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A novel study of the impact of supply chain complexity on the bullwhip effect

Authors:
Mohammed El-Beheiry[1]
Raghda Taha[2]
Tamer Ismail[3]
Yasmin Adel[4]

Affiliations:
[1]Department of Design and Production Engineering, Faculty of Engineering, Ain Shams University, Cairo, Egypt

[2]Department of Supply Chains Management, College of International Transport and Logistics, Arab Academy for Science, Technology, and Maritime Transport, Cairo, Egypt

[3]College of Engineering and Technology, Arab Academy for Science, Technology and Maritime Transport, Cairo, Egypt

[4]Department of Mechanical Engineering, French University of Egypt, Cairo, Egypt

Corresponding author:
Yasmin Adel,
yasmeen.adel@ufe.edu.eg

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Background: The coronavirus pandemic exposed global supply chain vulnerabilities, causing fluctuating demand for products. This resulted in the bullwhip effect, which posed a substantial challenge for supply chain management. This study focusses on the analysis of the effect of supply chain configurations and structure on the bullwhip effect.

Objectives: The research quantitatively studies the effect of the strategic supply chain structure at the design phase on amplifying the bullwhip effect. Furthermore, it studies the expected interaction during operation, which may further amplify or dampen it.

Method: The study introduces a simulation model and examines the influence of several design decisions and operations parameters and their interactions on the efficiency of supply chain operations. A simulation model is created for several supply chain configurations, each with distinct structure complexity. The bullwhip effect measures are collected and a factorial analysis is conducted to examine the interactions among the parameters and their impact on the performance.

Results: The findings indicate that an increase in demand unpredictability results in a greater bullwhip effect, irrespective of the inventory strategy or structural intricacy. But the level of increase does not necessarily match the increase in complexity and can be amplified or damped by interactions between operating parameters.

Conclusion: Supply network architects should consider the level of structural complexity to mitigate amplifications of demand variations and to optimise the supply chain's overall operation.

Contribution: The research represents a novel work to quantitatively link the bullwhip effect of a supply chain to the complexity of its supply chain structure.

Keywords: Bullwhip effect; simulation; factorial analysis; supply chain configuration; supply chain structure; supply chain complexity.

Introduction

The global outbreak of coronavirus disease 2019 (COVID-19) has shown vulnerabilities in supply chains on a global scale. Because of the fluctuating demand for products such as personal protective equipment (PPE) and electronic components, manufacturers worldwide are experiencing unprecedented levels of variation and uncertainty in their production schedules. These variations and uncertainties exploit supply chains to the bullwhip effect. This is further exposed in this era because of the complexity of supply chains. Today, a conventional supply chain is quite complex, as it spans across multiple countries on different continents. The instability in the gaming between demand and supply may take a couple of years to decrease and not stabilise. This proposes a new research area not yet explored: how the complexity of the supply chain affects the variation in demand expressed by bullwhip, and how these variations are impacted by changes in the supply network's operational conditions.

Practitioner supply chain managers consider complexity to be a significant obstacle. A survey carried out by Gartner, a consulting research company, revealed that 63% of the supply chain leaders surveyed saw increased supply chain complexity as the greatest threat to business continuity (Gartner 2019). According to a report by GEODIS, a transportation and logistics company, 70% of the participants evaluated their supply chain as highly complex or extremely complex (GEODIS India 2017).

Supply chain complexity has no single agreed-upon definition or measurement so many researchers have attempted to define and quantify it. According to Serdarasan (2013), the complexity of a supply chain can be divided into three types: static (structural complexity), dynamic (operational complexity) and decision-making (interactional) complexities.

The concept of the bullwhip effect was initially introduced by Lee, Padmanabhan and Whang (1997), but it had already been addressed as the Forrester effect in Forrester (2013). The bullwhip effect increases the difficulties of planning and leads to inaccuracies in forecasts, particularly among upstream participants. Sterman (1989) demonstrated that variations are magnified upstream of the supply chain as a result of the misinterpretation of the underlying causes of demand fluctuations. Despite extensive research, the bullwhip effect is still of great concern (Michna, Disney & Nielsen 2020).

An understanding of the bullwhip effect is crucial because by minimising or reducing it, we may enhance the profitability and efficiency of the supply chain (Goodarzi & Saen 2020). Bullwhip effect research can be categorised into three primary categories: analysing the sources of the bullwhip effect, developing strategies to mitigate its impact and developing methods to quantify it. This research belongs to the first category, where the effect of supply chain structure on the bullwhip effect is examined. El-Beheiry, Wong and El-Kharbotly (2004) demonstrate the impact of supply chain structure on the bullwhip effect. By conducting a simulation and empirical analysis, they demonstrated that the supply chain structure contributed to the amplification of variance among the upstream members. The primary aim of this study is to quantitatively demonstrate the potential impact of supply chain structure complexity on the bullwhip effect. This is achieved by assessing the structural complexity and measuring the bullwhip effect across various supply chain configurations.

It looks like the structural complexity of the supply chain plays a role in amplifying or dampening the bullwhip effect at different stages of the supply chain. This study tries to find out whether the structural complexity of the supply chain results in different bullwhip effect behaviours at different stages of the supply chain. As a result, supply chain architects can expect the behaviour of the bullwhip effect. At the same time, the planners of the supply chain can be informed about expected behaviour on changing some operating conditions; therefore they can manage the expected behaviour. At the same time, by changing these operating conditions, there will be some interactions between them resulting in unpredictable bullwhip effects.

Suppose that a new company wants to design its supply chain. The decisions that the architects make are long-term decisions and extremely hard to change. There are many factors considered when designing the supply chain such as availability of resources, availability of skilful workers and total supply chain cost. However, this study suspects whether the structural complexity of the supply chain affects the bullwhip. In other words, the selection of a supply chain structure could be thought of as a low-cost choice, yet this low-cost design may amplify the bullwhip effect, which results in higher costs.

So, the initiative of this research is to give an insight to the designers and planners that their choice of supply chain structure could result in amplified bullwhip. Also, the study suspects that the structure of the supply chain could interact with the operating conditions in further amplification or damping of the bullwhip over what is already known in the literature.

Hence, the study focusses on the supply chain structural complexity effect on the bullwhip in the supply chain knowing that the structure decisions are long-term decisions and how the operational conditions are further amplified/dampened with the structural complexity.

The main objective of this study is to find out whether the structural complexity of the supply chain affects the bullwhip effect across different stages of the supply chain and how the interaction between some operational parameters dampens or amplifies the bullwhip effect when a certain structure is chosen in the design phase.

