Mitigation of the Bullwhip Effect Using Distributed Ledger and Confidential Computing Technologies

ANTÓNIO DUARTE NEVES PARREIRA DE MATOS
(BSC in Computer Science)

Master's thesis to obtain the master's degree in Industrial Engineering & Management

Supervisors:
Doctor António João Pina da Costa Feliciano Abreu,
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Jury:
Chairman: Doctor Vitor Manuel Rodrigues Anes
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Thank you to everyone, my friends and family, to all of you—this work belongs to you.

Statement of integrity

I declare that this dissertation is the result of my personal and independent research. Its content is original, and all sources listed in the bibliographic references were consulted and are duly mentioned in the text. I further declare that all scientific and technical references relevant to the development of the work are duly cited and included in the bibliographic references.

The author

Antonio Duarte Matos

Lisbon, November 2024

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Resumo

A gestão moderna da cadeia de abastecimento enfrenta uma série de desafios, entre os quais a necessidade de globalização, indisponibilidade de materiais, crescente pressão regulatória e aumento requisitos tecnológicos. Entre estes desafios, a variabilidade da procura destaca-se devido ao seu impacto significativo na gestão de operações, particularmente num ambiente cada vez mais VUCA (Volatilidade, Incerteza, Complexidade, Ambiguidade). À medida que as empresas navegam neste cenário complexo, a necessidade de previsões precisas torna-se crucial para gerir eficazmente os stocks, reduzir interrupções e otimizar a eficiência operacional.

Esta tese explora a aplicação das tecnologias blockchain em combinação com tecnologias de computação confidencial para melhorar os métodos tradicionais de previsão e mitigar o efeito chicote — um fenómeno em que significativas flutuações na procura do consumidor levam a variações cada vez maiores nas encomendas feitas ao longo da cadeia de abastecimento. Ao possibilitar a partilha segura, anónima e fiável de dados em tempo real entre os participantes da cadeia de abastecimento, estas tecnologias oferecem mecanismos promissores para melhorar a gestão de stocks, reduzir custos operacionais e evitar interrupções na procura. A simulação demonstrou uma melhoria nas previsões sempre acima de 14%, podendo ultrapassar a marca dos 100% nos mais variados cenários testados, além de uma melhoria significativa na quantidade de stock gerido.

O estudo demonstra que a integração do blockchain e da computação confidencial na gestão da cadeia de abastecimento promete melhorar significativamente a precisão das previsões de procura, mantendo a privacidade e a segurança dos dados, contribuindo assim para operações da cadeia de abastecimento mais resilientes e ágeis.

Palavras-chave: Bullwhip Effect; Blockchain; Distributed Ledger Technologies; Confidential Computing.

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Abstract

The Modern supply chain management faces a range of challenges, including globalization obligations, material disruptions, increasing regulatory pressure, or increasing technological requirements. Among these challenges, demand variability stands out due to its significant impact on operations management, particularly in an increasingly VUCA (Volatility, Uncertainty, Complexity, Ambiguity) environment. As companies navigate this complex landscape, the need for accurate forecasting becomes crucial to effectively manage stocks, reduce disruptions, and optimize operational efficiency.

This thesis explores the application of blockchain technology combined with confidential computing to enhance traditional forecasting methods and mitigate the bullwhip effect—a phenomenon where significative fluctuations in consumer demand lead to increasingly larger variations in orders along the supply chain. By enabling a secure, anonymous, and reliable sharing of real-time data among supply chain participants, these technologies offer promising mechanisms to improve stock management, reduce operational costs, and prevent demand disruptions. The simulation demonstrated an improvement in forecasts always exceeding 14% and potentially surpassing the 100% mark across various tested scenarios, along with a significant enhancement in stock management efficiency.

The study demonstrates that integrating blockchain and confidential computing into supply chain management can significantly enhance the accuracy of demand forecasts while maintaining data privacy and security, ultimately contributing to more resilient and agile supply chain operations.

Keywords: Bullwhip Effect; Blockchain; Distributed Ledger Technologies; Confidential Computing.

Abbreviation List

AML Anti Money Laundering
API Application Programming Interface
BWE Bullwhip effect
CA Certificate Authority
CC Confidential Computing
CSS Cascading Style Sheets
DLT Distributed Ledger Technologies
ERP Enterprise Resource Planning
GDPR General Data Protection Regulation
HLF Hyperledger Fabric
HTML Hyper Text Modeling Language
HTTP Hyper Text Transfer Protocol
IoT Internet of Things
KPI Key Performance Indicator
KYC Know Your Customer
KYS Know Your Supplier
MSP Membership Service Provider
PoS Proof of Stake
PoW Proof of Work
SGX Software Guard Extensions
SS Safety Stock
SSL Secure Sockets Layer
TLS Transport Layer Security
VUCA Volatility, Uncertainty, Complexity, and Ambiguity

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1 Introduction

1.1 Motivation

The Supply chain management relates to all the processes and their inner activities involved, from the production to the delivery of a given product or service. These include all the actions performed by all the direct and indirect participants in the chain, whether they are customers, retailers, transporters, wholesalers, manufacturers, or material suppliers (Chin et al, 2015).

Currently, the supply chain is facing numerous challenges that impact its efficiency and effectiveness. Among them, globalization, regulatory compliance, material disruptions, technological integration, sustainability, and increasing requirements for relationship management. These sorts of issues arise from factors such as technological advancements, market dynamics or sustainability related concerns and legislation, among others. Also, The more nowadays-businesses are required to think global and expand beyond borders, the more they are exposed to multiple and various regional regulations, market demands, and supply-chain designs. Investing on a globalization compatible strategy requires these companies to cope with advanced and agile coordination and communication strategies that ensure goods are delivered on time, on quality, and on a cost-effective manner (Chopra et al, 2007).

More and more enterprises in the Industrial sector must comply with systematically increasing regulations regarding concepts such as product safety, environmental protection, or labor laws, that end up shaping the way operations in the supply chain are executed. Being up to date with all these regulations is quite challenging for companies as these naturally operate in multiple and dynamic jurisdictions (Harrison et al, 2019). Also, as the awareness of environmental and social issues gets more and more relevant, these corporates must urge to adopt sustainable-compliant practices in their operations, for instance, minimizing waste, reducing CO2 emissions, or ensuring ethical sourcing and labor standards.

Additionally, supply chains face additional non-avoidable risks such as eventual exposure to political instability, digital threats or even natural disasters that are each day more common. This forces companies to implement effective risk management strategies if they want to continue being active. (Tang et al, 2006).

Supply chains must also be quickly and effectively responsive to dynamic market configurations, these include agility to deal with multiple consumer profiles, different competitiveness landscape, economic scopes, and trends. Therefore, being capable of performing an accurate demand forecasting that attends to all these variables while being able to adjust their operations, accordingly, is critical to maintaining a competitive edge. (Ivanov et al, 2019).

The bullwhip effect (BWE) in supply chain management refers to the issues arising from variability in product demand, that could not be predicted by forecasting operations, especially when subjected to hard peaks on demand. This phenomenon is characterized by the amplification of demand fluctuations as they move forward in the supply chain, from consumers to material suppliers. These concepts are known in literature as *demand distortion* and *variance amplification (Fransoo et a, 2021).*

The causes of the bullwhip effect can be broadly categorized into operational and behavioral factors.

Among operational causes are:

- Forecasting inaccuracies leading to deficient inventory management.
- Lack of communication, collaboration and synchronization between supply chain partners often results in demand misalignment.
- Price fluctuations that result in irregular buying patterns, emphasizing demand variability and amplifying demand spikes.
- Longer lead times apart of being annoying to the costumers as the end products won't arrive on-time, can contribute to demand amplification.
- Putting and exaggerated focus on the optimization of certain processes without considering the supply chain as a whole, can lead to inefficiencies.
- Limited production further results in bigger demand amplification.

Behavioral causes include factors such as:

- Underestimation of delays in order processing, which leads to miscalculated orderings.
- Lack of expertise in correlation with an ineffective management of demand.
- Excessive fear of stockouts that can trigger an over-ordering behavior, resulting in more variability of demand in the supply chain ending up on creating or aggravating the BWE (Bhattacharya et al, 2011).

The occurence of BWE leads to several negative outcomes, from increased direct costs due to overproduction, delays, additional need for human, technical and material resources in a short period of time, management of excessive stock that translates into higher costs, and for some companies the worst of them - inability of meeting customer needs.

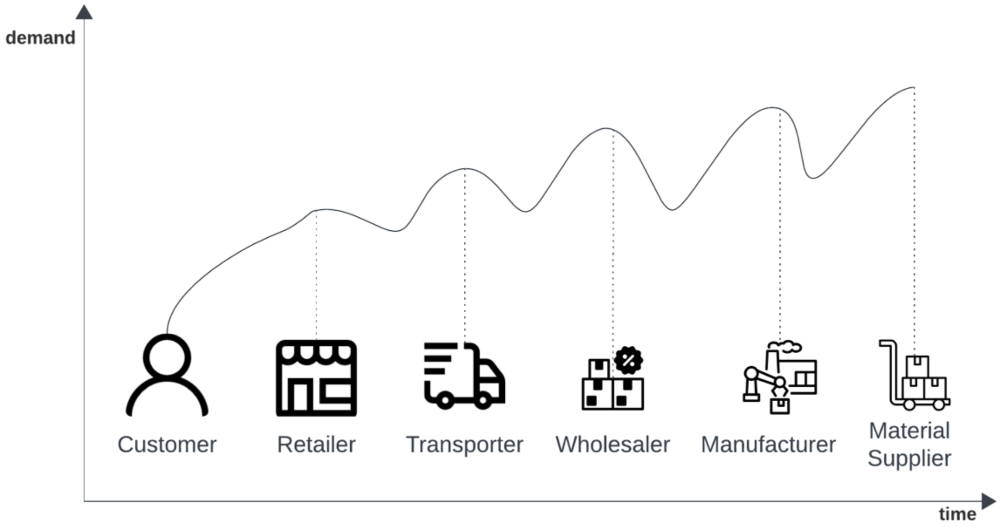

Figure 1.1 - Overview of the Bullwhip Effect

Certain authors defend that market behaviors are inherently unpredictable; As Burton G. Malkiel states in “A random walk down Wall Street”, it is not possible to precisely guess the market (customers) behavior, and trying to do so won’t result in a positive outcome (Malkiel, 2019). Despite the focus of the book being the financial markets, the same principles can be applied to other industries.

At the same time, companies in the supply chain leverage sophisticated forecasting methods trying to predict necessary stock levels as accurately as possible. These methods often collect data from multiple sources and must consider complex variables such as seasonality, consumer trends, and other relevant information. Despite these efforts, forecasting is an inexact science and must be approached with caution, meaning companies shouldn't count blindly on the figures forecasting activities provide.

This is a complex matter – In one hand, when forecasting figures are overestimated, companies are forced to manage excessive inventory which results in increased maintenance costs that arise from additional storage needs, insurance of more items, and eventual obsolescence as products might not be consumed in time. On the other hand, as discussed, underestimating demand can result in insufficient stock, that causes companies to be unable to satisfy their customer needs, which can result in a chain of negative outcomes, such as lost sales, negative customer feedback, and eventual loss of clients (Lee et al, 1997).

The Bullwhip effect (BWE) has been exhaustively identified and discussed in literature, thus, some initiatives have tried to act in such problematic. Nevertheless, most end up being insufficient due to several factors, such as:

- **Business secrecy and lack of trust** - Participants don't want to share confidential/private information towards a common solution as it can be used to their disadvantage by competitors or partners.
- **Competitive advantage** – Supply Chain participants, often see their management strategies and operations as competitive advantages. Therefore, they think twice before sharing information that could potentially reveal more than they wanted to share.
- **Regulatory and Privacy Issues** - Regulatory compliance, particularly concerning data privacy laws like General Data Protection Regulation (GDPR), impose restrictions regarding the nature and content of data that can be shared.
- **Systems integration** - Different participants in the supply chain use different IT systems that are by default not directly integrable, making it technically challenging to share information (Barrat et al, 2001).

1.2 Research question and objectives

This work aims to explore how Distributed Ledger Technologies (DLTs) combined with Confidential Computing (CC) can be leveraged to mitigate the Bullwhip Effect by discussing and demonstrating how these technologies can be applied on a supply chain environment to address the challenges of demand variability preventing or mitigating the occurrence of a bullwhip effect, while data privacy is confidentiality is preserved. By combining these technologies, the proposed solution seeks to enhance data transparency, trust, and collaboration among supply chain participants, ultimately reducing the negative impacts of the Bullwhip Effect.

The expected outcome of this work is to prove that DLT and CC can be effective on preventing or minimizing the bullwhip effect by enable participant to access new relevant and accurate data to improve their forecasted figures, without breaking any confidentiality or exposing business secrecy.

1.3 Hypothesis

For a forecasted figure *f1*, using traditional methods, there is a forecasted figure *f2* for the same period that can generate a more accurate estimation for the actual demand *D*, by applying Blockchain and Confidential computing technologies:

$$|D - f2| \leq |D - f1| \tag{1.1}$$

Where:

- *D* represents the actual demand,
- *f1* represents the demand forecasted figures using the traditional approach (no DLT or CC),
- *f2* represents the forecasted figures of a scenario that leverages the data shared and processed by DLTs and CC.

