Literature Review on Simulation Methods for the Bullwhip Effect

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Abstract. The bullwhip effect is the phenomenon where small fluctuations in consumer demand result in larger variations further up the supply chain. This poses significant challenges to supply chain efficiency, leading to increased inventory costs, stockouts, and inefficiencies in production planning. This paper presents a comprehensive literature review on the simulation methods used in research to study and mitigate the bullwhip effect. We examine the application of agent-based simulation (ABS), differential equation system specification (DESS), also known as system dynamics (SD), and discrete event simulation (DES) in understanding different aspects of the bullwhip effect across various supply chain scenarios. Each simulation approach offers different insights: ABS focuses on decentralized decision-making and human behavior, SD operates on a macro level and focuses on the behavior of the entire system, and DES simulates operational-level events. This review outlines the strengths and limitations of each method and identifies gaps in the current research, suggesting areas where further simulation-based studies are needed to develop more effective strategies for managing the bullwhip effect.

Keywords: Bullwhip effect · simulation model · simulation method · literature review · supply chain.

1 Introduction

In today's globalized and interconnected world, supply chain management is important in ensuring the efficient flow of goods from suppliers to end consumers. One interesting aspect of supply chain management is the *bullwhip effect* (Yang et al., 2021). The bullwhip effect refers to the amplification of demand fluctuations as one moves upstream in the supply chain. Even small variations in consumer demand can result in significant oscillations in orders, inventory levels, and production planning as those fluctuations work back through the supply chain, from retailers to manufacturers and suppliers. This effect often occurs due to incomplete information and leads to inefficiencies, including excess inventory, stock-outs, increased lead times, and higher costs (Yang et al., 2021). As a result, understanding and mitigating the bullwhip effect is essential for optimizing supply chain performance.

One of the primary tools employed to study and manage the bullwhip effect is simulation (Yang et al., 2021) (Braz et al., 2018). Simulation methods allow researchers and practitioners to model intricate systems, analyse their behavior under varying conditions, and test potential interventions without disrupting real-world operations. In supply chain research, different types of simulations, including agent-based simulations (ABS), system dynamics, and discrete-event simulations (DES), are widely used to understand various aspects of supply chain management (Yang et al., 2021) (Braz et al., 2018). Each simulation technique brings its own strengths and limitations, providing distinct insights into how supply chains function under uncertainty and variability.

Despite the interest in understanding the bullwhip effect and the use of simulations to study it (Yang et al., 2021), a significant research gap remains: there is no compiled literature review that synthesizes the existing body of knowledge on simulations used to investigate the bullwhip effect in supply chains. Most studies are narrowly focused on specific aspects of the bullwhip effect or on the application of individual simulation techniques. This paper aims to address this gap by summarizing and categorizing the available literature, providing a view of how different simulation methods have been used to study the bullwhip effects and what questions have been answered.

To address the research gap, this paper is structured around several key sub-questions:

- **What type of questions have been addressed, and why is the bullwhip effect still a significant topic of research?** This sub question aims to identify the areas where research has made progress in understanding the bullwhip effect, while also exploring why this effect continues to be studied in supply chain studies. Despite advancements, the bullwhip effect remains relevant due to its persistent impact on supply chain performance. Understanding why the bullwhip effect is still a necessity to study is crucial for performing a literature review.
- **What types of simulations are used to study the bullwhip effect?** A variety of simulation methods have been applied to analyze the bullwhip effect, each offering unique insights. SD operates on a macro level and focuses on feedback loops, time delays, and the behavior of entire systems. Agent-based simulations model individual entities as autonomous agents with distinct behaviors, interactions, and decision-making processes, making them useful for studying decentralized systems and human behavior on micro to macro levels. Discrete-event simulations work mostly at the micro level and model supply chain processes as sequences of events in time, focusing on queuing and workflows. This sub question reviews the application of these simulation types in the literature.
- **Which simulation methods are used for which types of questions, and why?** This sub question seeks to explore the relationship between specific simulation methods and the types of research questions they address.

