness. Just like in the cases of inventory adjustment times, the retailer's impact is greater because it is closer to the customer. When customer order learning delay is high, it takes longer for the retailer to recognize the change and adjust orders accordingly, resulting in a slower depletion of the backlog. This highlights the critical role of the retailer's responsiveness in maintaining efficient supply chain performance. In terms of inventory deviation, shorter learning delays lead to better performance, resulting in lower deviation. This is because quick recognition and response to changes in demand enable the

retailer to adjust inventory levels more accurately and promptly. Short learning delays are beneficial for both customer satisfaction, due to fast backlog depletion, and inventory cost, due to lower inventory deviation. However, this advantage is specific to this experimental setup where demand suddenly increases and remains at that level. In a scenario where demand fluctuates continuously, with frequent increases and decreases, fast learning might lead to oscillations, potentially destabilizing inventory levels.

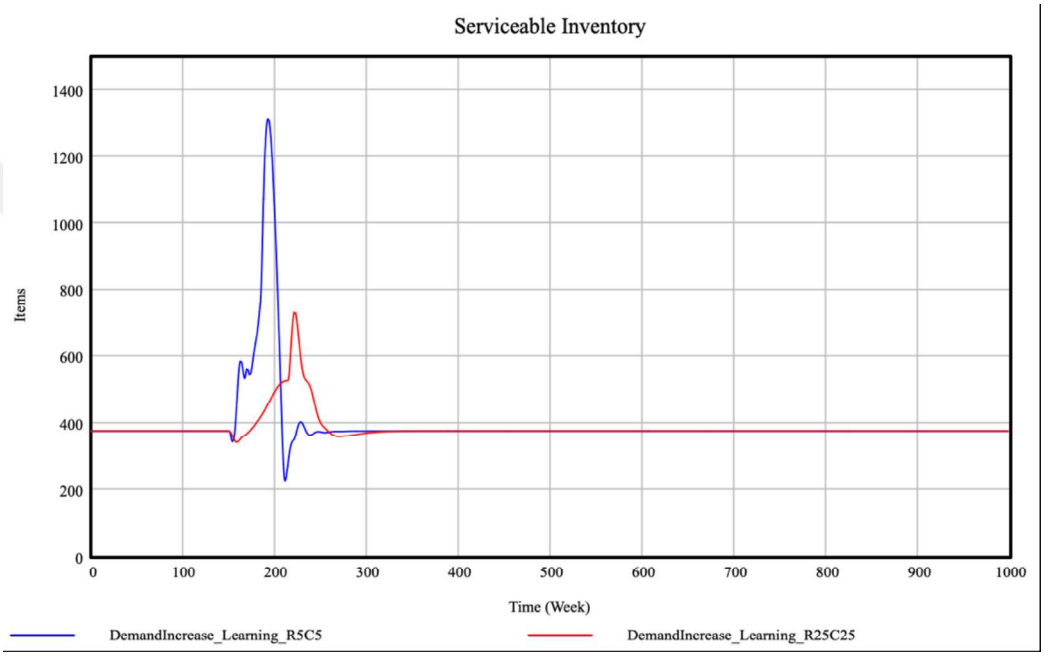

Figure 6.1. 2-echelon model serviceable inventory with demand fluctuations.

A single case was tested where demand fluctuates continuously, and in this scenario, fast learning led to more deviations in inventory, as illustrated in Figure 6.1. The retailer recognizes new information and updates its expectations accordingly, while the manufacturer updates based on the retailer's orders. Fluctuations occur because when demand changes frequently, rapid learning by the actors to align with the latest demand results in constant reordering. This quick succession of adjustments creates oscillations, as the supply chain actors continually try to catch up with the fluctuating demand. If both actors recognize changes more slowly, they would wait to ensure the demand change is permanent before adjusting and they would minimize constant reordering. This slower response allows for more stable inventory levels.

As illustrated in Figure 6.2., in the 2-echelon case, the manufacturer's inventory remains stable with a few fluctuations, even with long shipment delays. When customer demand surges at t=150, Serviceable Inventory experiences a sharp decline due to rapid stock depletion. As the manufacturer ramps up production to meet demand, Serviceable Inventory gradually increases and then remains relatively constant while the manufacturer adjusts its production to match the retailer's demand. The manufacturer's inventory increases sharply when the retailer's supply line is fulfilled and orders decrease, but then the manufacturer reduces production to avoid overstocking and finally stabilizes the inventory.