The rest of this article is organised as follows: the 'Literature review' section explores existing literature on the bullwhip effect and measures of supply chain structure complexity. The 'Methodology' section presents the developed simulation model used to quantify the bullwhip effect for the selected supply chain structures. The measure of complexity for the supply chain structure is outlined in this section, while the details of the numerical experimentation are provided in the 'Numerical experimentation' section. The 'Results and discussion' section presents the analysis and findings, while the 'Conclusion' section summarises the conclusions and offers future recommendations.

Literature review

Simon (1962) defined system complexity as a system made up of numerous numbers of parts that interact in a non-simple way; therefore, any supply chain could be categorised as a complex system. One of the earliest scientific contributions to supply chain complexity is in Wilding (1998), which was later extended by Vachon and Klassen (2002). They consider complexity to be the result of having numerous entities, several interconnectivities and many unpredictability, which result in a negative effect on delivery performance. Choi and Krause (2006) defined supply complexity as a result of three dimensions: the number of suppliers, their differentiation and their inter-relationships. Alvim, Santos and Rodriguez (2020) proposed an assessment of supply chain complexity. Lin et al. (2021) discussed the complexity of supply chains as they argued that management of complexity in supply chains has not been adequately established.

There has been increasing attention paid to supply chain complexity in both research and practice because of its importance (Bozarth et al. 2008). Better management and integration of supply chain complexity lead to better performance and higher customer satisfaction (Serdarasan 2013). Many companies consider complexity as a challenge they face in maintaining supply chain flow (Tarei et al. 2021). Supply chain complexity has a significant adverse impact on competitiveness, cost efficiency, customer satisfaction, product innovation and market share (Chand, Thakkar & Ghosh 2018).

Multiple variables contribute to the complexity of supply systems. The ever-increasing customer expectations, along with the products' short life cycles, are a major source of complexities within supply chains (Chand et al. 2018). In Serdarasan's (2013) study, the author examined various factors that contribute to the complexity of supply chains. These factors were further classified according to their origin as upstream, operational, downstream or external. The drivers they studied include supplier resourcing risk, supplier competency, regional strategies, shortening product life cycles and changing customer service. Manuj and Sahin (2011) stated that supply chain complexity arises from factors such as the volume of data, decision variables, relationships between variables, system constraints and performance trade-offs. On the other hand, Kavilal, Prasanna Venkatesan and Harsh Kumar (2017) linked complexity to the interconnected flows of materials, funds and information.

There exist varying viewpoints regarding the categorisation of supply chain complexity. Bozarth et al. (2008) categorised complexity into three distinct types: upstream complexity, internal manufacturing complexity and downstream complexity. They also differentiate between dynamic complexity, which refers to the uncertainty of a system, and detail complexity, which refers to the complexity of the components. Blome, Schoenherr and Eckstein (2014) categorised complexity as either supply complexity or product complexity. The concept of product complexity encompasses factors addressing product customisation, the number of components and product variety (Novak & Eppinger 2001; Vachon & Klassen 2002). Bode and Wagner (2015) investigated the structural drivers of upstream supply chain complexity and their consequences on the frequency of supply chain disruption. Choi and Hong (2002) categorised the structural complexity of supply chains into three types: horizontal, vertical and spatial. Horizontal complexity refers to the number of distinct entities present at a specific level within the supply chain. Vertical complexity, on the other hand, measures the number of tiers or levels within a supply chain. Spatial complexity measures the number of operational sites or the extent of geographic dispersion across those sites.

Some researchers investigate the effect of supply chain complexity on different dimensions of supply chain operations. Ma, Lou and Tian (2019) investigate how the price adjustment speed and historical price discount sensitivity affect the complexity and bullwhip of the supply chain. Poornikoo and Qureshi (2019) developed a system dynamics model with a fuzzy logic application to study how to dampen the bullwhip effect. They also focus on the operational decisions, not on the design of the supply chain. In their offer to understand the causes of the bullwhip effect, Paik and Bagchi (2007) list nine possible factors affecting the bullwhip effect. Some researchers study the huge bullwhip effect resulting from COVID-19 focussing on how firms can deal with them (Ivanov & Dolgui 2021; Magableh 2021; Scarpin et al. 2022; Zighan 2022). It should be noted that these focus on the operational side of the supply chain and do not include the structure and configuration of the supply chain.

Pinar-Perez, Ruiz-Hernández and Menezes (2021) investigated supply chain locational complexity, which is referred to as a part of supply chain structural complexity on profitability. They used pars-complexity as a measure of the structural complexity despite it being assumed as informational complexity as this metric quantifies the information generated by the flow of goods and services in the supply chain. They assumed that the pars-complexity has a hidden cost and hence they integrated the locational complexity in a facility location problem model as a decision variable to minimise supply chain cost. Their results showed that the developed model can reduce complexity-related costs.

Many researchers have tested the impact of supply chain structure elements on the bullwhip effect. One of the early trials was conducted by Paik and Bagchi (2006), who used a simulation study and factorial analysis to examine nine causes of the bullwhip effect, one of which is the number of echelons. Their results showed that the number of echelons may interact with other causes of the bullwhip effect that when the number of echelons is three or more the demand forecast updating is the most significant factor for the bullwhip effect. While if there are only two echelons, the price variation is the most significant one. The comparison between serial and divergent structures conducted by Dominguez, Cannella and Framinan (2014) showed that serial structures may lead to a reduced bullwhip effect. In another study by Dominguez, Framinan and Cannella (2014), the results indicated that the difference in the bullwhip effect is minor between the two structures when demand variability is constant. However, when demand suddenly increases (shock lens), the divergent structure suffers from a higher bullwhip effect at all echelons. Another comparison made between six different structures of the closed-loop supply chain was carried out by Tombido et al. (2020).The tested structures have five echelons with either serial or divergent forward structure, with serial or convergent reverse structure. The results focussed on the impact of reverse structure on the bullwhip effect, highlighting that serial reverse structures are more sensitive to changes in the number of collectors in the reverse flow. One of the few attempts to estimate the impact of supply chain structure on the bullwhip effect was conducted by Dominguez et al. (2015a). They quantitatively designed a measure to estimate supply chain divergence based on the number of echelons, the number of nodes per echelon and the total number of nodes in the supply chain. They tested serial and divergent structures using a simulation study, and the results imply that increasing supply chain divergence amplifies the bullwhip effect. Cannella et al. (2017) used the same divergence measure to estimate the effect of inventory record inaccuracy on the bullwhip effect across three different supply chain structures. They found that the bullwhip effect is exacerbated because of supply chain divergence.

In this work, Chatha and Jalil (2022) investigated the impact of supply chain structural complexity and operational complexity on manufacturing supply chain performance. They modelled the structural complexity by the number of customers and suppliers associated with the focal manufacturing facility, while the operational complexity is modelled as demand variability expected at the manufacturing facility. The supply chain performance is measured at the manufacturing firm in terms of its capacity utilisation, demand fulfilment and inventory level. Results showed that increasing structural complexity has a positive effect on the performance, but it rapidly deteriorates further increasing the complexity.