Understanding this connection is important to assess the suitability of various simulation approaches in capturing different aspects of the bullwhip effect. By identifying which methods are used for particular research problems, this sub question helps clarify how effectively current simulation techniques contribute to our understanding of the bullwhip effect.

The concluding section of this paper will present the most important findings from the literature review and provide an answer to the sub-question. In doing so, this paper contributes to a better understanding of how simulation methods can be used to study the bullwhip effect.

2 Methodology for Finding the Literature

This section details the methodology for conducting a literature review focused on simulation methods employed to analyze the bullwhip effect in supply chains. The systematic approach consists of several key stages, including defining objectives, conducting searches, refining the literature list, and composing the findings (Bryman, 2016).

2.1 Purpose and Scope

The aim of this literature review is to identify and summarize existing research on the simulation methods used to study the bullwhip effect in supply chains. The scope of the review includes:

- **Simulation Techniques:** Focus on various simulation methods such as Agent-Based Simulation (ABS), System Dynamics (SD), and Discrete Event Simulation (DES).
- **Bullwhip Effect:** Examination of how frequently these methods have been applied to understand and mitigate the bullwhip effect in both forward and closed-loop supply chains.
- **Applications:** Consideration of studies that highlight practical applications of simulation methods in real-world supply chain scenarios.

2.2 Literature Search Process

The study followed the following process to gain the litrature:

1. **Keyword Identification:** Begin by identifying relevant keywords associated with simulation methods and the bullwhip effect. The keywords used in this study include:
   - "bullwhip effect"
   - "simulation"
   - "supply chain"

- "Agent-Based Simulation"
- "System Dynamics"
- "Discrete Event Simulation"

2. **Database Selection:** Utilize reputable academic databases for your search, such as:
   - **Scopus**: Known for its comprehensive coverage of peer-reviewed literature.
   - **Web of Science**: Offers a wide range of multidisciplinary research.
   - **Google Scholar**: Useful for a broader search, including grey literature.
3. **Conducting Searches:** Perform thorough searches using Boolean operators (AND, OR, NOT) to combine the identified keywords effectively. The following combinations were used in this study:
   - Search for: *"bullwhip effect AND simulation"*
   - Search for: *"bullwhip effect AND supply chain"*
   - Search for: *"Agent-Based Simulation AND bullwhip effect"*
   - Search for: *"System Dynamics AND bullwhip effect"*
   - Search for: *"Discrete Event Simulation AND bullwhip effect"*
   - Search for: *"simulation AND supply chain"*
   - Search for: *"Agent-Based Simulation AND supply chain"*
   - Search for: *"System Dynamics AND supply chain"*
   - Search for: *"Discrete Event Simulation AND supply chain"*
4. **Filtering Results:** Review search results by examining titles, abstracts, and keywords. Set inclusion criteria which are as follows:
   - Only include articles published in peer-reviewed journals(with one exception in this paper).
   - Focus on studies published within the last 10 years for relevance(with two exceptions due to high amount of citations).
   - Exclude papers that do not specifically address simulation methods related to the bullwhip effect.
5. **Full-Text Review:** Access the full text of the selected articles. Evaluate their relevance and quality by considering:
   - The clarity of the methodology used.
   - The applicability of the simulation methods discussed in the context of the bullwhip effect.

- The results and conclusions drawn by the authors.

6. **Citation Analysis:** To uncover additional relevant literature, conduct citation analysis:
   - Review references cited in the selected papers to identify other significant works.
   - Use tools like Google Scholar to see how many times the selected papers have been cited by others, which can help identify influential studies.

This structured methodology ensures that the literature review is reproducible, and focused on relevant studies regarding simulation methods and the bullwhip effect. By following these steps, researchers can effectively locate the literature found in the paper.

3 Research Questions Concerning Simulation Methods for the Bullwhip Effect

Various simulation methods have been employed to analyze the bullwhip effect, including Discrete Event Simulation (DES), System Dynamics (SD), and Agent-Based Simulation (ABS). Each method offers unique insights and addresses specific research questions.