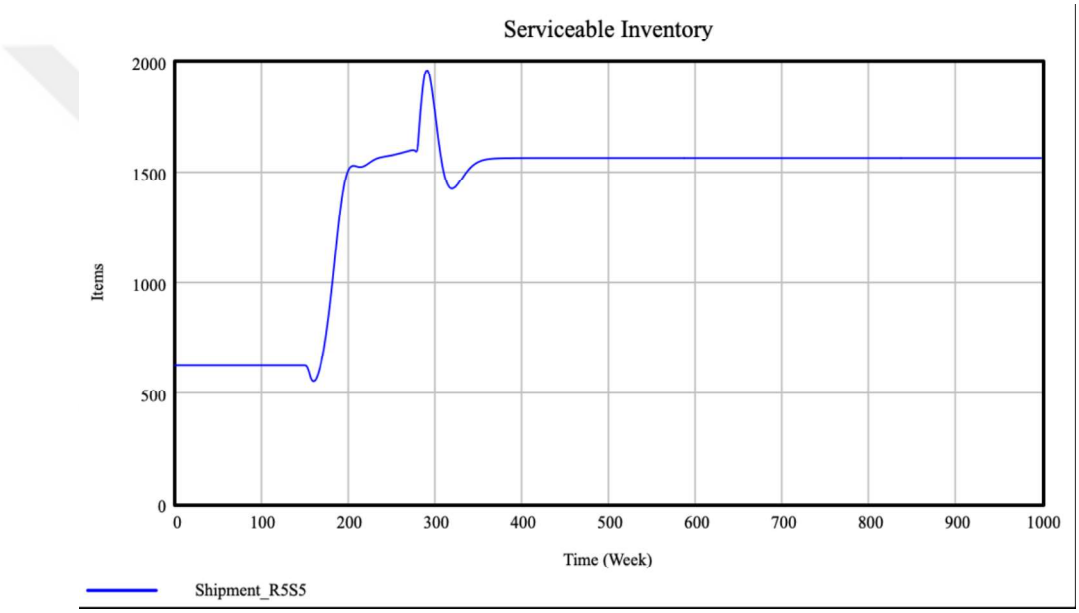

Figure 6.2. 2-echelon model serviceable inventory with high shipment delays.

In the 3-echelon case, when a distributor is added to the system while keeping all retailer and manufacturer parameters the same, long shipment delays lead to significant fluctuations in the manufacturer's serviceable inventory as illustrated in Figure 6.3. When shipment delays are prolonged, the distributor's role becomes pivotal yet challenging. In the 2-echelon case, where there are only the retailer and manufacturer, direct communication allows for timely adjustments in production schedules based on customer demand, minimizing the likelihood of significant inventory oscillations even when shipment delays are long. However, in the 3-echelon case with the addition of a distributor, long shipment delays introduce additional delays and misalignments in the ordering process between the retailer and manufacturer. This delay amplifies variability and leads to oscillations in the

manufacturer's inventory levels as they try to adjust production based on delayed or inaccurate information from the distributor.