Iftikhar, Ali and Stevenson (2024) tested empirically how supply chain complexity affects its resilience and robustness. They expressed the supply chain complexity with structural and operational dimensions in their survey. The results suggest that supply chain complexity has a positive influence on SC resilience and SC robustness.

Inman and Green (2024) investigated empirically the supply chain complexity effect on traceability, they did not have a clear definition of the supply chain complexity as the questions they used in the survey referred to structural, operational, informational complexities and generic questions about whether the supply chain is complex or not. The results indicated that in the absence of mediating effect of information sharing in the model the supply chain complexity positively impacts transparency and traceability, which is unlike some of previous findings in the literature.

Pant, Dutta and Sarmah (2023) used secondary data to empirically correlate between supply chain structural complexity and supply chain performance. They developed a supply chain structural complexity index based on five inputs that are the number of suppliers, number of suppliers' countries, number of products, number of plants and number of customers. Their results showed that complexity has a negative and significant effect on firm performance.

Issa et al. (2024) empirically investigated how structural and dynamic (operational) complexities may mediate the effect of green innovation on supply chain resilience. Their results showed that the effect of green innovation strategies is amplified in less structurally complex supply chains, while the contrary is deduced in the case of dynamic supply chain complexities.

Greater supply complexity negatively influences performance, and companies can improve their profits by 3%–5% if they manage complexity positively (Lin et al. 2021). Supply chain complexity may result in increased supply risk (Choi & Krause 2006; Craighead et al. 2007), reducing the performance of manufacturing plants (Bozarth et al. 2008), affecting the cost and service (De Leeuw, Grotenhuis & Van Goor 2013; Gimenez, Van der Vaart & Pieter van Donk 2012), resulting in supply chain disruption (Bode & Wagner 2015), leading to inferior customer service (Manuj & Sahin 2011), lower capital utilisation (Xiaoxiao & Zikui 2019) and decreasing supplier innovation (Choi & Krause 2006).

Several measurements of complexity have been proposed in the literature. Supply complexity measurements should include the number of direct suppliers, market dynamics and supply reliability (Bozarth et al. 2008; Vachon & Klassen 2002). Most techniques used to assess the complexity of manufacturing systems rely on the principles of entropy theory in computer science (Graessler & Yang 2019). It represents the total complexity value of a supply chain network as the sum of the complexity values of the nodes, the complexity values of the associated edges and the complexity of the network topology.

Choi and Hong (2002) establish a connection between the complexity of the upstream network and two factors: the number of echelons and the number of suppliers inside each echelon. In a similar manner, Craighead et al. (2007) classified structural complexity based on the number of supply chain participants and the level of interconnections among them. According to Modrak, Marton and Bednar (2013), complexity should be positively correlated with the number of nodes and links in a network. Additionally, a network with more echelons should exhibit higher levels of complexity. Modrak and Marton (2012) utilised an undirected network to depict the supply chain and employed a vertex degree index to quantify the structural complexity. Sivadasan et al. (2006) suggest including schedule variety and deviation from schedule in measuring the complexity. Isik (2010) proposed the inclusion of the difference between the observed and anticipated flow increases as a means of quantifying complexity.

Lu and Shang (2017) conducted a literature review on the measurements of non-visible structural factors that contribute to supply chain complexity. These factors include the links between suppliers, which lead to cooperative complexity and the links between a supplier and the buying firm's customer, which lead to eliminative complexity.

According to Gottinger (2012), although there is a lack of consensus on how to measure complexity, it is necessary to study complexity measurements to develop improved techniques for modelling and managing real systems. Lin et al. (2021) stated that the industry has not effectively established and extensively adopted complexity management, mostly because of the challenge of quantifying complexity. They argued that there is a discrepancy between some complexity measurements and rigorous proofs. Although many researchers (Adami, Verschoore and Sellitto (2021) and Chen et al. (2024) used Social Network Analysis (SNA)-based metrics to measure the structural complexity of the supply chain yet, there is no SNA metric developed especially to measure the structural complexity of the supply chain (Adami et al. 2021). Also, there is no single metric based on SNA that can express the structural complexity of the supply chain.

The bullwhip effect, alternatively referred to as demand information amplification, poses a significant challenge for supply chains (Yang et al. 2021). The bullwhip effect refers to the phenomenon where even a modest and predictable change in consumer demand leads to significant and unanticipated fluctuations in the volume of orders that providers need to fulfil (Wang & Disney 2016). This phenomenon is extensively researched in the supply chain management literature because of its significant role in causing inefficiencies in the supply chain. It results in overproduction, over-ordering, greater waste of inventory and higher consumption of raw materials and energy (He, Yuan & Zhang 2016; Hofmann 2017; Ferdows 2018; Zhao et al. 2018). The bullwhip effect leads to increased inefficiency, increased transportation waste, larger inventories and greater environmental harm (He et al. 2016).

Information distortion may be a significant factor in amplifying the bullwhip effect (Braz et al. 2018). There are other factors that can explain this phenomenon, including inaccuracies in demand estimation or forecasts, order batching, price fluctuations and shortages (Lee et al. 1997; Chen et al. 2000; Forrester 2013). Several researchers have studied the effects of bullwhips on supply chain performance (Abdallah 2016; Bhattacharya & Bandyopadhyay 2011; Geary, Disney & Towill 2006; Giard & Sali 2013; Miragliotta 2006; Wang & Disney 2016). A bullwhip is affected by behavioural factors that may be affected by the structural complexity of the supply chain (Arvan et al. 2019; Fahimnia et al. 2020; Perera et al. 2019; Yang et al. 2021). However, to the best of our knowledge, the effect of the structural complexity of the supply chain on bullwhip and its interactions has not been thoroughly studied in the literature. Other factors that affect the bullwhip are discussed in the literature such as sustainability (Lin et al. 2017), human behaviour (Dominguez et al. 2015b), inventory policies and returns (Chatfield & Pritchard 2013; Chong 2013).

Computer simulation is a commonly employed method for studying bullwhips and enhancing supply chain performance. This involves studying a system that exists or is designed by imitating a real scenario or system. It is used in the analysis of dynamic interactions in complex systems (Rong, Shen & Snyder 2008).