1.4 Dissertation Structure

This dissertation is organized into five main chapters. Chapter 1 introduces the research context, outlining the motivation behind studying supply chain management and technological solutions to mitigate the Bullwhip Effect, also presenting the research question, objectives, and hypothesis.

In Chapter 2, an in-depth literature review is conducted, focusing on both the fundamentals of operations management in Supply Chain and the challenges faced by the modern supply chain configurations. Then, it also dives into Distributed Ledger

Technologies, and Confidential Computing, to approach how these can potentially address the Bullwhip Effect.

Chapter 3 introduces the theoretical framework for implementing Distributed Ledger Technologies in supply chains. Exploring different Blockchain configurations, consensus mechanisms, and Confidential Computing, culminating in a proposed framework that integrates these elements.

Chapter 4 focuses on a practical implementation of a proof of concept. It describes the testing scenarios used to assess the blockchain-based supply chain against traditional methods. Key metrics such as forecasting accuracy, stock management, and disruption frequency are analyzed to demonstrate the model’s potential to act on the problematic of the study.

Finally, Chapter 5 presents the main conclusions of the study, summarizing the findings and offering suggestions for future research. The thesis concludes with a reflection on how blockchain and DLT frameworks can enhance supply chain forecasting, reduce disruptions, and improve operational efficiency.

2 A Comprehensive Review of Supply Chain Management and Technological Solutions to Mitigate the Bullwhip Effect

Supply chain management encompasses a wide range of activities meant to ensure a smooth flow of goods, information, and finances from the initial supplier to the final consumer. These operations are critical for maintaining efficiency, keeping costs low, and meeting customer demands. Figure 2.1, illustrates an overview of the key operations within the supply chain:

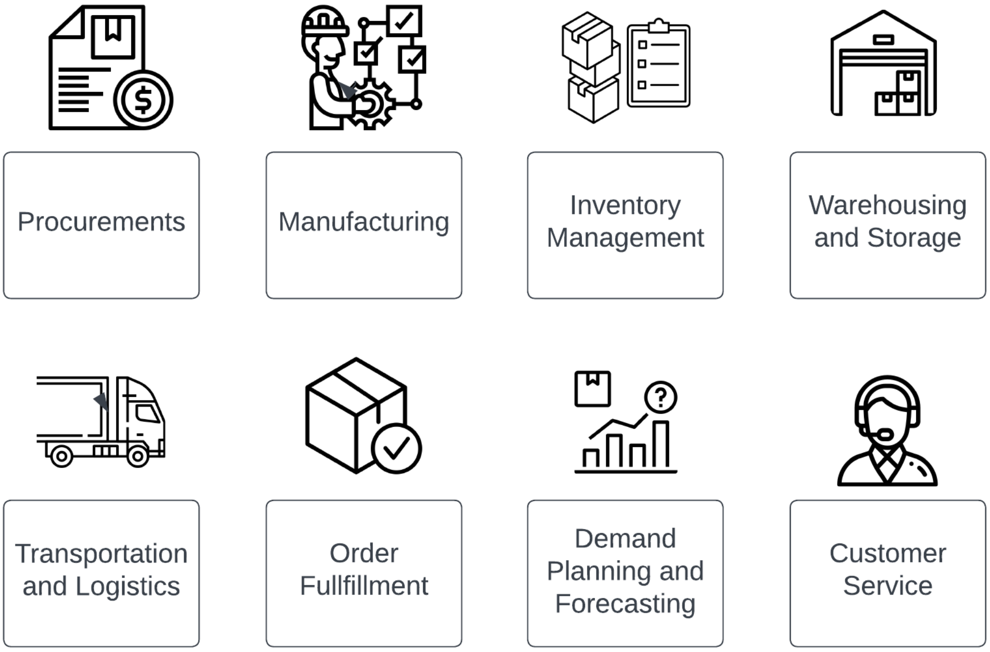

Figure 2.1- Supply chain key operations

- **Procurement:** Includes searching, negotiating and purchasing all raw and composed materials, components, or services required to produce the final product. In a nutshell, its main goal is to ensure good-quality materials are purchased at competitive prices (Monczka et al, 2008).

- **Manufacturing**: This stage refers to the process of transforming of raw materials into finished goods through manufacturing operations. Efficient production management aims for an optimal use of resources, production schedules, and quality control (Stevenson, 2014).
- **Inventory Management**: The costs associated with holding inventory and the need to meet customer demand are the two sides to take into account when it comes to inventory management. This requires an agile management of stock and order fulfillment (Silver et al, 1998).
- **Warehousing and Storage**: Warehouses play a vital role on raw material storage, work-in-progress items, and finished goods. When done effectively, these ensure accurately storage and physical accessibility to material, tools and products (Richards, 2017).
- **Transportation and Logistics**: Effective logistics management ensures timely delivery, cost efficiency, and the proper handling of units. The effectiveness of managing Transportation and Logistics has a direct relationship with the final price (Coyle, 2021).
- **Order Fulfillment**: This process includes processing, responding to, and delivering customer orders. It requires a high orchestration between supply chain activities to ensure that customers receive their products as they requested them. Ideally, customer requests and fully met (Chopra et al, 2016).
- **Forecasting and Planning**: An efficient demand forecasting helps planning production activities, procurements, and inventory management. It may require companies to look at historical data, market trends, and customer behavior. Optimally, forecasting figures must be contained withing a satisfactory threshold attending to the specific requisites of a given business. (Mentzer et al, 2004).
- **Customer Service**: Ensuring customer satisfaction is a critical component of supply chain management in today’s industrial world. Enabling the ability to manage returns, process customer inquiries, and post-sales assistance is key for operations. This encompasses product being delivered on time, in quantity, with the quality and the costs expected by a client (Johnston et al, 2005).

2.1 Operations Management – Definition and importance

Operations management seeks an efficient management of resources to produce and deliver products and services. Every organization manages its own specific operations, as all of them are involved on making products and/or services available (Slack et al, 2010).

The supply chain can be seen as network of suppliers, manufacturers, warehouses, distribution centers, and retailers, all working together to deliver products to the end consumer. Therefore, A management of operations done correctly ensures that each node of this network functions efficiently, minimizing delays, reducing costs, and maintaining high levels of customer satisfaction. If all nodes succeed the supply chain succeeds.

One of the main reasons why an efficient management of operations is key for companies is the impact it has on the financial life of a company. When done efficiently, operations management reduce operational expenditures in multiple ways, such as reducing the waste and noise resultant from production activities, optimizing resource utilization, and standardize processes.

Nowadays, by adopting methodologies such as Lean and Six Sigma, organizations can identify and solve some of the inefficiencies of their processes, which ultimately results in an effective reduction in costs. While Lean puts a strong focus on maximizing the value while minimizing the resources consumed, Six Sigma aims to improve the quality and avoid defective products. Both methodologies not only aim to reduce costs but also improve customer satisfaction, and therefore sales (Liker et al, 2004).

Additionally, a well performed management of operations, pursues an optimal utilization of material production resources, such as materials, and equipment. By performing a detailed planning and scheduling of production activities, organizations prevent overproduction and minimize inventory management costs, while reducing their downtime. This leads to an improved use of capital and operational budgets, facilitating the allocation of resources required by multiple relevant initiatives. Also, by optimizing routes, shipments, and leveraging economies of scale, organizations can significantly reduce these costs (Coyle et al, 2021).

2.2 Key Aspects of Efficient Operations Management in Supply Chain

Certain factors demand special attention to keep processes effective and resilient within the management of operations. This section discusses some of the most sensitive factors that are essential to achieve a well-coordinated and adaptable supply chain system.

2.2.1 Customer Satisfaction

Customers are the most important aspect of any business, regardless of the industry, because their satisfaction and loyalty directly influence revenue, growth, and the long-term sustainability of the organization. Thus, an efficient operations management must ensure achieving acceptable levels of customer satisfaction. This is increasingly important in current times in such competitive landscape. In short, companies must ensure an excellent delivery of products and services subject to quality standards. This plays a significant role in maintaining positive public feedback, fostering long-lasting relationships with customers, and increasing their customer network through the best form of marketing possible – mouth-to-mouth (Stevenson, 2007).

Another relevant aspect highly involved in customer satisfaction is Quality Control and Assurance. These processes are designed to ensure that the products and services delivered exceeded, or at least met client expectations. Quality outputs not only translate into a pleasant experience for the customer, but it also reduces the chances of delivering defective products to clients, which translates into costs and additional processes. (Evans et al, 2010).

Additionally, the ability to consistently comply with customer demand is important to ensure that products are available when needed. This not only mitigates the possibility of losing sales, but also invites clients to repeat business and stay loyal to these companies, given that happy customers are more likely to maintain an active relationship with the same company (Mentzer et al, 2004).

2.2.2 Competitive Advantage

Today's market landscape can be described as dynamic and highly competitive, therefore the ability of staying competitive is crucial for any organization in any industry. Competitive advantage refers to the ability one company has of outperform its competitors in one or multiple areas.

Increasingly over the years, agility has become essential for companies that aim to conquer or maintain a competitive advantage. One of the key aspects of the contemporary market is the rapidly changing customer preferences, market configurations, and technological advancements that affect the shape of the final product and the processes involved on its creation and delivery. Flexibility is critical aspect in this context, as it requires companies to be aware of the trends, requirements, and customer profiles if they want to be competitive. (Gaudenzi et al, 2016). A good example of that is the online shopping – companies that didn't succeed on complying with this new way of doing business certainly lost competitiveness to others that did.

The ability to innovate is another critical component of a competitive advantage. While industries face an increasingly fast pace of innovation, the ability to quickly adapt and integrate new technologies and procedures is crucial for offering better products and services. (Porter, 1985).

Optimizing processes and reducing costs are also key to the survival of modern organizations. Beyond cost efficiency – more and more relevant, the public image of a company that is known for operational excellence gains more value. Customers and partners are more likely to respect, trust and engage with companies that demonstrate operational excellence (Heizer et al, 2017). Moreover, companies renowned for their operational efficiency are also more likely to attract and retain distinguished talent, further solidifying their competitive position (Barney, 1991).

2.2.3 Risk Management

Risk management is essential for detecting, preventing, and mitigating the effects of potential undesired events on organizational processes - risks. Supply chains are inherently vulnerable to various risks, both internal and external, such as potential unavailability, natural disasters, political instability, economic fluctuations, or even cyber threats. Identifying, assessing, and mitigating these risks to protect the organization from potential disruptions and losses is fundamental to effective operations management (Christopher, 2016).

The first step when adopting a risk management procedure is the risk assessment. At this stage all potential risks should be identified and listed, considering all the processes that combined form the supply chain, from production to distribution. There are certain tools, such as Risk Assessment Matrices and Failure Mode and Effects Analysis (FMEA) designed to identify and prioritize risks based on their probability of happening and the impact they might cause (Tang, 2006). Once risks are identified, companies must focus on defining strategies to avoid or minimize the impact of these risks - known as mitigation and prevention barriers. For example, to mitigate the risk of a supplier being unable to meet demand, a possible prevention barrier is to avoid relying on a single supplier. (Chopra et al, 2004).

A continuity and reliability plan in operations management is another aspect of risk management. In a nutshell it means designing and implementing a plan to ensure the supply chain remains active and operational, and able to recover from eventual disruptions. To do so, companies implement strategies such as geographic diversification, safety stocks, internation law departments, or investment in redundant systems, which can leverage supply chain resilience (Dimitry et al., 2017).

2.2.4 Sustainability

It is 2024 by the time of writing this thesis and sustainability is one of the hot topics of the current society. It has become the word of the day as organizations, governments, and fundamentally, customers are more and more aware of the importance of the environmental cause, making them carefully evaluating how a certain company takes this subject into account before engaging on a new commercial relationship with them. This covers multiple aspects of the Environmental care, from reducing the waste produced to lowering carbon emissions. (Womack & Jones, 2003).

While Lean methodologies focus mostly on the minimization/elimination of waste, organizations are increasingly already investing in renewable energy sources and energy-efficient technologies to power their operations for a few decades at the time of this dissertation. This includes not only the reduction of their carbon footprint but also smart ways to take advantage of these to reduce costs (Porter & van der Linde, 1995).

Moreover, sustainability also includes the design of products with increased durability, reusability, and recyclability in mind, which helps to significantly reduce waste and resource consumption. (Guide et al, 2009).

Finally, social responsibility is another key aspect. For example by ensuring that the company practices safe, clean and fair working conditions for its employees, or ensuring that no communities are impacted in a negative way by any of its activities, companies get better incentives from government, social support and loyalty from customers (Carroll et al, 2010).

2.2.5 Technological Integration

Technological integration is no longer optional - it is a critical necessity for companies that strive to maintain certain levels of competitiveness. Emerging technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), Distributed Ledger Technologies, or mechanical automation, are revolutionizing processes by significantly improve the operational cost, efficiency, and effectiveness of operations. Organizations that fail to innovate, are at a higher risk of falling behind quite fast. This topic plays a key role on this thesis as it proposes the integration of cutting-edge technologies to solve well known industry problems.