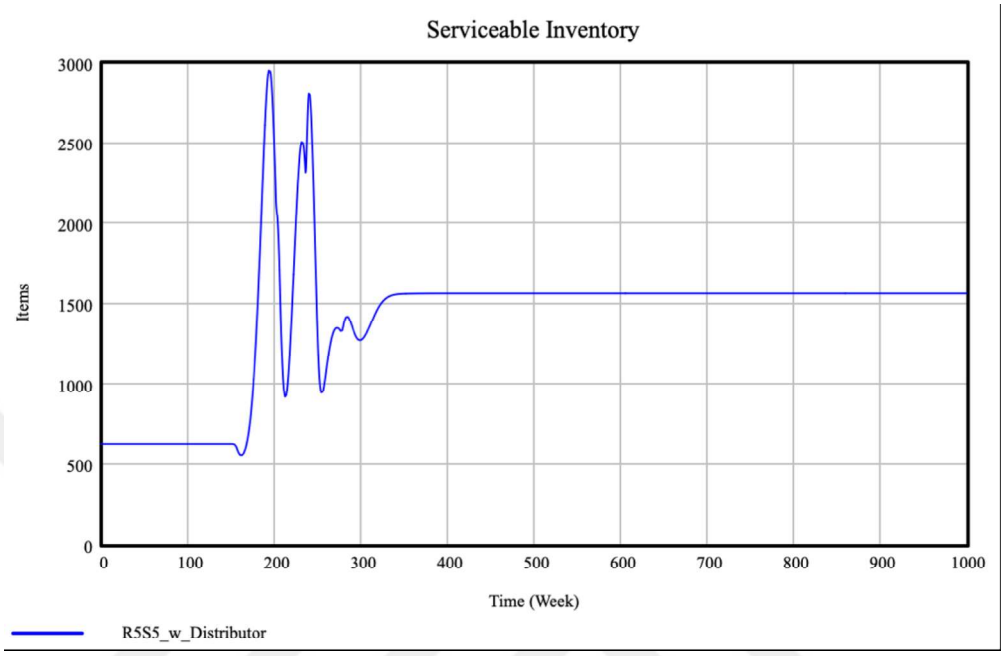

Figure 6.3. 3-echelon model serviceable inventory with high shipment delays.

When the distributor has a low adjustment time and responds quickly to changes, coupled with a long learning delay, oscillations are further intensified. This happens because, despite its rapid response to immediate demand changes, the distributor's ability to learn new trends in demand is delayed. As a result, its quick reactions may not align with the actual demand patterns over time, leading to erratic adjustments in inventory levels and worsening the oscillations and instability in the supply chain. This amplifies inventory adjustments upstream, causing greater instability in the manufacturer's inventory levels. When the distributor quickly responds to changes but the manufacturer lags behind in adjusting production, it creates a mismatch and results in the manufacturer's inventory oscillating. This occurs because the distributor places orders based on immediate demand signals, while the manufacturer's delayed response leads to inconsistent production that fails to align with the distributor's fluctuating orders, thereby causing instability in the manufacturer's inventory levels. As a result, the manufacturer faces challenges in maintaining consistent production schedules and meeting demand fluctuations effectively.

7. CONCLUSION

In analyzing the dynamics of the supply chain across various scenarios, the influence of key parameters such as inventory adjustment time, shipment delay, and learning delay on system responsiveness and inventory performance has been examined. These parameters play critical roles in how supply chain actors manage a sudden change in customer demand and maintain stable inventory levels.

The study shows a significant gap in existing research, as there are not enough sources that investigate the internal dynamics of a supply chain involving parameters such as inventory adjustment time, shipment delays, and learning delays, and their combined effects. While the significance of these factors is being discussed, there is a lack of sources that systematically explore the effect of these factors on the internal dynamics of a supply chain. Understanding these complex interactions is crucial for developing more efficient supply chain strategies and improving overall performance.

The findings highlight the critical impact of inventory adjustment times on supply chain performance. A swift response from the retailer is crucial for reducing demand backlogs, shortening backlog depletion time, and improving overall responsiveness, as it is closest to the end customer and manages the final stage of order fulfillment. However, while minimizing inventory adjustment times improves responsiveness, rapid adjustments lead to inventory oscillations and increased inventory deviation, making it harder to maintain inventory levels close to the target. To balance these effects, supply chain actors may implement robust demand forecasting and inventory management systems that enable quick, data-driven decision-making, or consider using safety stocks to mitigate the impact of demand fluctuations.

The study reveals that the best outcomes for the retailer in terms of stability are achieved when all supply chain actors synchronize their response times, ensuring efficient inventory management and consistent order fulfillment. Conversely, challenges arise when the retailer acts swiftly while upstream actors lag behind, leading to disruptions due to mismatched orders and fluctuating demands. Similarly, for the distributor, the best-case

scenario involves slower response times, which stabilize inventory levels and minimize fluctuations. Conversely, when both the retailer and distributor react swiftly but the manufacturer does not, significant inventory oscillations and instability occur, complicating order management for the distributor. In the case of the manufacturer, ideal conditions occur when both the manufacturer and distributor adjust slowly, promoting stable production schedules and inventory levels. Conversely, rapid responses from downstream actors coupled with slow adjustments by the manufacturer lead to order misalignment, increased inventory variability, and delays in fulfilling orders.

The study shows that the behavior of supply chain actors does not only affect their own performance but also significantly impacts other actors in the chain. When downstream echelons are highly responsive to changes in demand, their quick adjustments can negatively affect upstream echelons that respond more slowly. This mismatch in responsiveness leads to increased oscillations and instability in inventory levels upstream, as slower actors struggle to keep pace with the frequent changes in orders and demand signals from downstream. Consequently, the entire supply chain experiences greater variability and inefficiency, highlighting the importance of synchronized response times and coordinated adjustment strategies among all actors.