3.1 System Dynamics (SD)

System Dynamics (SD) or System Dynamics, is another prevalent simulation method used to explore the bullwhip effect. It focuses on the feedback loops and time delays inherent in complex supply chain systems, making it suitable for understanding how decisions over time influence system behavior.

Research Questions Addressed Key research questions addressed through SD include((Goodarzi et al., 2017), (Peña et al., 2021)):

- What are the long-term effects of demand variability on inventory levels and product quality?
- How do feedback loops within the supply chain exacerbate the bullwhip effect?
- What policy changes can effectively mitigate the bullwhip effect in perishable goods supply chains?

3.2 Agent-Based Simulation (ABS)

ABS is increasingly employed to study the bullwhip effect due to its ability to model interactions among individual agents (e.g., suppliers, manufacturers, and retailers) within a supply chain. This method captures the decentralized nature of decision-making and the complexities of agent interactions.

Research Questions Addressed The research questions explored using ABS include((Lohmer et al., 2020), (Islam et al., 2022),(Zarandi et al., 2007)):

- How do individual decision-making behaviors contribute to the overall bullwhip effect in supply chains?
- What role does information sharing among supply chain partners play in mitigating the bullwhip effect?
- How does the implementation of risk pooling strategies impact the dynamics of the bullwhip effect?

3.3 Discrete Event Simulation (DES)

Discrete Event Simulation (DES) is a prevalent methodology for modeling and analyzing intricate systems where events occur at specific, distinct points in time. In the context of supply chains, DES enables researchers to replicate the operational dynamics and assess the impact of various factors on the bullwhip effect within a controlled environment. This simulation method is particularly useful for capturing the complexities involved in inventory management and demand fluctuations that affect overall supply chain performance.

Research Questions Addressed The primary questions explored using DES include((Alabdulkarim, 2020),(Ali et al., 2020)):

- How do inventory policies influence the propagation of demand variability across different stages of the supply chain?
- What implications do lead times have on order quantities and inventory levels throughout the supply chain?
- What is the impact of centralized versus decentralized information sharing on the bullwhip effect?

4 Why Use Different Simulation Methods for the Bullwhip Effect?

To effectively analyze the bullwhip effect, various simulation methods were employed, each offering unique insights into the dynamics at play. This section explores three primary techniques((Yang et al., 2021),(Braz et al., 2018)): System Dynamics (SD), Agent-Based Simulation (ABS), and Discrete Event Simulation (DES). By examining these methods, the paper aims to highlight their specific applications and strengths in understanding and mitigating the bullwhip effect, ultimately contributing to improved supply chain strategies.

4.1 System Dynamics (SD)

System Dynamics (SD) is well-suited for analyzing the bullwhip effect because it focuses on the high-level, macro-scale behavior of entire supply chains. SD models capture feedback loops, time delays, and accumulations, which are critical in understanding how small variations in demand can snowball into larger fluctuations as they propagate upstream. This method is excellent for studying the long-term impacts of different supply chain policies, such as order batching, lead times, or inventory replenishment rules, on the bullwhip effect.

SD is especially helpful when the focus is on the interactions between various components of the supply chain and how they collectively influence system-wide behaviors. By modeling feedback mechanisms, SD helps explain how different factors amplify demand variability and contribute to the bullwhip effect over time.

4.2 Agent-Based Simulation (ABS)

Agent-Based Simulation (ABS) is particularly useful for studying the bullwhip effect because it models individual entities (agents) within the supply chain, such as suppliers, manufacturers, and retailers, as autonomous decision-makers. These agents can have distinct behaviors, interact locally, and adapt to changes in their environment. This decentralized approach makes ABS ideal for studying complex systems with heterogeneous actors, which is a hallmark of supply chains. ABS helps to capture the micro-level behaviors that give rise to macro-level phenomena, such as the amplification of demand variability, which is central to the bullwhip effect.