One of the technologies driving a technological revolution in supply chain management is the Internet of Things. IoT in a nutshell, connects devices to systems, providing real-time monitoring and collection of data across the supply chain. It mainly consists of physical devices equipped with sensors that can track the location, the condition, the temperature, the atmospheric pressure among other attributes of the device or place – *thing* – where they are installed. For instance, they can be used to check good in transit in real-time, promoting visibility and transparency. Also, later on the usage of this data can optimize routes, monitor inventory levels, or even predict maintenance needs, improving the operational efficiency and reducing the downtime, among other possibilities (Atzoriet al, 2010).

Artificial Intelligence is another transformative technology in operations management. It can be used to process and analyze enormous amounts of data, to identify patterns, collect information, predict eventual outcomes and enable all type of informed decisions. In supply chain management, AI can for instance, improve the demand forecasting, optimize inventory levels, define improved safety stocks, or automate all types of tasks. Machine learning models can also extend these implementations to perform corrective actions and tune fining these processes. (Sharma et al, 2018).

Blockchain and Distributed Ledger Technologies are also gaining adoption in supply chain management due to their ability to provide secure, transparent, and immutable transactions. It also streamlines processes such as payments by automating them through the execution of automatic smart contracts without the need of a central authority. This decentralized nature can for instance increase the trust among supply chain participants that by default don't necessarily trust each other (Kshetri, 2018). This Dissertation puts a strong focus on this technology.

Mechanical automation, powered by state-of-the-art robotics and cutting-edge manufacturing technologies, is revolutionizing production and warehousing operations. Automated systems can perform complex tasks with high precision and speed, reducing labor costs while minimizing errors. In warehouses, automated guided vehicles and robotic arms handle tasks such as picking, packing, and sorting, improving throughput and efficiency (Wang et al., 2016).

Data-driven decision-making is another key aspect of the technological integration. While the technology itself does not take business decisions, it significantly aids the decision maker on the collection, processing, and analysis of data through AI, Big Data, and analytics, which leads to an improved planning and resource allocation (Davenport & Harris, 2007).

2.2.6 Scalability and Flexibility

Particularly in the dynamic and rapidly changing landscape of supply chain management the concept of scalability and flexibility is critical to an efficient management of operations.

Ability to scale means that organizations are able to adapt themselves to diverse and dynamic market configurations such as rapid growth on sales. This ensures that, for instance, when demand grows or shrinks abruptly, or new markets are explored, the supply chain can effectively adapt its capacity and operation to meet these demands in an efficient and cost-effective manner. As an example, scalable physical warehouses enables the eventual addition of new distribution centers, while scalable manufacturing processes allow for increased production volumes without compromising their quality (Heizer et al, 2020).

Flexibility, on the other hand, means to the capacity to adjust efficiently to changes at the product level, for instance responding to abrupt changes on customer preferences, usage of a product, market conditions, or supply chain disruptions. When performed effectively, it allows an organization to change their suppliers, production processes, or even their strategy with a reduced impact. This type of agility is key for maintaining competitiveness in a more and more dynamic market environment (Stevenson, 2007).

It is also worth to emphasize that customer wishes are more and more diverse and personalized, requiring supply chains to be both scalable and flexible (Kotha, 1993).

2.3 Challenges faced by the Supply Chain

The success of a supply-chain network depends on the success of each of its participants, and on the synchronization across every member. This also means, an efficient management of operations on each participant. There are, however, innumerous factors that threat to disrupt these activities, leading to inefficiencies, increased costs, or customer dissatisfaction as depicted in Figure 2.2. Along this section some of those challenges are discussed and analyzed, to provide the reader with a more complete understanding of the complexities of supply chain management.

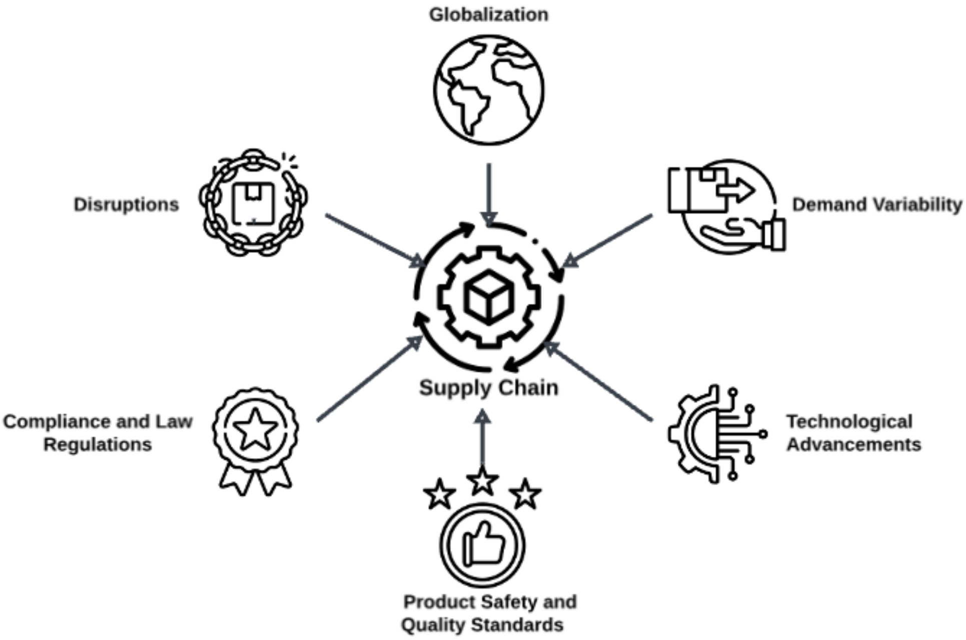

Figure 2.2 - Challenges faced by the Supply Chain

2.3.1 Globalization

Globalization, while being a “source of infinite opportunities” for companies willing to expand their operation geography, promising growth and expansion, also introduces a vast list of challenges. While companies will extend their operations across international borders, they find quite complex issues that threat to impact the efficiency and effectiveness of their operations and the supply chain overall. One of the main hurdles caused by globalization is the complexity that managing international operations is subjected to. Companies must be agile when dealing with different market demands, regulations, and supply lines sizes and configurations.

Also, each country has its own business legislation regarding service guidelines, quality, safety, and environmental impact, which means companies need to implement processes that can be tweaked to comply with all the local laws of the jurisdictions they are operating in. This pushes companies to implement complex coordination and communication strategies that ensure goods move smoothly across borders without being stooped, suffer delays or added with extra costs (Chopra & Meindl, 2016).

Regulatory compliance is a probably the most important challenge in global supply chain management. Companies must adhere to each a year growing list of regulations. This goes from trade laws, customs specific procedures, Anti-money Laundering (AML) and governmental restrictions. The non-conformity can result in hard penalties, delays, disruptions and even unavailability of the final product on the target market. Therefore, staying up to date with all regulations to ensure they remain compliant is crucial to ensure the seamless continuity of operations. This often requires significant resources, specific law departments or legal consultancy to ensure full compliance (Lee, 2013).

Cultural and social differences also affect an international supply chain as each region of the globe has a unique set of consumer preferences, behaviors, and market configurations. To benefit from expanding to new markets, companies must adapt their products and marketing efforts to fit the specific needs and expectations of different public, which requires an in-depth preparation (Gaudenzi et al, 2016).

Additionally, globalization typically leads to longer or wider supply chains, sometimes dependent on multiple jurisdictions, providers and partners. This increases the complexity of managing lead times and inventory. Given that these deliveries have to travel greater distances, often by multiple transport means, while subjected to eventual geopolitical instability, natural disasters, or logistical bottlenecks, the implementation of practices that analyses all potential risks and seek the continuity of the supply chain, specifically designed to act on globalization. (Dmitry et al, 2019).

2.3.2 Supply Chain Disruptions

Supply chain disruptions are unexpected events that interrupt the normal flow of goods and materials within a supply chain. These often have major impacts on the ability of companies to ensure a product is delivered to its final customer, maintain sufficient and adequate inventory levels, while achieving their financial targets. Understanding the inner causes that lead to these supply chain disruptions, as well as developing strategies to mitigate these risks, is crucial for maintaining supply chain resilience and efficiency. These causes can have multiple types of natures, such as natural disasters, political instability, economic fluctuations, technological failures, supplier issues, logistical bottlenecks, among others (Martin, 2021).

2.3.3 Technological advancements

Technological advancements have significantly transformed the way supply chain management is performed by offering new tools and methods to improve efficiency, visibility, and coordination. Nevertheless, integrating these technologies into existing supply chain processes comes with a list of challenges. Ensuring cybersecurity, maintaining accuracy and integrity of data, and achieving a seamless integration across different systems that often are managed by different parties, are substantial hurdles that organizations need to address (Dmitry et al, 2019).

As digital technologies become an increasingly important part of a supply chain, they also increase the digital threat, such as data breaches, hacker attacks, and espionage as the companies have an increased online presence. These threats can disrupt operations, compromise sensitive data, lead to high financial losses and ultimately push a company out of business. Implementing strong cybersecurity mechanisms, which includes encryption, advanced user access control, and continuous monitoring, is crucial to protect supply chain operations systems and the data in them contained from malicious actors (Melnyk et al, 2016).

In parallel, ensuring data veracity, integrity and confidentiality is challenging due to the vast amount of data generated and shared across multiple digital sources. During the last century, most industrial systems are fed with data that originaties from multiple origins, such like IoT devices, Enterprise Resource Planning (ERP) systems, or other network sources. Data versioning, eventual errors, deficient access management and information inconsistencies can lead to poor decision-making, process inefficiencies, and augmented costs, specially nowadays as systems tend to become more and more automatic. Setting data quality standards and utilizing the right methodologies and tools can help maintain the accuracy and integrity of supply chain data. But this also comes with costs associated to it (Wang et al., 2016).

Typically various stakeholders are involved in supply chain, from suppliers, manufacturers, logistics providers, and retailers, each of them using their systems and platforms, and sometimes these are not fully compatible. Achieving an accurate integration and interoperability among their systems can be challenging. Organizations must invest in technologies that facilitate data exchange and process integration, such as application programming interfaces (API) and integration solutions. But this comes also with the need to establish protocols as the systems need to talk to each other but they must know how to talk to each other. Standardizing data formats and communication protocols can also enhance interoperability and streamline operations (Sodhi et al, 2012).

Also, introducing new technologies often faces resistance from employees and partners used to legacy processes and systems. Effective change management strategies, including stakeholder engagement, training programs, and clear communication of the benefits, are essential to overcome resistance and ensure successful technology adoption. And this is a statement since the last century. It also is associated with some costs, as companies require dedicated persons or teams actively looking onto the technological advancements. On the other hand, if companies don’t, they won’t definitely be up to date with the cutting edge technological advancements (Kotter, 1996).

2.3.4 Compliance and Legal Regulations

Getting up to date with compliance and legal regulations in this complex landscape is a nightmare for every organization in supply chain management. They must adhere to an “infinite” list of laws and regulations that dictate rules and procedures to various aspects of their operations. This is especially relevant for companies acting internationally, as they are part of supply chains that extend to multiple countries, each setting its own set of laws. Among these, they find multiple trade regulations, national level procedures, and business restrictions, which be significantly different across regions. For instance, the European Union's GDPR imposes strict requirements on data privacy, affecting the way companies handle and process personal identifiable data across their jurisdictions, forcing companies from other regions to implement these before exploring the european market (Voigt et al, 2017).

Labor laws and ethical standards compliance is also crucial for maintaining social responsibility within supply chains. It involves regulations such as minimum wage laws, safe working conditions, and preventing child labor or even forced labor. Regular audits and assessments of suppliers are necessary to verify compliance with these standards (Locke, 2007).

Shifts in trade policies and tariffs can have significant effects on supply chain operations. Changes in trade agreements, tariff adjustments, and trade restrictions can alter the costs and flow of goods across borders. To mitigate the impact of such disruptions, companies must stay informed about these changes and adapt their supply chain strategies accordingly. This could involve diversifying suppliers, sourcing strategies, and exploring new markets (Baldwin & Evenett, 2009).

2.3.5 Product Safety and Quality Standards

Ensuring that product safety and quality standards are being followed is essential for meeting regulatory and customer expectations. Regulations like the U.S. Food and Drug Administration requirements and the homologue for the European Union enforce strict standards for product safety and quality that when no met, goods and service are blocked from entering the market. To work around this, companies look to implement effective quality management systems and inspections to ensure they comply with those standards, sometimes specific for certain markets. Non-compliance can lead to product recalls, legal actions, and a loss of customer trust (Trienekens et al., 2008).

2.3.6 Relationship Management

A reliable sourcing is fundamental to maintaining a smooth and efficient supply chain. Companies must ensure that their suppliers consistently deliver high-quality products and materials on time, that they comply with regulations and that the next nodes of the network accomplish their part to deliver the product to their client. This involves companies to perform know your supplier (KYS) and know your client (KYC) processes and detailed audits. Beyond that, companies must ensure that their suppliers and clients follow certain quality and ethical standards, such as fair labor practices, compliance with regulations for a certain product and in some cases conduct Anti Money Laundering (AML) scans (Trienekenset al., 2008).

Ensuring that suppliers meet performance standards is critical for supply chain efficiency and effectiveness. Key performance indicators (KPIs) such as delivery timeliness, quality metrics, and cost efficiency must be established and monitored. Regular performance reviews and feedback sessions with suppliers can help address issues proactively and maintain high performance standards. Collaborative performance improvement initiatives can also foster innovation and continuous improvement in the supply chain (Krause, Handfield, & Scannell, 1998).