The findings also underscore the significant role of shipment delays in inventory management. Short shipment delays allow for lower target inventory levels due to the expectation of rapid replenishment. However, this leads to high backlogs and prolonged depletion times during sudden demand spikes, as the available inventory cannot cover the surge. Having extra inventory coverage can be beneficial in managing such a surge, as it serves as a buffer to meet sudden increases in customer orders, thereby minimizing backlogs and ensuring timely fulfillment of requests. When a distributor is involved in the supply chain, long shipment delays significantly amplify oscillations in the upstream echelons. This occurs because delays in communication and coordination between the distributor, retailer, and manufacturer disrupt the timing of production adjustments and inventory replenishments. Furthermore, if the distributor has a low adjustment time and responds quickly to changes, coupled with a long learning delay, oscillations are further intensified.

The study demonstrates that extended learning delays significantly impact supply chain performance by exacerbating backlog accumulation and prolonging backlog depletion times. Moreover, longer learning delays contribute to increased deviations in inventory levels, highlighting the challenge of maintaining stability when responses are delayed. It's important to note that these observations are specific to experimental conditions where demand experiences a sudden increase and remains stable thereafter. In a scenario where demand fluctuates continuously, rapid learning causes inventory levels to oscillate and reduce overall stability.

When a downstream echelon, such as the retailer, experiences long shipment delays but has short learning times and low inventory adjustment times, the result is a mixed impact on their inventory management. The retailer quickly recognizes and responds to the demand change due to its fast learning and adjustment capabilities. However, the long shipment delays mean that new stock takes longer to arrive, leading to high demand backlogs and prolonged depletion times during sudden demand spikes. This lag causes frequent inventory oscillations as the retailer continuously adjusts orders to match demand while waiting for delayed shipments. Consequently, there is increased inventory deviation, with significant volatility and instability in maintaining target inventory levels.

Integrating a capacity constraint into future research would enhance understanding of supply chain dynamics by simulating scenarios where the production capacity restricts rapid adjustments to demand fluctuations. This approach may offer insights into how the constraint interacts with inventory management parameters and affects overall internal dynamics, including backlog depletion times and inventory deviations. Furthermore, expanding the study to include additional echelons would broaden the scope of analysis to encompass more layers of the supply chain hierarchy. This expansion would allow for a deeper examination of how delays and adjustments propagate through multiple levels. Finally, incorporating a closed-loop supply chain perspective could enrich the study by considering the complexities of product returns, recycling, or refurbishment processes alongside traditional supply chain dynamics. This approach would allow for a comprehensive analysis of how delays and adjustments impact both forward and reverse logistics, influencing inventory management, sustainability efforts, and overall system efficiency. Moreover, future research could explore information sharing between supply

chain actors to investigate its impact on overall performance. Understanding how improved communication and data transparency influence decision-making and operational efficiency could provide valuable insights into optimizing supply chain dynamics and responsiveness.

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APPENDIX A: MODEL EQUATIONS

(01) Adj=
(Retailer SupplyLine/Retailer Replenishment Rate-Exp sr)/Adj t

(02) Adj t=
10

(03) Adjustment for Retailer Inventory=
(Desired Retailer Inventory-Retailer Inventory)/RIAT
Units: Items/Day

(04) Adjustment for Retailer SupplyLine=
(Desired Retailer SupplyLine-Retailer SupplyLine)/SRAT
Units: Items/Day

(05) Adjustment for Serviceable Inventory=
(Desired Serviceable Inventory-Serviceable Inventory)/SIAT
Units: Items/Day

(06) Capacity=
500000
Units: Items/Day

(07) Customer Delivery=
Sales
Units: Items/Day

(08) Customer Order=
New Demand
Units: Items/Day

(09) Demand Backlog= INTEG (
Customer Order-Customer Delivery,
100)
Units: Items

(10) Desired Retailer Inventory=

(Expected New Demand*Retailer Shipment Delay)*Retailer Inventory Coverage
Units: Items

(11) Desired Retailer Shipment Rate=
MAX(0 , Expected Sales+Adjustment for Retailer Inventory)
Units: Items/Day