Additionally, ABS can model diverse strategies, such as inventory policies or demand forecasting methods, and analyze their emergent effects on the entire system. It is particularly useful for studying decentralized decision-making environments where individual actors have limited information, reflecting real-world supply chains.

4.3 Discrete-Event Simulation (DES)

Discrete-Event Simulation (DES) is often used for operational-level analysis of supply chains. It models the supply chain as a series of discrete events, such as order placements, deliveries, and inventory replenishments, making it ideal for analyzing the bullwhip effect in terms of specific processes. DES is highly granular, allowing for detailed exploration of the impact of individual events and interventions on the performance of the supply chain.

DES is particularly suited for studying the impact of operational changes, such as adjustments to lead times, lot sizes, or order processing strategies, on the bullwhip effect. By simulating these events over time, DES provides insights into how specific interventions might reduce demand variability and improve overall supply chain efficiency.

4.4 Differences Between the Techniques

- **Agent-Based Simulation (ABS):** Models individual actors (agents) in the supply chain with unique behaviors and interactions. It is decentralized and focuses on micro-level dynamics that lead to emergent, system-wide phenomena like the bullwhip effect.
- **System Dynamics (SD):** Focuses on the macro-level structure of the supply chain, emphasizing feedback loops, delays, and accumulations. It is used to study the overall behavior of the system over time.
- **Discrete-Event Simulation (DES):** Models the supply chain as a sequence of events, focusing on the operational level. It provides a detailed, event-driven analysis of how specific processes impact the system.

Each technique offers unique strengths depending on the level of analysis (micro vs. macro) and the type of questions being addressed, making the choice of method crucial for investigating different facets of the bullwhip effect.

5 Discussion of Findings

The appendix attached to this review contains Table 1, this Table contains the research question, simulation method and explanation for each paper that was analyzed in this paper. This chapter will examine and discuss unexpected simulation choices made by researchers in these papers.

One of these papers investigates the effects of the bullwhip effect in centralized and decentralized supply chains (Goodarzi et al., 2017). The model chosen by the researchers for this is System Dynamics (SD). This choice can be considered odd because decentralized systems typically require a more granular approach, focusing on how individual entities interact and how these interactions lead to emergent behaviors. ABS can model these interactions in a more detailed and realistic way by simulating each entity's decision-making process. SD tends to smooth out such granularity, which might oversimplify how decisions at different levels of the supply chain influence cash flow. While SD can certainly model high-level cash flow behavior, ABS might have been a more appropriate choice for decentralized supply chains.

The paper written by Wang (Wang, 2011) researches the topic of the bullwhip effect on perishable product supply chain using a System Dynamics model. The study mostly focuses om system-wide demand and inventory changes in which SD is a good fit. However, the perishable aspect of this research might have fit better with other simulation methods. Perishable products have specific, time-sensitive processes, such as production, transportation, and expiration. DES is well-suited for modeling these discrete events, especially when it's important to track the exact timing of shipments, spoilage, and inventory depletion.

In some cases, the use of a hybrid simulation approach could have provided a more comprehensive understanding. For example, the integration of Agent-Based

Simulation (ABS) with System Dynamics (SD) or Discrete Event Simulation (DES) could offer the best of both worlds, capturing both the high-level feedback loops and the detailed agent-level interactions or discrete events.

One such paper that could have benefited from a hybrid approach is the study by Ali et al. (Ali et al., 2020), which focuses on the bullwhip effect in a multi-echelon supply chain for fast-moving consumer goods using DES. While DES is excellent for modeling event-driven processes such as inventory replenishment and order placement, a hybrid approach incorporating ABS could have added depth to the analysis. The supply chain involved multiple actors with decentralized decision-making, such as retailers, wholesalers, and manufacturers. ABS would have allowed for more detailed modeling of how each entity behaves under different information-sharing strategies, providing additional insights into the behavioral dynamics at play in a multi-product, multi-echelon system. However, the downside of using the hybrid approach is the increased complexity of simulation and the reproducibility.