Also, an effective supplier and partner management requires close collaboration and coordination across the supply chain. This involves sharing information, aligning goals, and working together to solve problems and seize opportunities. Often maintaining a constant communication and accountability is key to maintain a key relationship with their customers (Stank et al, 2001).

2.3.7 Demand Variability

Variability in demand is not only natural as it should be expected as markets are dynamic. At the same time, this is one of the main challenges faced by participants of the supply chain. The ability to "predict" customer demand accurately is important for efficient supply chain management, as it directly impacts production planning, inventory management, and distribution. However, accurately forecasting demand is performed with limitations due to the inherent unpredictability of market behaviors, seasonal fluctuations, and external factors such as economic conditions and competitive actions. One of the primary reasons for demand variability is the dynamic nature of customer preferences and behaviors - consumers today have access to a wide range of products and services and can easily switch preferences based on trends, marketing influences, and personal experiences. This variability makes it challenging for companies to maintain accurate demand forecasts, leading to either excess inventory or stockouts (Mentzer et al, 2004).

As it is in other words stated in the book "A random walk down Wall Street", it is not possible to accurately predict the customer behavior to a 100% degree, and trying to do makes no sense (Malkiel, 2019).

One of the factors that result in variabilities in demand are the seasonal fluctuations, as these further complicate demand forecasting. Many companies experience major variations in demand based on seasonality, characterized by certain events or seasons depending on the geographic locations. For instance, retail sales typically spike during the Christmas season and cold beverages also tend to sell more during the summer season. As a result, companies must account for these patterns in their forecasting (Fisher et al., 1994).

Some external factors, such as the current state of the economy, political context, and competitiveness, have also a direct impact on the variability of demand. Economic conditions, such as a scenario of austerity can lead to reduced consumer spending, while economic booms can increase demand. At the same time political stability in certain markets can heavily disrupt supply chains. Additionally, actions taken by competitors, such as the release of a new product or a new pricing strategy, can influence consumer behavior and demand for specific products. This includes promotions, loyalty programs and other marketing activities (Chopra et al, 2016).

The **Bullwhip Effect** is a specific manifestation of the demand variability challenge in the supply chain. It occurs when fluctuations in consumer demand cause progressively larger variations in the consequent orders placed with upstream suppliers. This systematic amplification of variability in demand results from delays in information or purchase orders, fluctuations in prices, or supply chain wrong forecasting activities (Lee et al, & Whang, 1997).

To address these challenges, companies act to implement forecasting techniques and tools. Time series analysis, causal models, and simulation models are some of the commonly adopted methods to try to predict and obtain a threshold of future demand based on historical data and known patterns, in the most accurate way as possible (Fildes & Goodwin, 2007). Despite these efforts, forecasting remains an inexact science. Overestimating demand can lead to excess inventory management, which incurs storage costs and risks obsolescence, while on the other hand, underestimating demand can result in stockouts, lost sales, and dissatisfied customers (Silver et al., 1998).

Collaboration and information sharing between supply chain partners can also enhance forecasting accuracy. By sharing demand or sales data, market insights, and production plans, companies can align their efforts and develop more accurate forecasts. However, this can also compromise the competitivity and business secrecy of the participants (Holweg et al., 2005). This is the main reason why coming up with a solution is difficult.

2.4 Supply chain management in a VUCA world

In an increasingly unpredictable world, companies in the supply chain are forced to implement strategies to effectively address these uncertainties. The concept of VUCA—Volatility, Uncertainty, Complexity, and Ambiguity—has become an essential conceptuall framework to classify and analyze the challenges that modern supply chains face. Initially created by the U.S. military to describe the post-Cold War world, VUCA has since been adopted across various fields, including supply chain management, to represent the turbulent and rapidly changing business environment that organizations must navigate today.

During the last few years, the global supply chain has been particularly affected by VUCA elements, with disruptions caused by economic fluctuations, geopolitical tensions, technological advancements, and unforeseen events like the COVID-19 pandemic, the Russian-Ukrainian conflict or the crisis in the Middle east. These factors have made it increasingly difficult for companies to forecast demand, manage resources, and maintain operational efficiency. Consequently, supply chain managers must not only deeply understand the specific challenges posed by each VUCA vertical but also design and implement strategies that enable their organizations to remain agile, resilient, and competitive in this volatile environment (Becker, 2023). Table 2.1 summarizes this concept.

Table 2.1- VUCA Description and challenges

VUCA	Short Description	Challenges	Ref.
Volatility	Fast, unpredictable changes in demand or supply.	Requires agile responses and flexible systems.	(Bennet et al, 2014)
Uncertainty	Lack of predictability in market trends or events.	Accurate forecasting is hard; needs robust risk management.	(Ivanov et al, 2020)
Complexity	Many interconnected factors and stakeholders.	Hard to manage; changes can have unexpected impacts.	(Shoemaker, 2018)
Ambiguity	Unclear cause-and-effect relationships in supply chains.	Decision-making is tough; needs strong leadership.	Shoemaker, 2018)

In such landscape, only the companies that can quickly adapt to new challenges and define agile strategies are well positioned to survive. Naturally, the ability to accurately forecast in such conditions is directly related with the success or unsuccess of a given organization. Only by adopting a flexible and coherent forecasting approach that is in line with the demands of a VUCA environment, companies can significantly enhance their resilience, agility, and overall supply chain performance (Ivanov et al, 2020).

The following section dives into Demand Variability and Forecasting, with particular emphasis on the Bullwhip Effect.

2.5 Forecasting Methods and Demand Variability

Predicting demand levels accurately is a major challenge faced by companies across various industries. The key hurdle in demand forecasting arises from the inherent variability and unpredictability of customer behavior that cannot be guessed exactly. This way predicting as accurately as possible (forecasting) based on the information companies possess, is key to prepare their operations and overcome eventual hurdles due to demand figures being over or under the normal trends.

Forecasting in inventory management involves the usage of historical data and analytical models to predict future demand for products. Accurate forecasting is critical for optimizing inventory levels, reducing costs, and improving service levels. Various forecasting methods are employed to predict future demand, each has its own strengths, weaknesses and limitations. In the effort to perform an accurate forecast, multiple demand forecasting methods are employed to predict future demand more accurately. (Silver et al, 1998). These methods range from simple techniques, such as moving averages, to more complex models, like machine learning algorithms. The selection of an appropriate forecasting method depends on several factors, including the nature of the data, the level of expertise required, and the specific needs of the organization. In table 2.2, an analysis of several common forecasting methods is presented, highlighting their advantages and disadvantages.

Table 2.2 - Forecasting methods

Forecasting Method	Advantages	Disadvantages	Ref
Simple Exponential Smoothing (SES)	Easy to implement; Low cost; Low data requirements	Unrealistic forecasting; Does not contemplate seasonality or trends;	(Gardner, 1985)
Double Exponential Smoothing (Holt's Method)	Handles trends; Easy to implement;	Unrealistic forecasting; Does not contemplate trends;	(Muchayan, 2019)
Triple Exponential Smoothing (Holt-Winters Method)	Handles trends and seasonality; Easy to implement; High Accuracy	Requires parameter estimation.	(Makatjane et al, 2016)
Autoregressive Integrated Moving Average (ARIMA)	Flexible and powerful; Handles various data types	High computational cost; Requires significant data and expertise	(Makatjane et al, 2016)
Seasonal Autoregressive Integrated Moving-Average (SARIMA)	Extends ARIMA for seasonal data	Very complex; High data and expertise requirements	(Ebhuoma et al, 2018)
Box-Jenkins Methodology	Simple approach; High Accuracy	Complex; Time-consuming to implement	(Makridakis et al, 1997)
Time Series Decomposition	Intuitive; Separates trend, seasonality, and noise	Can be less accurate; Requires decomposition of components	(Hyndman et al, 2019)
Regression Analysis	Explains relationships between variables; Widely used	Assumes linearity; Can be complex with multiple variables	(Draper, 1998)
Vector Autoregression (VAR)	Handles multivariate time series; Captures interdependencies	Very complex; High computational cost and data requirements	(Lütkepohl 2013)
State Space Models and Kalman Filters	Handles time-varying processes; Accurate	Very complex; High data and expertise requirements	(Chukhrova, 2017)
Multiple Machine Learning and Artificial Intelligence Algorithms	High accuracy; Handles complex, nonlinear relationships	Very high computational cost; Requires extensive data and expertise	(Goodfellow, 2016)

After a detailed analysis of several forecasting methods, the Triple Exponential Smoothing (Holt-Winters Method) has been selected to sustain this study. This method is highly implementable and integrable within the existing IT resources that most companies already possess, in fact it can be effectively utilized using simple tools such as the most used spreadsheets. Furthermore, it is cost-effective, requiring minimal investment in specialized software or hardware.

Also, the Holt-Winters Method provides accurate forecasting figures, making it suitable for handling seasonal variations and trends in demand. Unlike more complex methods such as machine learning, it does not necessitate extensive technical expertise, allowing for broader adoption and ease of use across different organizational levels.

2.5.1 Triple Exponential Smoothing

Also known as the Holt-Winters Method, the Triple Exponential Smoothing (TES) method is a time series forecasting technique that accounts for both trends and seasonality. It extends Double Exponential Smoothing by adding a third equation to capture the seasonal component, making it suitable for data with patterns that repeat over a fixed period, which makes sense for products subjected to seasonality.

Formula:

Level Equation:

$$L_t = \frac{\alpha Y_t}{S_{t-L}} + (1-\alpha)(L_{t-1} + T_{t-1}) \tag{2.1}$$

Trend Equation:

$$T_t = \beta(L_t - L_{t-1}) + (1-\beta).T_{t-1} \tag{2.2}$$

Seasonal Equation:

$$S_t = \gamma.\frac{Y_t}{L_{t-1}} + (1-\gamma).S_{t-L} \tag{2.3}$$

Forecast Equation for *m* periods ahead:

$$\hat{\mathrm{Y}}_{\mathrm{t+m}} = (L_t + mT_t)S_{t-L+1+(m-1)modL} \tag{2.4}$$

Where:

- L_t is the level at time t,

- T_t is the trend at time t,
- S_t is the seasonal index at time t,
- $\hat{Y}_{t+m}$ is the forecast for m periods ahead,
- $\alpha, \beta, and\, \gamma$ are the smoothing parameters for the level, trend, and seasonal components, respectively,
- $\hat{Y}_t$ is the actual value at time t,
- L is the length of the seasonal cycle.

2.6 Initiatives applying Distributed Ledger Technologies to mitigate the Bullwhip Effect

Table 2.3 gives the reader an overview on multiple research activities analyzing the feasibility of blockchain to mitigate the Bullwhip Effect. The adoption ability and concerns regarding secrecy, privacy and confidentiality are mentioned.

Table 2.3 - Initiatives applying DLT to mitigate the BWE

Initiative	Description	Ref
The impact of digital technologies on operational causes of the bullwhip effect – a literature review	Observes how new digital technologies could be used to mitigate the BWE. Highlights data-security issues without delving deeply into Blockchain. Mainly academic.	(Wiedenmann et al, 2019)
A Blockchain architecture for reducing the Bullwhip effect	Designs and evaluates a blockchain architecture to address the BWE. Findings indicate improvements in inventory management and mitigation of the BWE but lack mechanisms to protect sensitive data.	(Engelenburg et al, 2018)
Lassoing the bullwhip effect by applying blockchain to supply chains	Proposes a theoretical model supported by blockchain technologies to mitigate the BWE. Points to privacy and business secrecy issues but does not provide specific measures for processing private information.	Ghode et al (2022)
Blockchain-coordinated supply chain to minimize bullwhip effect with an enhanced trust consensus algorithm	Proposes a blockchain approach to mitigate the BWE in SC. Concludes that blockchain technologies improve participant actions but does not address business secrecy and privacy problems.	(Sarfaraz et al, 2021)
Reducing the bullwhip effect to enhance maritime service resilience: The power of blockchain technology for cutting down the market uncertainty in the maritime supply chain	Examines the capabilities of blockchain technologies in mitigating the BWE, with a focus on maritime supply chains. Lacks a production-ready approach and does not address privacy and confidentiality issues.	Zhao et al (2023)
Value Analysis by Adopting Blockchain Technology to Mitigate Bullwhip Effect	Compares three blockchain-supported models: No Information shared (same outcome), Data purchased by manufacturer (benefits manufacturer but lacks transparency), and Data transparency (better BWE mitigation but lacks privacy/confidentiality solutions).	Zhou et al.(2022)
Utilizing blockchain technology in sustainable supply chain management: benefits, challenges, and motivations	Explores benefits and challenges of blockchain in supply chain management, emphasizing the need for accurate information sharing to mitigate the BWE. Highlights regulatory and	Hannila (2023)

Initiative	Description	Ref
	legal challenges regarding data privacy, ownership, and liability. Discusses the inclusion of confidential computing for data protection.	

By examining various forecasting models and initiatives aimed at mitigating the BWE, it is easily concludable that the most widely used forecasting models are not designed to incorporate additional real-time data to enhance their calculations. Furthermore, many initiatives have failed to adequately address data privacy and confidentiality concerns.

Even though among those initiatives few have highlighted these issues, at the time of this dissertation, no blockchain-based model designed to mitigate the bullwhip effect has addressed the data confidentiality concern. Furthermore, any study has proposed or discussed the combination of blockchain with confidential computing.