(12) Desired Retailer SupplyLine=
Desired Retailer Shipment Rate*Expected Shipment Delay
Units: Items

(13) Desired Serviceable Inventory=
Expected Retailer Order*Manufacturer Shipment Delay*Serviceable Inventory Coverage
Units: Items

(14) Effof Available = WITH LOOKUP (
Ratio2,
([(0,0)-(3,3)],(0,0),(0.5,0.5),(0.885947,0.885947),(0.934827,0.933566
),(0.983707,0.9645),(1.0387,0.9865),(1.09369,0.996504),(1.14868,0.9995),(1.2
,1),(3,1)))

(15) Effof Available2 = WITH LOOKUP (
Ratio3,
([(0,0)-(3,3)],(0,0),(0.5,0.5),(0.885947,0.885947),(0.934827,0.933566)
,(0.983707,0.9645),(1.0387,0.9865),(1.09369,0.996504),(1.14868,0.9995),(1.2
,1),(3,1)))

(16) End user= INTEG (
Sales,
0)
Units: Items

(17) Exp sr= INTEG (
Adj,
1)

(18) Expected New Demand=
SMOOTH3(New Demand,New Demand Learning Delay)
Units: Items/Day

(19) Expected Retailer Order=
SMOOTH3(Retailer Order, Retailer Order Learning Delay)
Units: Items/Day

(20) Expected Sales=
Expected New Demand
Units: Items/Day

(21) Expected Shipment Delay=
Exp sr
Units: Day

(22) FINAL TIME = 1000
Units: Day
The final time for the simulation.

(23) Indicated Orders=
Desired Retailer Shipment Rate+Adjustment for Retailer SupplyLine
Units: Items/Day

(24) INITIAL TIME = 0
Units: Day
The initial time for the simulation.

(25) Manufacturer Shipment Delay=
3
Units: Day

(26) Manufacturing Rate=
MIN(Capacity,WIP/Manufacturing Time)
Units: Items/Day

(27) Manufacturing Time=
5
Units: Day

(28) MaxPossible EndUser Shipment=
Retailer Inventory/Retailer Shipment Delay

Units: Items/Day

(29) MaxPossible RI Shipment=
Serviceable Inventory/Manufacturer Shipment Delay
Units: Items/Day

(30) New Demand=
1*(100+ 1*(STEP(150,150) - 0*STEP(50,550))) + 0*RANDOM UNIFORM (100, 500, 445)
Units: Items/Day

(31) New Demand Learning Delay=
25
Units: Day

(32) Outflow=
Effof Available*Retailer SupplyLine
Units: Items/Day

(33) Outflow2=
Effof Available2*Demand Backlog
Units: Items/Day

(34) Production Orders=
MAX((Expected Retailer Order+Adjustment for Serviceable Inventory),0)
Units: Items/Day

(35) Ratio2=
MaxPossible RI Shipment/Retailer SupplyLine
Units: 1/Day

(36) Ratio3=
MaxPossible EndUser Shipment/Demand Backlog
Units: 1/Day

(37) Retailer Delivery=
Retailer Replenishment Rate
Units: Items/Day

(38) Retailer Inventory= INTEG (
Retailer Replenishment Rate-Sales,
300)
Units: Items

(39) Retailer Inventory Coverage=
1.5
Units: 1

(40) Retailer Order=
Indicated Orders + 0*(STEP(200,500) - STEP(200,550))
Units: Items/Day

(41) Retailer Order Learning Delay=
9
Units: Day

(42) Retailer Replenishment Rate=
Outflow
Units: Items/Day

(43) Retailer Shipment Delay=
2
Units: Day

(44) Retailer SupplyLine= INTEG (
Retailer Order-Retailer Delivery,
100)
Units: Items

(45) RIAT=
10
Units: Day

(46) Sales=
Outflow2
Units: Items/Day

(47) SAVEPER =

TIME STEP
Units: Day [0,?]
The frequency with which output is stored.

(48) Serviceable Inventory= INTEG (
Manufacturing Rate-Retailer Replenishment Rate,
375)
Units: Items

(49) Serviceable Inventory Coverage=
1.25
Units: 1

(50) SIAT=
10
Units: Day

(51) SRAT=
5
Units: Day

(52) TIME STEP = 0.03125
Units: Day [0,?]
The time step for the simulation.

(53) WIP= INTEG (
Production Orders-Manufacturing Rate,
500)
Units: Items