Based on the aforementioned literature, various observations can be deduced. It is important to study the effect of supply chain complexity and bullwhip as they are considered among the most difficult problems that supply chains face as discussed by Bode and Wagner (2015) and Bozarth et al. (2008) for the former and Wang and Disney (2016) for the latter. Choi, Dooley and Rungtusanatham. (2001) argue that comprehending the complexity of a system is the initial stage in comprehending its behaviour, particularly its interaction with bullwhip. Lin et al. (2021) states that there has been a lack of effort in creating tools to measure the level of complexity in supply chains. Furthermore, there has been limited research on the relationship between complexity tools and other factors, such as the bullwhip effect. Even the index presented by Dominguez et al. (2015b) does not measure all aspects of structural complexities as it depends only on the number of tiers, the number of nodes per tier and the total number of nodes in the supply chain. Other factors related to the number of links, the number of links emanating from each node and reverse nodes and links are not considered in their supply chain divergence measure. Consequently, supply chain experts rely on their intuition to handle complexity-related issues. Despite the importance of various sources of complexity and their effects on supply chains, little attention has been paid to that in the literature (Govindan, Soleimani & Kannan 2015). A critical issue is to analyse the bullwhip effect through a complex network discipline, verifying the impact of different topologies on the bullwhip effect (Tejeida-Padilla, Flores-Cadena & Morales-Matamoros 2010). According to Sellitto et al. (2019), complexity measurement is widely used to evaluate variety and uncertainty in supply chains. However, the use of complexity measurement to support control actions remains an open issue.

This study conducts a quantitative experiment to analyse the influence of increasing supply chain structure complexity on the bullwhip effect across various stages of the supply chain. Four distinct supply chain configurations covering almost all types of supply chains and having different levels of complexity were selected to measure the bullwhip effect across different operational factors. The structural complexity will be measured using the measure proposed by Modrak et al. (2013). This measure is superior to other measures or indices mentioned in the literature as it covers all supply chain structure elements, and the measure is modified to represent the reverse flow elements. A simulation model was developed for each configuration. The effect of the interaction between the simulated operational parameters, such as demand variability at the most downstream members, inventory policies at the retailer and distributors with supply chain structure complexity, will be discussed. Another contribution from the managerial perspective is that the research helps the supply chain architects (designers) to predict how their decisions affect the performance of their supply chain, especially the bullwhip effect.

Methodology

In order to quantitively investigate the relation between supply chain structural complexity and bullwhip, several supply chain configurations are considered representing widely used structures in real life such as serial, divergent and convergent supply chains. The structural complexity of the supply chain is measured using the modified flow complexity indicator (MFC). The MFC metric represents structure attributes such as the number of tiers, number of links, node criticality, etc. For each tested structure, a discrete event simulation model is developed to mimic the operational parameters of the supply chain and measure the bullwhip effect for each structure. A factorial analysis experiment is conducted to find significant interactions. It should be noted that as complexity is expressed as a function, the general results can be extended to structures not covered in the study as long as a certain trend exists.

We can claim that this is the first attempt to prove quantitatively that the bullwhip effect is affected by the supply chain structure. Hence, we adopted the structural complexity measures as a quantitative parameter representing the SC structure; from the literature review, it was found that one of the most adequate structural complexity measures is the MFC. Modified flow complexity indicator evaluates structural complexity based on the number of tiers, nodes and links and their configuration in the supply chain. How this is calculated is mentioned using Equation 1 to Equation 4 in the section 'Structural complexity measurement'.

In the section 'Developed simulation model', the logical relation between factories, distributors and retailers is discussed. It shows how each entity behaves. Later, this logic will be used for any entity within the simulation model.

Structural complexity measurement

Instead of focussing on some preconfigured structures such as serial or divergent structures, the study adopts a measure of structural complexity proposed by Modrak et al. (2013). The supply chain structure complexity was assessed using an MFC, which is based on the flow complexity indicator (FC) developed by Crippa, Bertacci and Larghi (2006). This measure finds a value for structure complexity by considering the tiers, nodes and links in a supply chain. In that sense instead of having nonparametric structures A, B, etc., there will be values for structural complexities that are believed as the higher the values, the more complex the structure is.

In that sense, it is an attempt to generalise the findings for different structures not covered here to an extent.

Modified flow complexity depends on weighing the total number of tiers, nodes and links of the supply chain structure as given in Equation 1. Three weights are used, which are α, β and γ to weigh the effect of the number of tiers, nodes and links on the calculated index as given in Equations 2–4:

$$MFC = \alpha \cdot T + \beta \cdot N + \gamma \cdot LK \quad \text{[Eqn 1]}$$

$$\alpha = \frac{TN - N}{(T-1) \cdot N} \quad \text{[Eqn 2]}$$

$$\beta = \frac{TN}{N} \quad \text{[Eqn 3]}$$

$$\gamma = \frac{LK}{L} \quad \text{[Eqn 4]}$$

where T is the number of tiers of the supply chain structure; N is the number of nodes in the supply chain structure; L is the number of output links per node, that is, if two links emerge from the same node, they are counted only once; TN is the number of nodes with repeating the node count if it supplies different nodes at different tiers and if several links emerge from the same node to the same tier, it is counted as one link, if they emerge to nodes in two tiers it will be counted as two and LK is the number of links at the supply chain structure.

While calculating the value of T an additional tier will be added representing the reverse flow and any link contributing to reverse flow is counted as two links as reverse flow increases the complexity of the supply chain structure. For example, consider the divergent supply chain shown in Figure 1. T in that case is the forward number of tiers in addition to one additional tier representing the reverse flow (i.e. T = 3 + 1 = 4). N is the number of nodes in the forward flow in addition to each node having reverse flow as it is duplicated (counted again) (i.e. N = 7 + 4 = 11). L is the number of links in the forward flow per node in addition to twice the number of links in the reverse flow per node (i.e. L = 3 + 2 × 4 = 11). TN is the sum of the number of nodes in the forward flow, and if a node supplies more than one tier it is counted as many tiers it supplies and the number of nodes from which reverse flow originated, if it supplies more than one tier in the reverse flow it is counted as many tiers as it supplies (i.e. TN = 7 + 4). Finally, LK is calculated as the number of links in the forward structure in addition to twice the number of links in the reverse structure (i.e. LK = 6 + 2 × 4 = 14). Hence, the MFC can be calculated, and the result is MFC = 25.

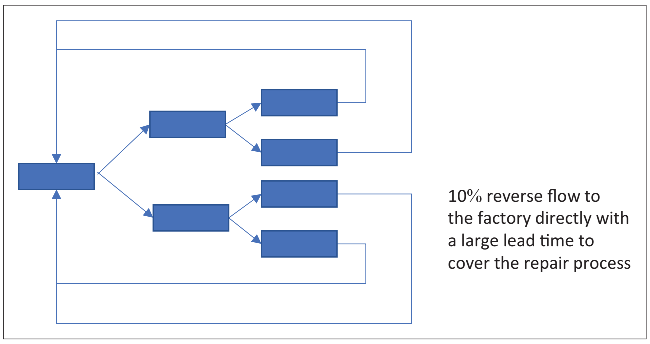


FIGURE 1: A divergent supply chain.