2.7 Distributed Ledger technologies Frameworks

There are currently several production-grade DLT frameworks ready to use. The following table provides an overview of some of the most important DLT/Blockchain frameworks.

Table 2.4 - DLT Frameworks

Framework	Public vs Private	Advantages	Disadvantages	Ref
Hyperledger Fabric	Private	Open source, integrable with confidential computing, big ecosystem and community	Complex configurations, limited support	(Androulaki, et al, 2018)
Ethereum	Public and Private	big ecosystem and community	Community is mostly focused on DeFi and Web3 projects	(Teng et al, 2022)
Corda	Private	Bult-in features, support, direct integration with confidential computing through conclave	Very much focused on financial industries, smaller community, expensive regarding academic purposes	(Ramadoss, 2022)
Canton	Private Domains in Public Network	Bult-in features, functional paradigm using DAML	Very much focused on financial industries, smaller community, expensive regarding academic purposes	(Digital Asset, 2024)
Solana	Public	Considerable ecosystem and community	smaller set of developers, mostly designed for web3 and DeFi use cases	(Song et al, 2024)
Stellar	Public	Easy to use, customizable use cases, not free but quite cheap to use on their public network	Their level of transparency would not suit use cases requiring a certain degree of confidentiality	(Mazières, 2015)
Polkadot	Public	High interoperability, scalability, robust ecosystem	Complexity in implementation, relatively new and evolving	(Burdges et al, 2020)

Framework	Public vs Private	Advantages	Disadvantages	Ref
Hedera	Public	High throughput, low transaction fees, strong governance model	Limited smart contract capabilities, smaller ecosystem compared to others	(Chakraborty, 2023)

After an analysis of the various blockchain frameworks listed in the Table 2.4, Hyperledger Fabric has been selected for this study. This choice resides mostly on the requirements of supply chain management, particularly when trying to mitigate the bullwhip effect.

Hyperledger Fabric stands out due to its permissioned and private nature, which is crucial for enterprises concerned about data exposure. Companies in the supply chain often handle sensitive information that they do not want to expose, and this framework's architecture ensures controlled access and data privacy. Additionally, it is compatible with confidential computing, providing an additional layer of security and privacy, which is essential for handling confidential forecasting data and transactions (Brotsis et al, 2020).

The robust ecosystem and community support around Hyperledger Fabric also plays a significant role when selecting a Blockchain framework. A strong community means better support, a wealth of resources, and continuous improvements, which facilitates the implementation of a new solution. The wide availability of tools and frameworks tailored for Hyperledger Fabric makes it practical and efficient for deployment in production environments (Cachin, 2016).

Hyperledger Fabric is also recognized for its versatility and adaptability, being able to handle complex supply chain processes with its modular architecture. This flexibility allows for customization according to specific organizational needs without compromising on performance or security. Moreover, Hyperledger Fabric excels in confidential computing, integrating technologies like Intel SGX and IBM Enclave to ensure high levels of data privacy and security. This makes it particularly suitable for applications that demand stringent data protection (Bradenburger et al, 2018).

3 Theoretical Generic Framework

In the rapidly evolving landscape of supply chain management, the integration of cutting-edge technologies has become pivotal for enhancing efficiency, transparency, and security. This chapter presents a comprehensive exploration of DLTs and Confidential Computing, diving into their specific components, potential synergies, and applications. The chapter aims to provide a theoretical overview on these technologies to demonstrate that these technologies combined can be leveraged to mitigate the bullwhip effect while ensuring privacy and confidentiality.

This chapter starts by defining what DLTs are, diving deep into their core concepts such as consensus mechanisms, smart contracts, and cryptographic principles. Next, the concept of Confidential Computing is introduced, followed by a detailed view into its main purpose of ensuring data privacy and security through secure enclaves and trusted execution environments. Then, the interplay between DLT and Confidential Computing is then explored, highlighting how their integration can address complex as illustrated in Figure 3.1.

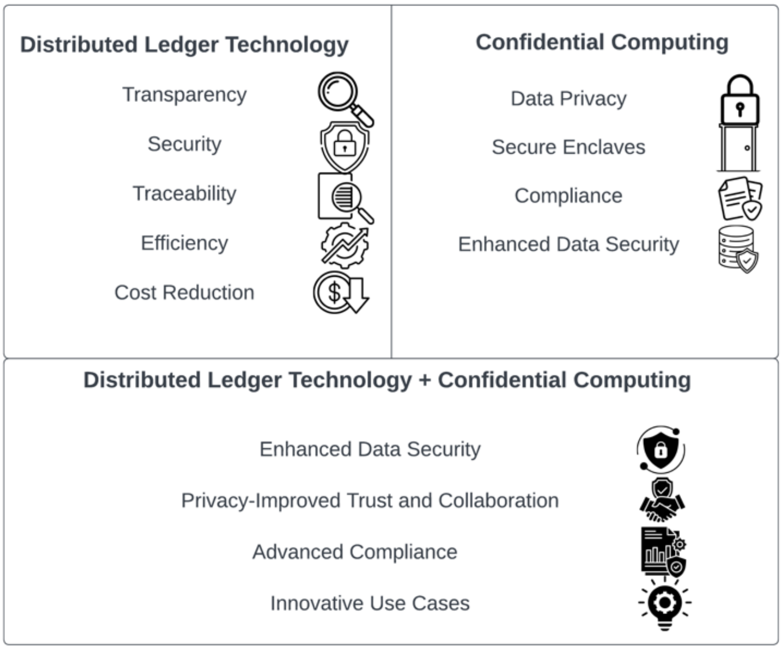

Figure 3.1 - Blockchain and confidential computing key features

3.1 Distributed Ledger Technologies

Distributed Ledger Technology is a concept used to refer to a set of technologies that provide digital transaction, registry, and consensus in a distributed manner. The most widely adopted family of DLTs are known as Blockchain (El Ioini et al, 2018). Currently there several blockchain framework ready to provide developers with the tools necessary towards the implementation of multiple use cases.

To gain a deeper understanding of how Blockchain functions, it is important to first clarify several key concepts that form the foundation of the technology.

3.1.1 Cryptography

In essence, cryptography is not only the most fundamental aspect of blockchain, but of every single distributed system where multiple entities can have access to and interact with. In this particular case, it ensures the security and integrity of a blockchain network by providing all the means that provide authentication and trust.

Cryptography is not a new science – it is far from being so as it has been around for several centuries. It underpins the methods used for secure communication while protecting sensitive / confidential / private information from unauthorized access (Menezes et al, 1996).

When it comes to Blockchain technologies, there are three main essential functionalities it provides designed to ensure authentication, prevent network vulnerabilities, and eventual hacking.

3.1.2 Cryptographic Hashing

Hashing can be seen as a function that by receiving a certain input parameter (whether it is a number, a set if characters, a dataset, or other digital inputs), generates a unique output that identifies the original set (Satoshi Nakamoto, 2008). These functions are deterministic and preferably, collision resistant. In a nutshell, hashing functions are meant to create unique hashes from original values through the execution of mathematical operations that enable to identify a certain resource, while ensuring that no reverse operations can return the original value.

This characteristic is crucial in Blockchain to ensure the ledger is well-ordered, transparent and tamper-proof, as every transaction is ultimately identified by their hash, which would make any false attempt to deny or fool the history of transactions be detected (Figure 3.2).

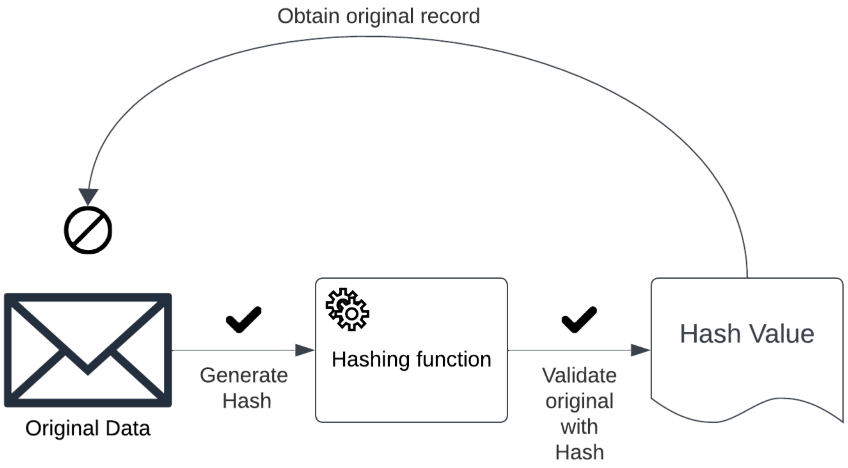

Figure 3.2 - Cryptographic Hashing

3.1.3 Public and private key cryptography

Public and private key cryptography, commonly known as asymmetric cryptography, are essential techniques used to secure digital communications.

A public key refers to a cryptographic asset that can be publicly shared, while private keys are kept in secrecy. These keys are asymmetric and logically linked to each other and generated as a pair by using cryptographic. These properties enable secure communication ever since private keys are not shared.

Their most important use cases are:

- **Digital signatures** – In this case, a record is signed using the owner's private key. Since other entities have access to the corresponding public key, they can verify the signature, confirming the authenticity and integrity of the original record.
- **Confidentiality encryption** – This case works the other way around. The creator of a message encrypts it using the recipient's public key, meaning that only the intended recipient, who possesses the corresponding private key, can decrypt and access the message.

These techniques are fundamental not only for the role it plays in blockchain technologies but in multiple areas. For instance, the whole internet relies on it to ensure privacy and security over non-trusted channels. To be more specific, SSL/TLS protocols utilize cryptography to protect data in transit, enabling secure communication between web browsers and servers. Without these cryptographic techniques, sensitive information transmitted over the internet would be vulnerable to interception and unauthorized access (Legatheaux, 2018).

Figure 3.3 Illustrates how what digital signing and confidential encryption provide.

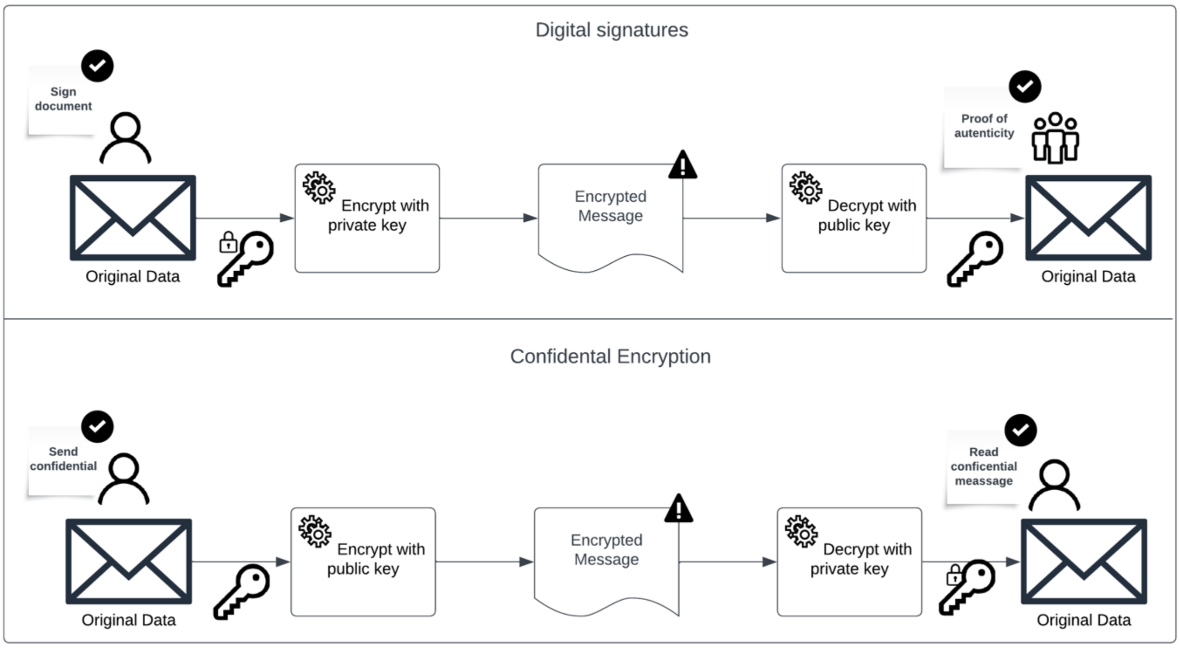

Figure 3.3 - Public vs private key management

3.1.4 Blockchain Ledger

Overall, the blockchain ledger is the plain data structure used to store transactions (Ghiro et al, 2021). In more detail, the name Blockchain originates from the way these ledgers are structured in regards of the transactions stored in them. Each transaction can be seen as a block of data logically ordered that brings consensus and provides a reliable state. In essence, each block contains a set of information such as the Timestamp, the content of that transaction and the hash resultant of the hashing the data content of the previous block. To maintain a constant coherence, the first block that is created by default once the ledger ready to be interacted with is the first block of the chain, also known as the Genesis Block. (Komalavallim 2020).

Figure 3.4 gives an overview of the concept of Blockchain.