6 Conclusion

This paper reviewed the simulation methods employed in researching the bullwhip effect. The bullwhip effect is the phenomenon where small fluctuations in consumer demand lead to increasingly amplified variations further up in the supply chain. This results in a less efficient supply chain, which contributes to higher inventory costs, stockouts, and inefficiencies in production planning. The simulation methods used by researchers to analyze this effect are Agent-Based simulation (ABS), System Dynamics (SD), Discrete Event Simulation (DES) and since recent studies a hybrid combination of these. Each simulation method has its own unique use cases. Therefore, selecting the appropriate simulation method for studying specific aspects of the bullwhip effect is significant. To address the missing overview of literature surrounding the bullwhip effect the following sub-questions have been answered.

1. **What type of questions have been addressed, and why is the bullwhip effect still a significant topic of research?** The bullwhip effect remains a critical area of study due to its substantial impact on supply chain efficiency and the complexity of modern supply chains. Researchers have addressed several key questions, including how different supply chain structures and information-sharing practices affect the bullwhip effect (see section 3), as well as the operational policies that worsen demand variability (see section 3). Studies have also investigated the role of behavioral factors, such as decision-making under uncertainty and forecasting inaccuracies, in contributing to the bullwhip effect (see section 3).

These inquiries highlight the importance of understanding the bullwhip effect, particularly as global supply chains become increasingly intricate. Continued research is essential for developing effective mitigation strategies as the bullwhip effect remains an unsolved problem within the supply chains. Thus, necessitating

ongoing research of advanced simulation techniques and innovative supply chain policies to overcome the bullwhip effect.

2. **What types of simulations are used to study the bullwhip effect?** The analysis revealed that different simulation methods are employed based on the specific aspects of the bullwhip effect being studied. SD is primarily used for macro-level analysis, ABS focuses on individual decision-making behaviors, and DES is applied for operational-level processes (section 4). Recent studies also showed the possibility of combining multiple simulation methods for different aspects of the simulation, this increases the complexity significantly.

3. **Which simulation methods are used for which types of questions, and why?** It was found that the choice of simulation method often aligns with the complexity of the research question and the characteristics of the system under study. However, many researchers did not adequately justify their choice of the simulation method, making it challenging to evaluate the appropriateness of their approaches (section 4 and section 3).

Despite the valuable insights gained, this study faced limitations, particularly the short timeframe of just seven weeks for conducting the literature review. As a result, a limited number of papers were reviewed, which may not fully capture the breadth of existing research on simulation methods related to the bullwhip effect. Future research should involve a broader literature search to uncover additional studies, particularly those that may have employed dubious methods. This would enhance understanding of the diverse simulation approaches available and their effectiveness.

Furthermore, a significant limitation identified in this review is that many researchers do not explicitly justify their choice of simulation method. In several cases, methods like SD, ABS, or DES were presented without adequate explanation, making it difficult to assess whether the chosen approach aligns with the complexity of the research question. More thorough justification of method selection in future studies will help ensure that the simulation techniques employed are appropriate for the specific research context (see section 5).

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7 Appendix

Research Question	**Type of Simulation Method**	**Explanation**
How do blockchain technology and collaboration strategies impact supply chain resilience, especially in managing the ripple effect during disruptions? (Lohmer et al., 2020)	Agent-Based Simulation (ABS)	The authors chose ABS to model the behavior of individual entities within a supply chain. This allows the analysis of complex interactions and disruptions. ABS was particularly useful for simulating the decentralized nature of blockchain-coordinated supply chains and assessing how disruptions propagate through the network.
What are the causes of the cash flow bullwhip effect in both centralized and decentralized supply chains? (Goodarzi et al., 2017)	System Dynamics (SD)	The authors use SD to model and analyze the interactions between different parts of the supply chain. This method allows them to simulate how cash flow is affected by the bullwhip effect over time in both centralized and decentralized systems, providing insights into how information flows and decision-making impact overall supply chain performance.
How can a fuzzy Agent-Based Simulation reduce the bullwhip effect in supply chain systems under uncertainty in demand, lead times, and order quantities? (Zarandi et al., 2007)	Agent-Based Simulation (ABS) combined with Fuzzy Logic	The authors used an Agent-Based Simulation to simulate the interactions between supply chain participants, incorporating fuzzy logic to account for uncertainty in demand, lead times, and order quantities. This approach allowed them to optimize ordering policies and reduce the bullwhip effect more effectively than traditional analytical methods by handling imprecise information through fuzzy time series and a genetic algorithm module.
How can the bullwhip effect be minimized in a supply chain using an optimized inventory management strategy in the beer game? (Alabdulkarim, 2020)	Discrete Event Simulation (DES)	The authors chose DES because it allows for precise modeling of inventory and ordering processes in the beer game supply chain. The simulation incorporates an EOQ inventory policy and additional rules, such as no backlog and consideration of orders en route, to minimize costs and reduce the bullwhip effect.