Developed simulation model

This research aims to investigate the impact of structural complexity on the bullwhip effect. Consequently, a few supply chain structures will be simulated and analysed. Each structure will consist of three tiers: manufacturing, distribution and retailing. Each retailer sells goods to consumers following a Poison distributed demand 'D'. If there are multiple retailers, we assume they will all face the same demand distribution. The retailers' inventory is replenished by one or more distributors, depending on the supply chain configuration under study. Similarly, the distributor(s) replenish their inventory from one or more production facilities, also based on the supply chain configuration under study. There is no backlog and shortage results in lost sales. There is a chance of 10% that any outgoing order at a retailer is reversed to the factory; in that case, the lead time is very large to cover the re-manufacturing and refurbishment activities. So reverse flow re-enters the factory as ready-to-be-used products. Retailers and distributors employ the (S, s) inventory policy, wherein an entity restocks its inventory up to a level 'S' when the present inventory reaches the reorder point 's'. It takes a relatively small amount of time to deliver the products. If there are not enough products available, the orders are backlogged until fulfilled (i.e. when the inventory level reaches the re-order point of s_D, s_f for the retailer and distributor, respectively), an order is sent to the distributor (factory) to send S_d (S_f) items, which are used to restock the items at the time of delivery to S_d (S_f). The lead time is equal to the lead time between the retailer and the distributor. Factory is assumed to have an unlimited supply. This supply chain is modelled using simulation to test the relation between the structure complexity and the bullwhip effect; the simulation logic is shown in Figure 2.

From the aforementioned model description, the following assumptions are drawn:

- Stochastic demand is assumed with Poison distribution.
- The demand is the same for all retailers.
- All members follow (S,s) inventory policy.
- No backorders at levels and all shortages are considered lost sales.
- There is a chance of 10% that any outgoing order at a retailer is reversed to the factory.
- Lead times are known, deterministic and constant between various members.
- At manufacturing facilities, there is enough capacity to produce the quantities needed.

Numerical experimentation

The main objective of this article is to discover whether there is a relationship between the supply chain structural complexity and inventory tactical decisions with the bullwhip effect. Four different designs having various complexity measures are selected to be simulated. The selected designs representing the major materials flow patterns are serial, divergent, convergent and general. The four designs and their complexity measures are given in Table 1. The consumer demand is modelled as Poisson distribution at the consumers with three values of the mean demand as given in Table 2. The inventory policy parameters at the factory and distributor are changed (the maximum inventory level S_f and S_d) while

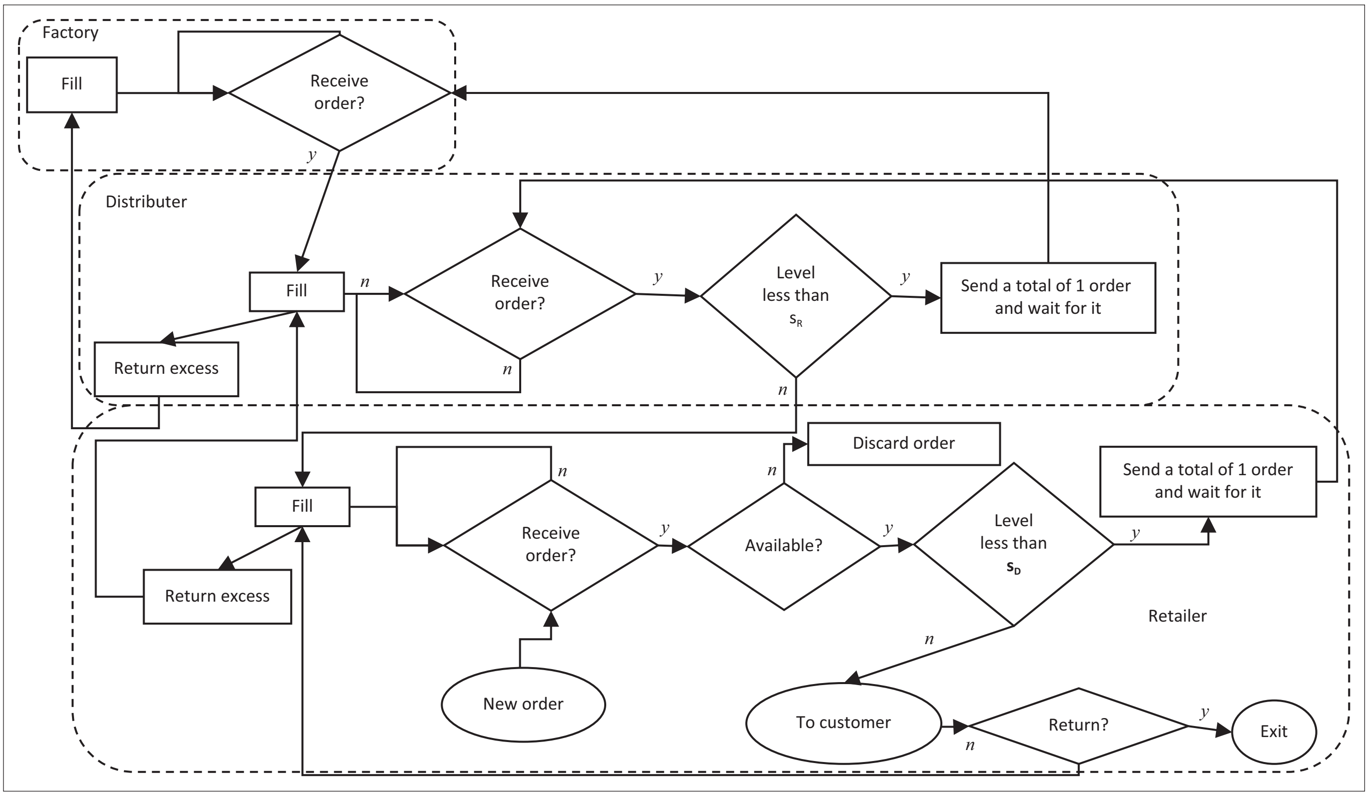
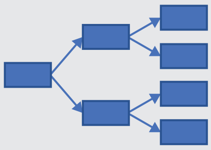
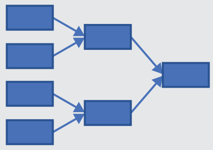
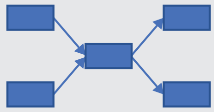


FIGURE 2: The flowchart of the model used.

TABLE 1: The selected supply chain designs for numerical experimentation.