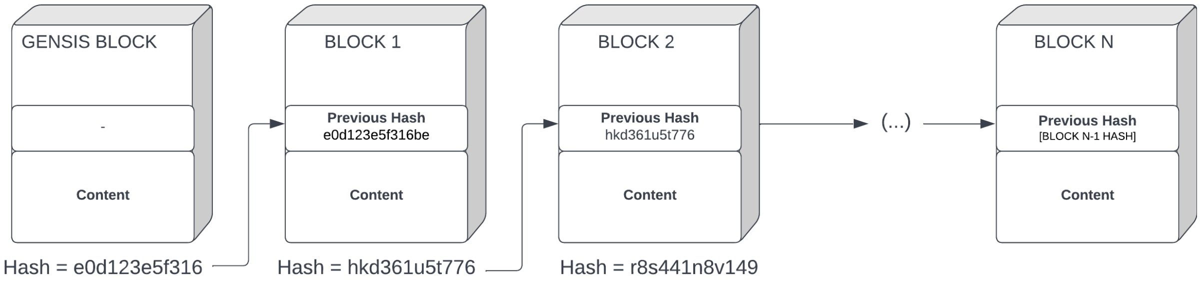

Figure 3.4 - Blockchain ledger

The distributed ledger is the most fundamental aspect of blockchain based solutions as it ensures them to be trustable, tamperproof, and transparent, as any attempt to deny or affect the state of a block would immediately be noticed as it would break the chain as that the hash of the previous block would not match the one stored in the next block (Figure 3.5).

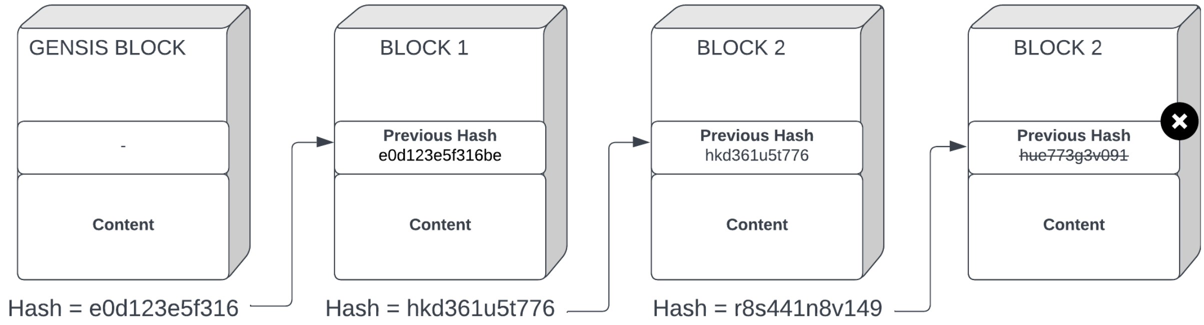

Figure 3.5 - Blockchain ledger deny attempt

3.2 Consensus protocols

A consensus protocol can be summarized as a secure distributed protocol that dictates how the network components interact to sign and add a new block to the blockchain. In a nutshell, a blockchain consensus protocol enables a majority of participants of a given blockchain network to agree on the appending of blocks to the blockchain in the same and unique order (Cachin, 2017).

There are different approaches and different protocols in place that rely on consensus-based algorithms that have on different goals depending on the nature of each solution and the topology of those networks. Some examples are:

- Proof of work (PoW) (Kiayias, 2020) – These algorithms require participant nodes to solve cryptographic challenges in order to validate a transaction. The first node to solve the problem gets to validate, sign and add the new transaction as a block to the ledger. This node is afterwards rewarded with grants that aim to compensate the computational efforts. This way participants are incentivized to play an active role to maintain the network. These algorithms are very much energy consuming, oriented for public blockchains and typically associated with cryptocurrencies.

- Proof of stake (PoS) (Kiayias, 2020) – While PoW algorithms rely on cryptographical work executed by every peer attempting to get the reward, in PoS the probability of a node being chosen to validate the next block is proportional to the amount of stake (amount of native token locked as collateral) held by that node. Instead of relying on computational power, as in Proof of Work (PoW), PoS uses the ownership of tokens. Tokens are digital assets native to the blockchain platform, often used as a representation of value, utility, or ownership within that ecosystem as a form of economic commitment. It is pretty much more energy efficient than PoW and is typically associated with public blockchains meant to implement use cases or Dapps (Distributed applications).
- Proof of History (PoH) (Yakovenko, 2018) - Proof of History is a sequence of computation that provides a way to cryptographically verify the passage of time between two events. It creates a historical record that proves that a transaction occurred at a specific moment in time. This is unlike traditional blockchain mechanisms, where the consensus on the time order of events is reached by agreement of most nodes.
- Proof of authority (PoA) – In PoA, transactions are validated by a defined group of validator nodes. In most cases these algorithms are used in permissioned blockchains, that are typically frameworks used for enclosed and private ecosystems. In such cases, the network is composed by only a reduced number of participants as the validation flow ends up being more centralized.
- Multiple Pluggable Consensus approach (Androulaki et al., 2018) - A pluggable consensus framework in some blockchain technologies such as Hyperledger Fabric, is not characterized by a single consensus algorithm like PoW or PoS, but rather allows different implementations based on the needs of the network and the use cases depending on it. These in most cases are extensions of PoA and given the permissioned nature of those frameworks, the concern over decentralization is not as big when compared with public blockchains.

3.2.1 Smart Contracts

Smart contracts can be seen as self-executing contracts that contain a pre-agreed set of terms between the parties involved written in lines of code. When these conditions are met, the smart contract automatically executes the agreed-upon actions, without the need for intermediary oversight. This execution is immutable and it results in a transaction subsequently leading to the creation of a new block in the blockchain ledge (Buterin, 2014).

These smart contracts are coded in programming languages that are compatible with blockchain their correspondent Blockchain framework. Some of the most known smart contract languages are listed on table 3.1.

Table 3.1 - Smart contract languages

Smart Contract Language	Frameworks	Description	Ref.
Chaincode (go)	Hyperledger Fabric	Management of ledger state through transactions.	(Zappoli, 2022)
Solidity	Ethereum	High-level language for implementing smart contracts.	(Crafa et al, 2020)
Rust	Solana, Polkadot	Popular in blockchain environments that require high throughput and low latency.	(Crafa et al, 2019)
DAML	Canton	Designed to focus on the logic of their applications without worrying about the underlying ledger technology.	(Bernauer 2023)
Vyper	Ethereum	Alternative to Solidity with a goal to provide a more straightforward and secure language for Ethereum smart contracts.	(Sierra, 2019)

The following example illustrates a scenario in which a landlord agrees to rent an apartment to a tenant using a smart contract system to automatically manage the rental agreement .

- **Agreement:** The smart contract encodes the terms of rental amount, lease duration, monthly payment schedule), payment currency, and the penalty fee for late payments.
- **Rent:** Tenant agrees upon paying the rent based on the specified conditions.
- **Contract Activation and Monthly Processing:** Upon mutual agreement, the smart contract becomes active and is recorded on the ledger as an ongoing contract. Each month, the contract automatically checks whether the rent payment has been made.
- **Payment Conditions and Penalties:** If rent is paid on time, the smart contract records the payment and remains in effect for the next period. If the rent is not paid by the due date, the smart contract imposes an additional penalty fee, which is added to the following month's rent.
- **Contract Termination:** The smart contract is programmed to automatically terminate upon reaching the end of the lease term. At this point, it executes final checks for any outstanding payments or penalties and concludes the agreement.

In this case each time an action regarding an active contract is executed, the state of the ledger is updated to reflect the current state. Figure 3.6 illustrates the same workflow expressed in Business Process Model and Notation.

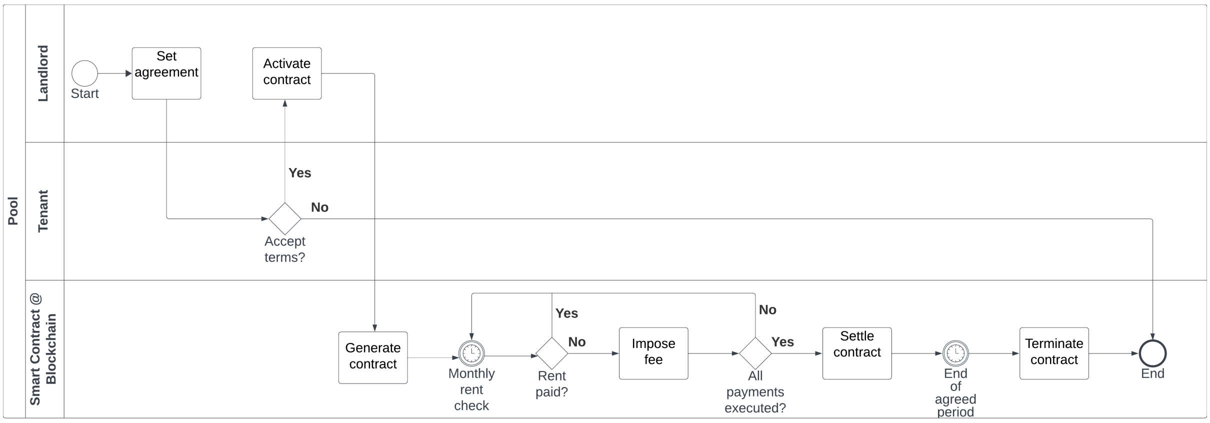

Figure 3.6 - Rental agreement smart contract example in BPMN

3.2.2 Blockchain nodes

Blockchain nodes play an essential role in blockchain networks. These can be seen as processes running on computers responsible to process and coordinate the execution of smart contracts while keeping the system updated.

Nodes can be split into different types:

- **Participant nodes:** Nodes that represent a participant or a set of participants in a blockchain network. These nodes are responsible for running the smart contracts on behalf of the participant that owes them. They must contain the smart contracts required for the use cases.
- **Validator nodes:** These nodes are responsible for validating the transactions and ensuring the ordering, coherence and integrity of the transaction's resultant from the execution of smart contracts following the rules of the consensus algorithm used by that framework. These nodes ensure that no double-spending problems happen, and that the information stored is correct and trustable.

Each of these types of nodes can be specified into multiple types of categories depending on the architecture of the blockchain framework in use.

3.2.3 Blockchain Holistic view

Blockchain solutions incorporate each component discussed along this chapter - Cryptography, Blockchain Ledger, Consensus Protocols, Smart Contracts, and Nodes. In this section, we integrate these components to illustrate how they work together to build the backbone of the blockchain technology (Tapscott et al, 2016). This holistic understanding is crucial to comprehend the functionalities of blockchain, including its role in mitigating the bullwhip effect in supply chain management.

The core of a solution running on a blockchain are the participants within the network. Each participant is uniquely identified through digital certificates that leverage public-private key cryptography. This method ensures that identity verification is secure, enabling participants to conduct transactions with a high level of trust and security. Once authenticated, these participants can trigger transactions, which can range from simple exchanges of digital assets to more complex operations facilitated by smart contracts (Swan, 2015).

The smart contracts function as self-executing digital agreements, where the terms and conditions are encoded directly into the contract's programming. These contracts autonomously enforce their execution when the contained criteria are met. The automative nature of smart contracts significantly enhances the efficiency and reliability of transactions conducted on the blockchain, ensuring that they are executed as intended without manual intervention (Christidis et al, 2016). This not only brings automation as speed and avoid human error.

The validation of transactions within the blockchain network is ensured by validator nodes, whose roles differ depending on the consensus mechanism implemented. These nodes are essential in mantaining the blockchain's integrity. Once transactions are checked, they are transformed into blocks that are securely encrypted and linked to previous blocks, thereby creating a continuous, tamper-proof chain—the blockchain (Wood, 2014; Zheng et al., 2017).

These elements combined not only ensure the security and immutability of the ledger, but also builds a historical record that is transparent and traceable, the main attributes the industry can benefit from adopting it. (Yaga et al., 2018).

Figure 3.7 displays a conceptual diagram that aims to provide an overview on how these components work together.

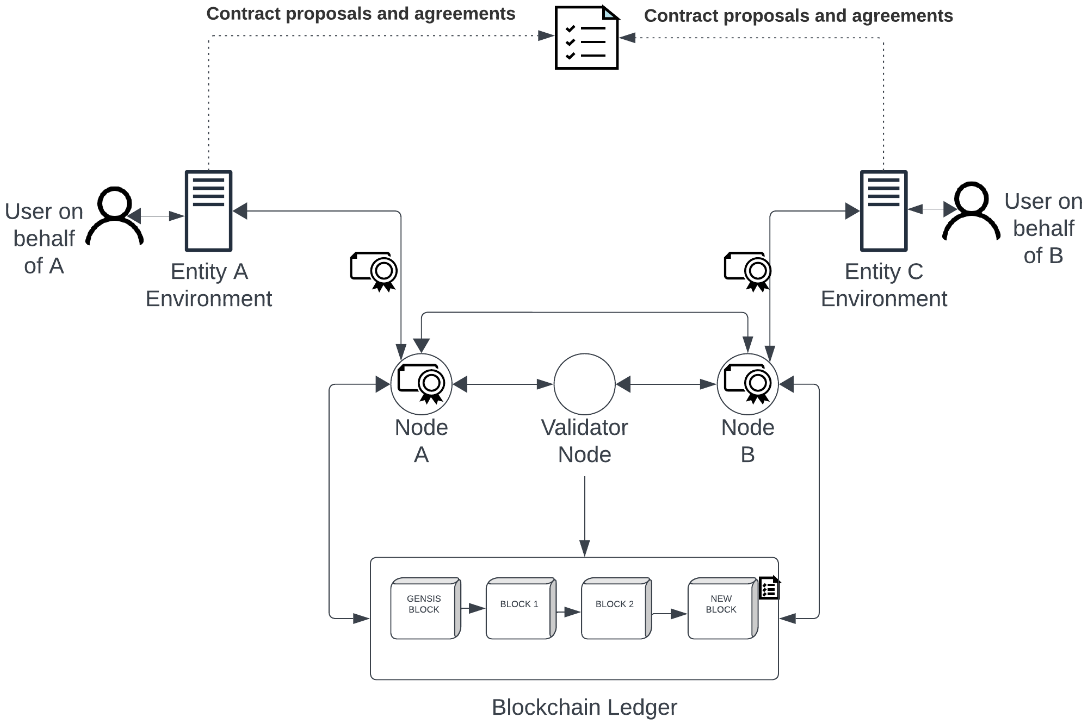

Figure 3.7 - Blockchain conceptual diagram

3.2.4 Public vs Private blockchains

Public blockchains, like Bitcoin and Ethereum, have significantly shaped the general understanding of blockchain technology. These blockchains operate on the assumption that users do not necessarily trust each other and there is no need for a trusted third party. This characteristic ensures that transactions can be verified and executed securely without the need for mutual trust among users. Public blockchains achieve this through the validators nominated by the decentralized consensus mechanisms, which validate and record transactions across a distributed network of nodes (Buterin, 2013).