How does stochastic lead time and information sharing affect the bullwhip effect in a multi-product and multi-echelon supply chain of fast-moving consumer goods (FMCG)? (Ali et al., 2020)	Discrete Event Simulation (DES)	The authors used DES to model the supply chain at multiple echelons and to simulate the effects of different lead times and information-sharing strategies (centralized and decentralized) on the bullwhip effect. DES was chosen because it allows for detailed modeling of complex systems, such as multi-product supply chains, and provides insights into how demand variability and lead time fluctuations propagate through the system.
How can information sharing and risk pooling mitigate the bullwhip effect in a supply chain with stochastic lead times? (Islam et al., 2022)	Agent-Based Simulation (ABS)	The authors used ABS to model the interactions between different supply chain entities (e.g., retailers, wholesalers, and manufacturers) and simulate the impact of information sharing and risk pooling on reducing the bullwhip effect. ABS was chosen because it allows for dynamic modeling of complex systems, which is essential for capturing the decentralized decision-making processes and stochastic lead times characteristic of supply chains.
How does the bullwhip effect manifest in the semiconductor supply chain, and how can discrete event and Agent-Based Simulation capture its impacts on demand fluctuations? (Ehm, 2012)	Hybrid Model (Discrete Event Simulation + Agent-Based Simulation)	The authors combined both discrete event simulation (DES) and agent-based simulation (ABS) to model the semiconductor supply chain, aiming to capture both the operational processes and the behavior of supply chain participants. The hybrid approach was chosen due to the complexity of the semiconductor industry, where the bullwhip effect leads to demand amplification across different supply chain tiers.

How can system dynamics and Agent-Based Simulation be integrated to study emergent structures in supply chains, and what are the impacts of different supply chain policies on these structures? (Schieritz & GroBler, 2003)	Hybrid Model (Agent-Based Simulation + System Dynamics)	The authors used a hybrid approach that integrates SD for macro-level analysis of system-wide feedback loops and aggregate behaviors, and ABS for micro-level modeling of individual agents' interactions and decision-making processes. This combination allowed them to study both the overall system dynamics and the emergent behavior of individual agents within the supply chain.
How does demand variability and lead time affect the performance of non-perishable product food supply chains in a monopolistic environment? (Kumar & Nigmatullin, 2011)	System Dynamics (SD)	The authors use SD to model and analyze the relationships and behaviors within the food supply chain. This method allows them to study how variations in demand and lead time impact inventory levels, stockouts, and overall supply chain performance. The SD approach provides a tool for strategic planning and business decision-making.
How do changes in consumer demand, retailer and wholesaler order cycles, and delivery delays cause the bullwhip effect in perishable product supply chains? (Wang, 2011)	System Dynamics (SD)	The authors used SD to model the causes of the bullwhip effect in perishable product supply chains, focusing on the amplification of demand variability across different levels of the supply chain. This method allowed them to simulate the effects of order cycles, delivery delays, and inventory levels, providing insights into how to stabilize the supply chain and reduce the bullwhip effect through strategic changes like improving order coordination and information sharing.

Table 1: Research questions, simulation methods, and explanations for papers on the bullwhip effect.