Variable	Serial	Divergent	Convergent	General
Visual				
T	4	4	4	4
N	4	11	8	7
L	4	11	9	7
TN	4	11	8	7
LK	4	14	9	8
Alpha	0	0	0	0
Beta	1	1	1	1
Gamma	1	1	1	1
MFC	8	25	17	15

T, the number of tiers of the supply chain structure; N, the number of nodes in the supply chain structure; L, the number of output links per node; TN, the number of nodes; LK, the number of links at the supply chain structure; MFC, modified flow complexity.

TABLE 2: Parameters used in the model.

Factor	S_f	s_f	S_d	s_d	D
Values	900, 1200, 1800, 2500, 4000	100	180, 250, 400, 600	20	2, 4, 8

the reorder point is kept unchanged, as well as the inventory policy parameters at the retailer. All tested parameters are given in Table 2.

From Table 1, we build four simulation models for the different structures shown in the headers of Table 1.

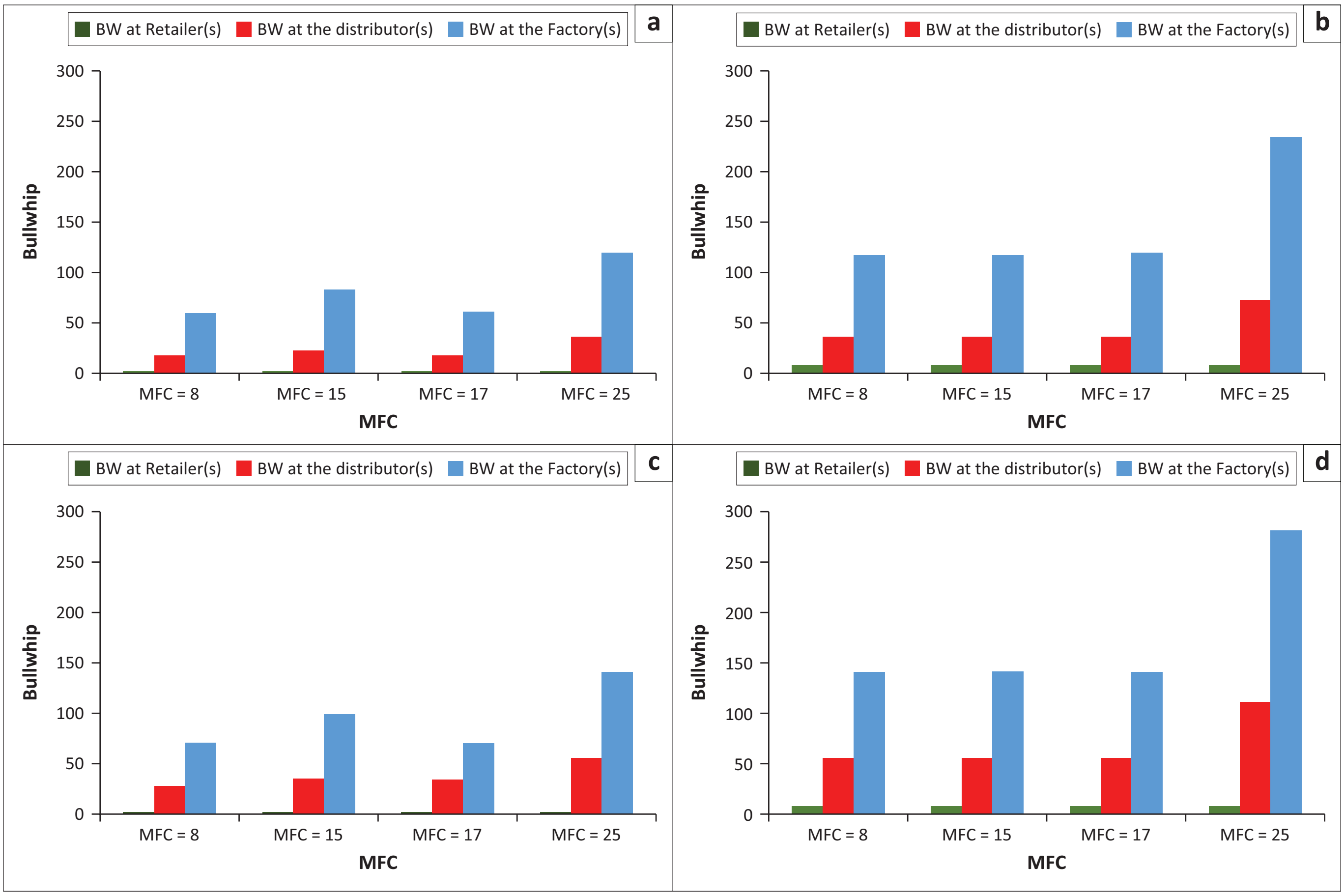
Instead of focussing on the four configurations, we want to extend the results to cover other configurations not covered here. So factorial analysis is adopted with a measurement related to structural complexity, MFC in that case. In other words, the structural complexity of the four configurations is represented by levels in the factorial analysis: 8, 15, 17 and 25. These values are the MFC indicator values as calculated in the 'Structural complexity measurement' section. It is a weighted average of the number of tiers, nodes and links of any supply chain structure.

A simulation model was developed for each tested supply chain structure using ProModel 32bit on an Intel i3-4050u, 4GB RAM and 64-bit Windows 10 notebook. The used demand and inventory parameter values are given in Table 2. For each combination of the values in the table, five replications are run, each for 100 years with a similar warm-up period. The same stream feed is used for distribution so that the comparison stays valid. After running the model, the standard deviation of delivery quantity for both the distributor and the factory is computed (i.e. the quantity delivered to the retailer and the distributor, respectively).

Results and discussion

The presence of the bullwhip effect phenomenon can be noticed in the tested structures, as shown in Figure 3. In each of the four instances, there was an increase in demand variability (measured by the standard deviation of demand) from the retailer(s) to the factory(s). The bullwhip effect is shown to intensify when the demand standard deviation at the retailer(s) increases, from a standard deviation of 2 (as shown in Figure 3[a] and 3[c]) to a standard deviation of 8 (as shown in Figure 3[b] and 3[d]), which match all results in previous literature. The inventory policy significantly contributed to the amplification of the bullwhip effect. Specifically, when the demand standard deviation at the retailers was 2 and the inventory policy stayed the same (as in Figure 3[a] and 3[b] and also in Figure 3[c] and 3[d]), the bullwhip has increased in both cases. The structure of the supply chain from MFC = 8 to MFC = 25 has shown an effect in damping the bullwhip for structures with low and moderate complexities (MFC = 8,15 and 17). The inventory policy also affects the results. When the demand variation is fixed (as in Figure 3[a] and Figure 3[c] and also as in 3[b] and 3[d]), the bullwhip has increased because of the change in the inventory policies. It is obvious from the figure that the structure affects the level of increase and not necessarily that the more complex ones show more bullwhip.