On the other hand, private or permissioned blockchains operate differently. They are often designed to function within a specific organization or group of organizations where trust relationships, legal contracts, and regulatory frameworks are already in place. In such environments, the assumption of not trust is not necessary. Private blockchains can be highly efficient and effective as they integrate with existing trust frameworks and trusted third parties. This allows for streamlined operations and can result in greater efficiency compared to public blockchains. The controlled access and permissions in private blockchains also enable better compliance with regulatory requirements and more effective management of sensitive information (Strehle 2020).

In most cases private or permissioned blockchains are implemented on the context of consortium or collaborative use cases. For this reason, use-cases that require a certain degree of confidentially would fit into private blockchain networks where all the participants are well-known, and data is not exposed to entities that do not participate in it. This should be the case of a supply chain consortium composed by multiple participants built to mitigate the bullwhip effect.

3.2.5 Blockchain initiatives: Innovating across diverse sectors

The 'Genesis block' of blockchain initiatives is Bitcoin. In the white paper published by Satoshi Nakamoto (Nakamoto, 2008), the author proposed a revolutionary digital currency system designed to create a decentralized electronic currency, enabling participants to transact without the need for central authorities. Implemented in 2009, Bitcoin remains the most notable and recognizable implementation of blockchain technology to this day.

Not long after the wider adoption of bitcoin, it became evident that the underlying technology had quite the potential to enable use cases beyond a digital currency. This decentralized, transparent, and secure nature of blockchain, revealed a broad spectrum of potential use cases across various industries. Entrepreneurs and software developers understood that the principles of DLT could be applied to create immutable records of any form of data exchange, extending well beyond the realm of monetary exchanges. Among some of those initiatives can be found Ethereum, Ripple, Hyperledger, Digital Assets and Solana. The following table illustrates a set of implementations that made use of Blockchain technologies to implement distributed solutions in a form of use cases (Table 3.2).

Table 3.2 - Blockchain initiatives beyond Bitcoin

Industry	Initiative	Technology	Year.	Use case	Ref.
Banking & Finance	JPM Coin/Onyx	Quorum	2019	Digital Coin	https://www.jpmorgan.com/onyx/coin-system
	Drex	Hyoerledger Besu	2024	Central Bank Digital Currency	https://www.bcb.gov.br/estabilidadefinanceira/drex
	Kube	Hl Fabric	2020	Distributed KYC	https://www.kube-kyc.be/en/

Industry	Initiative	Technology	Year.	Use case	Ref.
Supply Chain	TradeLens	HL Fabric	2018	trade digitization platform	https://www.tradelens.com/
	Food trust	HL Fabric	2017	Improve transparency and accountability in the food supply chain.	https://www.ibm.com/products/supply-chain-intelligence-suite/food-trust
Real Estate	Propy	Ethereum	2017	global property store and decentralized title registry	https://propy.com/browse/
Energy	Power Ledger	Ethereum	2016	energy trading platform	https://www.powerledger.io/
Gov	Estonia's E-residency	KSI Blockchain	2012	blockchain to secure public services data.	https://guardtime.com/timestamping
Education	Blockcerts	BTC Blochchain	2016	creating, issuing, viewing, and verifying blockchain-based certificates.	https://www.blockcerts.org/
Art	Web3 Music Association	Proprietary	2024	Explore the benefits of a blockchain-based collaborative platform	https://web3music.org/login-area/
Insurance	ClaimShare	Corda	2020	Solve double-dipping frauds	https://corda.net/modal/claimshare/
Healthcare	MediBloc	Ethereum	2017	Platform for decentralized medical information	https://medibloc.com/
Distributed Ledger Technologies	Catalyst Blockchain Manager	HL Fabric, HL Besu, Corda, Canton, Stellar, Polygon	2020	Enterprise solution designed to facilitate the creation of blockchain solutions	https://catalyst.intellecteu.com/

Some of these Blockchain frameworks were released a few years before this dissertation, and some of these industries are increasingly leveraging on them to implement all types of solutions. The last row of those initiatives' pinpoints Catalyst Blockchain Manager, a product that aims to facilitate the creation, management, and integration of blockchain solutions, which reflects the increased need for tools aimed to speed-up and ease the adoption of these technologies. This means the industry is transitioning from a proof-of-concept state to a wide adoption.

Another relevant development when it comes to the adoption of these Blockchain technologies in regulated industries happened in 2023, when DTCC, Clearstream and Euroclear (DTCC, Clearstream, Euroclear, 2023), released an important paper that highlights the transformative impact of digital assets and DLT in financial markets, pointing out to the dematerialization of securities markets. In a nutshell the paper emphasized the gradual adoption of DLT, the common acknowledge of the benefits proposed by these technologies, a set of challenges in commercialization and how DLT can act on them. This is quite relevant given these being major financial infrastructure entities with extensive influence and expertise in the global financial markets.

During the end of the same year, Forbes released an article listing the 6 most important Web3, Blockchain and Cryptocurrency trends in 2024 (Marr, 2024). Emphasizing that blockchain adoption is getting more and more traction, transitioning from being a research topic to a trustable solution.

3.3 Confidential Computing

Information security is one of the biggest challenges of today's world. This concern is quite known to the wide public. During the last few years, a new set of data regulations emerged worldwide, such as the European Union's General Data Protection Law that intend to give individuals control over their personal data and to unify the regulation within the EU to facilitate business. Its key principles are:

- Lawfulness, fairness, and transparency
- Purpose limitation
- Data minimization
- Accuracy
- Storage limitation
- Integrity and confidentiality (security)
- Accountability

(Degeling et al, 2018)

Beyond the rules that impose strict and clear instructions for companies, businesses are not willing to share their business secrecy in an increasing competitive landscape.

These two factors threatened the adoption of collaborative solutions (Which also affects blockchain in real use case applications given the transparent nature of it, that lays onto collaboration and data sharing). Also, as considerable business start to adopt cloud-based infrastructures where they rely on a third party to maintain their data accurate and secure, these concerns have just increased since then. To address these concerns the confidential computing surges as a solution that aims to protect data in use through hardware-based trusted execution environments named enclaves (Confidential Computing Consortium, 2021).

These enclaves aim to ensure that data is not accessible even when being processed by any entity, including the owner of the physical machines where the processing of data is being executed (Mulligan et al, 2021).

In essence, this ensures privacy, confidentiality and secrecy between participants and their artifacts. This technology has been implemented by Intel and its name is Intel SGX, that introduces new platform extensions such as a Memory Encryption Engine and new CPU instructions (SGX1 and SGX2 to enable applications to create private memory regions protected from privileged software throughout state-of-the-art computer science hardware and software mechanisms to encrypt data in use in the main memory of the system without compromising performance (El-Hindi et al, 2022)..

There are two main aspects involving in memory data protection:

- Encrypting full system memory
- Encrypting individual virtual machine memory and isolating the VM memory from the hypervisor (hypervisor is a type of computer software, firmware, or hardware that creates and runs virtual machines) (Mulder et al, 2023).

To further explain this concept, let’s consider an illustrative example - A given company explores a business opportunity to offer outsourcing services of one of its teams of workers to a given client that is based in a region where certain professionals are banned from traveling to the country. Additionally, both the supplier and the customer firms are not allowed to know what is the person that is banned – They just need to know at least one person in the group is banned.

To do so, the company uses a software that implements confidential computing so they can access a list containing all the people banned from the enclave. The company submits an encrypted version of the list of the team workers that is unlocked in the enclave and simply returns if the team passed the background check or not (Figure 3.8).

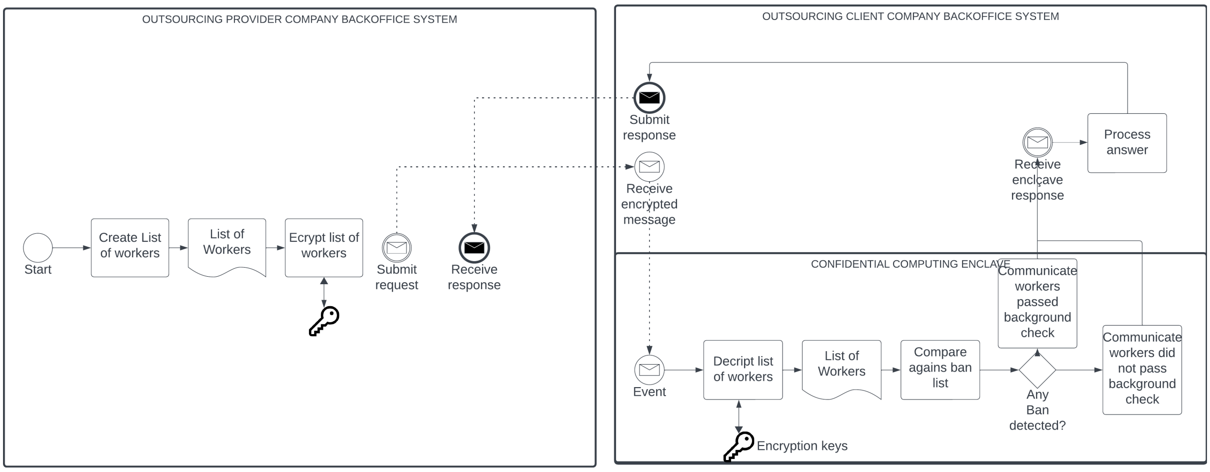

Figure 3.8 - Confidential Computing Enclave Example

3.3.1 Use Cases using confidential computing.

Confidential computing enables a new set of possibilities that were not imaginable before as it enables to process data in an encapsulated environment, making it confidential. Despite most of the uses being related to data-privacy regulations, there have been some other use cases adopted in multiple industries as listed on table 3.3.

Table 3.3 - Use Cases using Confidential Computing

Sector	Description	Reference
Healthcare	healthcare providers utilize patient data to train AI models. This aids clinicians in providing quicker, more effective diagnoses and treatments for specific patient groups, while ensuring complete data privacy, even when integrating additional personal information.	(Ambiel, 2024)
Finance	Banks and financial bodies can use confidential computing for tasks like anti-money laundering by employing secure enclaves to run AI-based risk assessment algorithms. Further applications include fraud detection, surveillance of dubious transactions, loan application analysis, interest rate determination, and credit scoring. As an example, HSBC uses confidential computing to enhance data security and regulatory compliance.	(Brue, 2023)
Governmental	Different gov agencies could better cooperate to serve the public. For instance, the U.S. Center for Disease Control and the U.S. Food and Drug Administration could combine confidential datasets dealing with vaccine development and generate results that neither agency could have arrived at alone—with zero exposure of sensitive data. An example of a governmental application of this technology is the project Gaia-X, that develops, based on European values, a digital governance that can be applied to any existing cloud/ edge technology stack to obtain transparency, controllability, portability and interoperability across data and services. This technology is still in early stages and new advancements are expected to arise soon. Despite both technologies are considered in early stages, there have been some initiatives combining them.	(Gellenberg et al. (2024)

3.3.2 Combination of DLT and Confidential Computing

At first glance, combining DLT and CC may seem counterintuitive, given that blockchain emphasizes transparency, collaboration, and trust, while CC prioritizes confidentiality and privacy. However, as discussed in Chapter 1, many existing solutions for addressing the Bullwhip Effect in supply chains struggle to accommodate confidentiality, limiting their applicability in a real-world setting. Integrating DLT with CC can ultimately open the door to further explore additional use cases, as it enables the secure, trustful and transparent aspects of DLT, while leveraging CC to comply with data privacy requirements.

For instance, data can be categorized into public and private. While public data can be fully shared across blockchains, private cannot. A good example of a combination of both technologies is the project ClaimShare, the project that won the Insurtech challenge in 2020 by R3 Corda (https://corda.net/modal/claimshare/). ClaimShare aims to reduce insurance fraud by detecting and preventing duplicate claims across different insurance companies. Insurance fraud is a significant issue in the industry. Its occurrence indirectly leads to higher premiums for overall customers and losses for insurers. Each time a claim is filed, its public details are sent to a shared ledger. An AI component looks at the public data of the claim, and in case of two records match - the Enclave requests insurers to share their private records in a confidential manner. When they match, a double-dipping attempt is confirmed, and a fraud is marked down or prevented (Brown, 2021).