When altering the structural complexities, it becomes evident that increasing the MFC results in amplified bullwhip effects, particularly between MFC values of 8 and 25. For MFC values of 15 and 17, the increase in bullwhip amplification is not consistent. It is reduced for D=2 and remains relatively stable for D = 8. The amplification of bullwhip is clearly influenced by the increase in demand variability, the change in inventory policy and the increased complexity of the supply chain structure. In order to address the impact of the bullwhip effect, it is necessary to examine the interaction between these three components. To do this, factorial analysis is conducted to analyse the outcomes of the various tested structures, demands and inventory policies at both distributors and factories. The findings of this analysis can be found in Figure 4 and Figure 5.



BW, bullwhip; MFC, modified flow complexity.

FIGURE 3: The bullwhip at four different instances: (a) D = 2, Sf = 1800, Sd = 180; (b) D = 8, Sf = 1800, Sd = 180; (c) D = 2, S_f = 2500, S_d = 400 and (d) D = 8, S_f = 2500, S_d = 400.

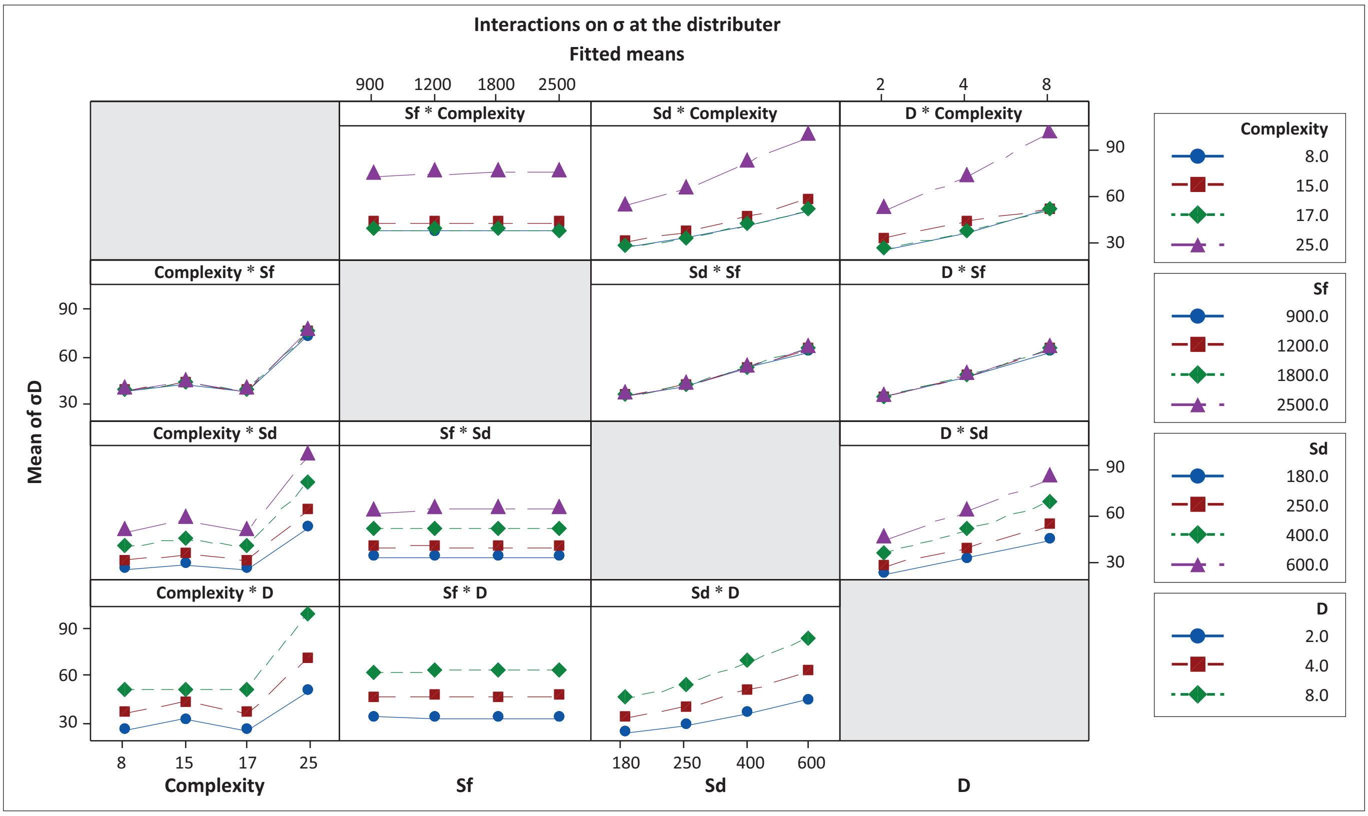


FIGURE 4: Interactions of the factors affecting the standard deviation of delivery quantity at the retailer.

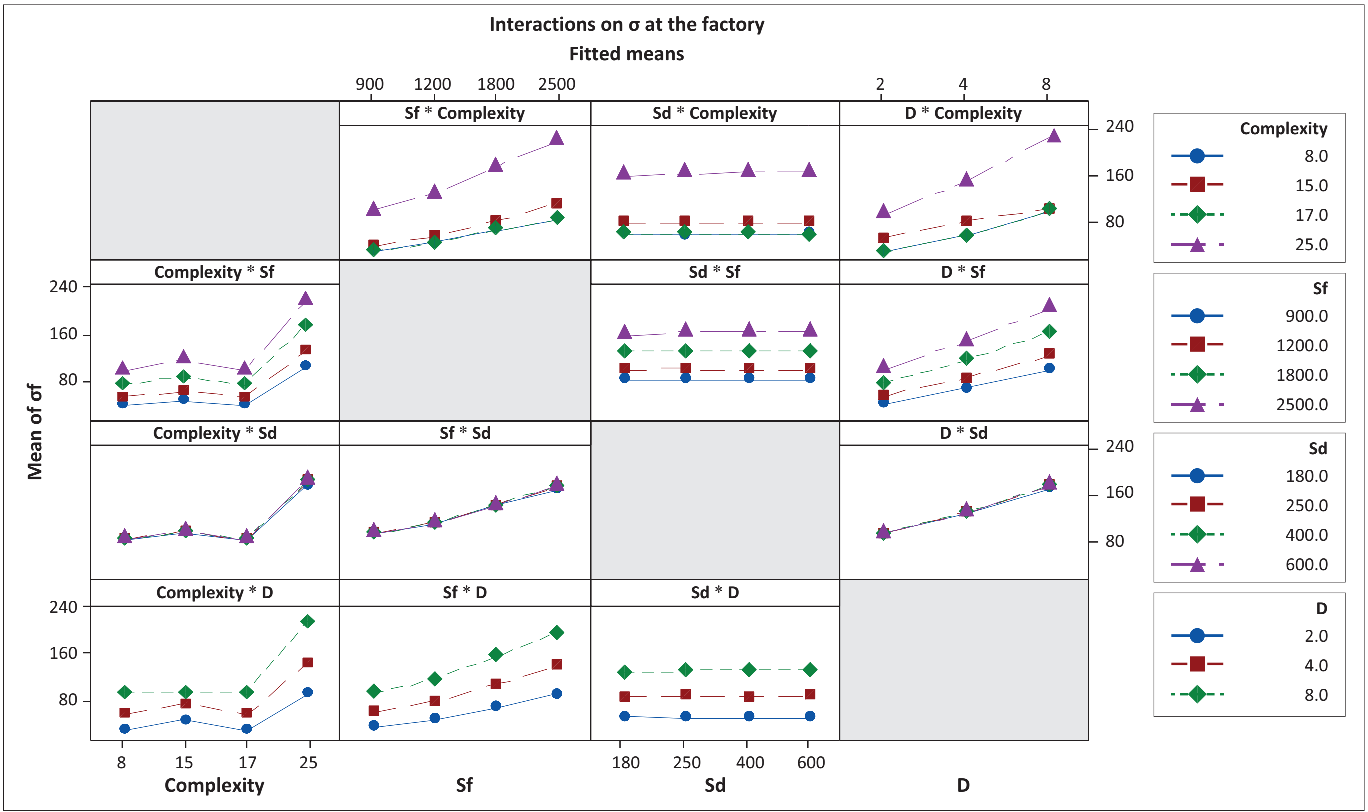


FIGURE 5: Interactions of the factors affecting the standard deviation of quantity delivery quantity at the distributor.

Figure 4 illustrates the interactions between various parameters at the distributor stage. It is evident that an increase in demand variability leads to a higher bullwhip impact, regardless of the inventory policy or structural complexity. This is evident in the first column of graphs on the right. This aligns with the findings in the literature that the primary cause of the bullwhip effect is the variation in demand at the most downstream member. Based on the second column of graphs from the right in Figure 4, it can be observed that the inventory policy implemented by retailers contributes to the increase in the bullwhip as the 'up to' inventory level increases. This increase can be interpreted as a result of the practice of order batching at retailers. This is recognised as one of the factors that amplify the bullwhip effect (El-Beheiry et al. 2004). Changing the inventory policy S_f (order batching) at the distributors did not have any discernible impact on the bullwhip effect. The graphs overlap for all values of S_f, as shown in the second column from the right. This is because the batching at the upper stream member not affecting the bullwhip at the lower stream member. For this same reason, the graphs in the third column showing the interaction of S_f at the distributor are overlapping with the different factors. The fourth column illustrates the interaction between supply chain complexity and other factors. Supply chain complexity influences the bullwhip, contributing to its amplification when demand fluctuation and inventory 'up to' level increase at the retailer level. Because the inventory 'up to' quantity at the distributor (S_f) does not impact the bullwhip at the distributors, the curves coincide when the 'S_f' values are changed. The impact of the supply chain complexity is clearly evident when the MFC is high, specifically at a value of 25. However, at intermediate values, a conflicting tendency emerges, as observed at complexity levels of 15 and 17. The complexity of 15 exhibits a higher standard deviation (s_d) compared to the complexity of 17. This can be attributed to the presence of more factories at the most upstream stage, which helps mitigate the bullwhip effect at the distributors. Specifically, the most upstream stage includes 2 factories at MFC = 15, but only 4 factories at MFC = 17. It is noteworthy that this inconsistency diminishes as the demand variability increases. Specifically, when the demand standard deviation is 8, the bullwhip is nearly identical for MFC values of 15 and 17.

Figure 5 measures the bullwhip effect at the factories measured by s_f. All factors exhibit similar behaviour, except for the interaction with the inventory 'up to' quantity at the retailer level, which shows no impact on the bullwhip. However, the bullwhip effect increases as the 'up to' quantity at the distributor level increases. This is because the inventory policy influences the bullwhip at the higher level just as it reflects the order batching to the higher stage.

Conclusion

This research seeks to quantitatively illustrate the relationship between the structural complexity of the supply chain and the bullwhip effect. The study also examines the potential interaction of operational factors, such as demand variability and inventory policy parameters, on the bullwhip. The findings demonstrated that the bullwhip effect is influenced by the structural complexity of the supply chain, and it intensifies as the complexity of the chain increases. Moreover, variations in demand and the parameters of inventory policy contribute to the amplification of the bullwhip effect throughout all levels of the supply chain. This amplification increases with the supply chain complexity increase, especially at higher levels of the MFC.

In comparing the study outcomes to the literature, it is widely acceptable that increasing the structural complexity (serial and divergent) leads to an increase in the bullwhip. No trials were made to try to relate another type of structure's complexities to the bullwhip effect (convergent and general). However, increasing the demand variability affects the results. When the demand variability is high, only the divergent structure (highly complex structure) amplifies the bullwhip effect. The effect of structure complexity diminished because of the high demand variability from the retail. Also, it was found that inventory max level interacts with the complexity in further amplifying or damping the bullwhip, but if this interaction takes place at a distributor, it does not significantly affect the bullwhip at the factory and vice versa.

The study suggests that supply network architects should consider the structural complexity when building supply chains. This might potentially reduce fluctuations in demand among upstream members, hence enhancing the overall operation of the supply chain. Yet, more investigation of the supply chain structural complexity measures should be made to ensure that all structural parameters are included such as the maximum number of links emerging from a node, a node is being supplied from a sub-supplier tier, etc. Nevertheless, because of the sporadic nature of demand among higher-level members, it may be necessary to develop new measures to accurately assess the bullwhip effect in circumstances of intermittent demand. Furthermore, further investigation into the influence of supply chain structural complexity in such scenarios may be required.

This study is a quantitative study based on the (S,s) inventory policy and on the logic used in the simulation. Although the logic is common in some supply chains such as FMCGs, consumer electronics, pharmaceuticals, etc., every industry has different dynamics within its supply chain. So, the study could be extended and applied in the supply chain of specific industries. Other inventory policies such as (Q,r) need to be analysed.

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Competing interests

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Authors' contributions

The authors have met all the criteria for authorship and contributed positively. M.E.-B. is the main supervisor who suggested the idea. Y.A. collaborated with M.E.-B. to develop the methodology and conduct the formal analysis. T.I. further developed the methodology alongside R.T., who worked on the software and wrote the initial report. All authors participated in analysing the results.

Ethical considerations

This article does not contain any studies involving human participants performed by any of the authors.

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Data availability

The authors confirm that the data supporting the findings of this study are available within the article.

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