4 Implementation of a Proof of concept

The primary goal of this chapter is to develop a proof-of-concept that demonstrates how combining DLT and CC can effectively mitigate the Bullwhip Effect in supply chain management. Building on the concepts discussed in Chapter 3, this chapter presents a scenario designed to showcase the advantages of sharing and utilizing demand-driven real-time data among participants, resulting in more accurate forecasting compared to traditional methods.

This implementation aims to allow participants to access real-time demand data, while the CC component ensures the protection of sensitive information, preventing the exposure of confidential data. To evaluate the effectiveness of the proposed solution, performance metrics are compared to those of a traditional approach (that does not implement DLT and CC), using the same input for demand.

4.1 Business Scenario

To facilitate the comprehension of the supply chain, the product being requested by customers is a “cola bottle”. The flow of orders begins when the retail store places an order to the transporter, who then requests stock to the distribution center. The distribution center, in turn, places an order with the producer, who finally orders glass (the raw material) from the raw material supplier to manufacture the cola bottles in function of the demand received. This sequence ensures that every participant reacts to the demand it receives and triggers the next node of the network, in a chain-reaction manner as depicted in figure 4.1.

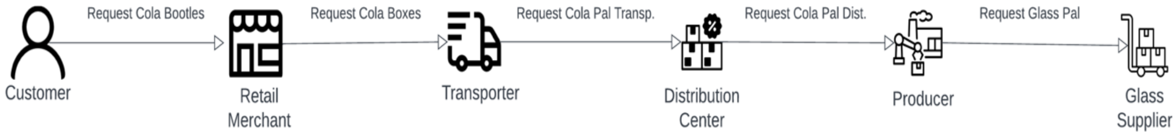

Figure 4.1 - Supply chain workflow

4.1.1 Participants

The Network of participants is composed by the following participants:

- Customer – Inputs the demand at the retail level. The customer initiates the demand for cola bottles by placing an order through a user interface. This entity symbolizes the end consumer whose needs drive the entire supply chain.
- Retail merchant – This participant functions as a supermarket where customers purchase cola bottles. The Retail Merchant is responsible for managing inventory levels, placing orders to transporters, and ensuring that the product is available on the shelves for customers.
- Transporter – The Transporter is responsible for moving the cola bottles from the Distribution Center to the Retail Merchant. This participant simulates the logistics involved in the transportation of goods.
- Distribution Center – Acts as an intermediary between the Producer and the Retail Merchant. The Distribution Center receives, stores, and manages the cola bottles produced by the Producer before dispatching them to the Transporter, that hands them to the Retail Merchant.
- Producer – This entity is responsible for manufacturing the cola bottles using raw materials. The Producer is at the heart of the supply chain, converting raw materials (in this case, glass) into finished products ready for distribution.
- Raw material supplier – The Raw Material Supplier provides the glass required by the Producer to manufacture cola bottles. As the starting point of the supply chain, this participant's role is crucial in ensuring that the Producer has a steady supply of the necessary materials to maintain production continuity.

4.1.2 Standard Forecasting and purchase orders

Each participant receives their corresponding demand each month (m). the consequent operations (such as stock management, safety stock definition and consequent purchase orders) are consequent of the processing of demand.

To forecast the demand for a given month, all participants except the user as they don’ use the Triple Exponential Smoothing method, which applies the pre-defined *α, β,* and *γ* parameters established at the beginning of the simulation.

If a participant cannot fulfill the demand for a given month, the order is flagged as a disruption, highlighting a break in the supply chain.

4.1.3 Product Ordering Units Mapping

The final product is transformed into its final form along the chain, and each participant manages certain units depending on the level of the supply chain they are. For instance, while a customer buys a certain number of “Cola Bottles”, the Retail Merchant requests a certain number of “Boxes of Cola Bottles”. The table 4.1 details the units and quantities managed by each participant.

Table 4.1- Simulation units’ conversion

Unit	Requested by	Requested to	Definition	Composition
Cola bottle.	Customer	Retail	Represents a single unit, as for example a 33cl bottle.	-
Cola Box.	Retail	Transporter	Box containing unit bottles.	1 Cola Box = 25 Cola bottle
Cola Pal Transp.	Transporter	Distribution Center	Pal containing boxes from Distribution Center Adapted for Transportation.	1 Cola Pal Transp. = 10 Cola Box
Cola Pal Dist.	Distributer Center	Producer	Pal containing boxes raw from production	1 Cola Pal Dist. = 1 Cola Pal Transp.
Glass Pal.	Producer	Glass Supplier	Pal containing the glass to build bottles	1 Glass Pal = 1.5 Cola Pal Dist.

For any given demand at a specific level in the supply chain, the quantity ordered is adjusted to the smallest unit increment that meets (or exceeds by the minimum difference the demand, expressed in the units processed by that entity). This means that the demand is translated into unit used by the next participant, as shown in Table 4.1.

For example, the demand at the retail level is expressed in 'Cola Boxes,' . However, the transporter must receive a request in 'Cola Pal Transp'. In this case, if the Retail Merchant requires 60 cola bottles, then it must request 3 boxes of 25 units each, which results in 75 units.

Units equivalence equation:

$$\begin{aligned} 1\,Glass\ Pal &= 1.5\,Cola\ Pal\ Dist. \\ &= 1.5\,cola\ Pal\ Transp. \\ &= 15\,Cola\ Box = 375\,Cola\ Bottle) \end{aligned} \tag{4.1}$$

Table 4.2 illustrates the number of boxes the Retail Merchant would need to request for different sample number of bottles.

Table 4.2 - Cola units to Cola boxes conversion

Month	Retail		
	Bottle needs	Is divisible by 25?	Final ordered figures in Cola Boxes
January	50	Yes (Exact Number)	2 (2*25 = 50)
February	60	No (Round up to next multiple of 25)	3 (3*25 = 75)
March	65	No (Round up to next multiple of 25)	3 (3*25 = 75)
April	70	No (Round up to next multiple of 25)	3 (3*25 = 75)
May	21	No (Round up to next multiple of 25)	1 (1*25=25)
June	1	No (Round up to next multiple of 25)	1 (1*25=25)
July	15	No (Round up to next multiple of 25)	1 (1*25=25)

4.1.4 Displayed metrics

For every month simulated, the user interface displays the following metrics.

- Input:
  - Actual client demand at retail-merchant per month
- Traditional Forecasting:
  - Forecasted figures.

  - Safety stock.
  - Order needs.
  - Purchase order.
- DLT Based Forecasting:
  - Forecasted figures.
  - Safety stock.
  - Order needs.
  - Purchase order.
- KPIs
  - Error (total difference between forecasting and actual demand)
  - Total stock managed.
  - Total number of disruptions.

Additionally, the TES model requires at least a year of previous demand that is going to be provided. Appendices O and P display a screenshot of the application implemented.

4.1.5 Past Demand pre-loaded

The Triple Exponential Smoothing forecasting method requires some data to be fulfilled prior to its execution. The more data it can count on, the more accurate the estimations are for the following season, especially attending to the fact that the simulation highly considers both seasonal and trend factors. The Table 4.3 displays the demand figures pre-loaded upon the execution of the simulation, that pretend to simulate a scenario containing some seasonality and trend factors. These figures are also displayed on the client user interface.

Table 4.3 - Demand figures prior to simulation

Month	Demand at retail (cola bottles)
January	500
February	550
March	600
April	620
May	700
June	1000
July	2000
August	3000
September	2500
October	1500

Month	Demand at retail (cola bottles)
November	1000
December	750
January	560

For the remaining participants, the demand they receive as input derive from the initial demand defined at the Retail Merchant (Table 4.3), by applying the conversion factor defined in table 4.2.

The figure 4.2 illustrates in a graph this demand figures. These represent a scenario in which the demand along the period suffered some seasonality. In more detail, from January to May the demand for this product stays low (under 1000 units), whilst from June to August the demand follows an increasing pattern until it reaches its peak during the month of August, and then inverting the trend to decreasing systematically until the month of November, when it starts stabilizes again under the 1000 units.

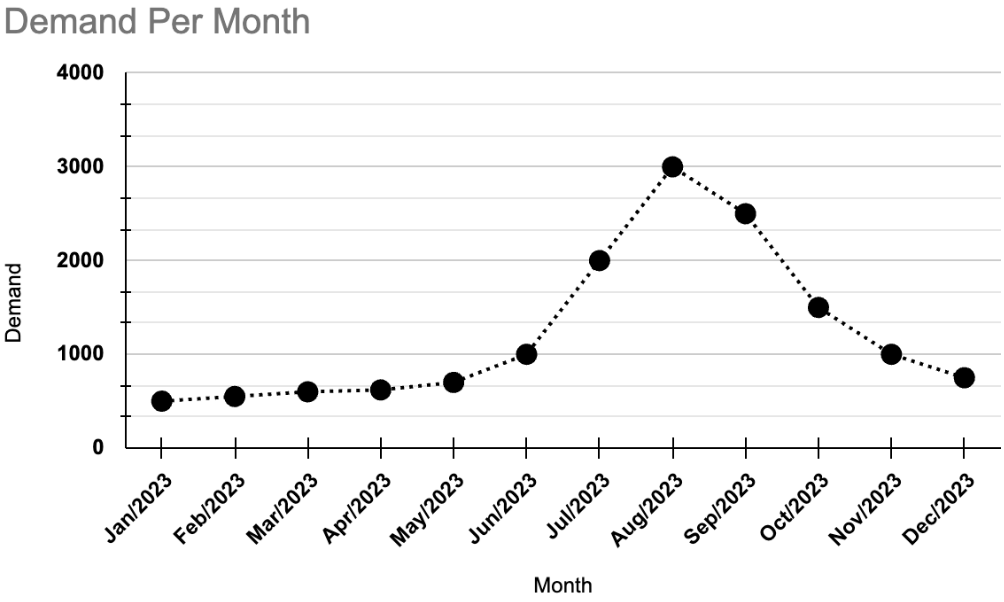

Figure 4.2 - Demand figures pre-loaded onto simulation

If the simulation used a forecasting method that would ignore the seasonality factor, this demand by itself would already be enough to generate a noticeable bullwhip effect, given that the increase on demand rapidly evolves to figures up to 6 times higher than the lowest registered.

The remaining participants have also processed a demand that is calculated in function of the figures of the demand at the retail level and expressed in correspondent units, as shown on Table 4.4.

Table 4.4 - Demand figures by participant

Month	Retail Demand (bottles)	Transporter Demand (Boxes)	D. Center Demand (Cola Pal)	Producer Demand (cola Pal)	Supplier Demand (Glass)
January	500	20	2	2	2
February	550	22	3	3	2
March	600	24	3	3	2
April	620	25	3	3	2
May	700	28	3	3	2
June	1000	40	4	4	3
July	2000	80	8	8	5
August	3000	120	12	12	8
September	2500	100	10	10	7
October	1500	60	6	6	4
November	1000	40	4	4	3
December	750	30	3	3	2

4.1.6 Traditional Scenario VS Blockchain and CC Scenario

As the goal of this simulation is to showcase that the scenario that uses Blockchain and CC has an increased performance in comparison with the default scenario when subjected to the same inputs. To demonstrate this fact, the user interface shows both scenarios being fed by the same input (demand). In short, the difference between both approaches is that in the scenario that uses DLT and CC, participants have access to “real-time” data that is used in combination with the forecasted data to improve their forecasting figures orders, making them more aligned with the actual demand.

4.1.7 Stock Management and purchase orders

The management of stock considers the current demand plus the reaction to a stock disruption (missing units) In regards of the available stock and the safety stock policy.

In this simulation, the safety stock policy used follows the Standard Deviation Method that is calculated the following way:

$$Safety\ Stock = Z \times \sigma e \tag{4.2}$$

Where:

- Z represents the Z-score corresponding to the desired service level.
- σe represents the standard deviation of the error resulting from the absolute difference between forecasted and actual demand, for the last three months.

Based on the Safety Stock calculated for the next month, the order needs for the month (m+1) is given by:

$$Order\ needs\ = Forecasted\ figures\ for\ month\ (n + 1)\ +\ Safety\ Stock - \ Current\ Stock \tag{4.3}$$

Where:

- $Forecasted\ figures\ for\ month\ n + 1$ represents the forecasted demand for the next month.
- $Safety\ Stock$ results from the calculation of the SS.
- $Current\ Stock$ represents the amount of stock that is still currently available after operations and eventual disruptions.

In case of an increasing demand, the safety stocks gets systematically higher as it follows the forecasted figures, which systematically results in higher orders to the next nodes, resulting in increasingly higher figures. This phenomenon is called Bullwhip Effect.

4.1.8 Ledger Information Reliance

In the DLT and CC based approach, participants look to the demand data shared on ledger in the attempt of improving their forecasted figures. However, the demand at a customer level in real life is continuous along the month while the order requests are processed once with final figures. This means that the demand written on-ledger would never be the final amount for a given month. For instance, if the purchase order is done at the 25th day of a given month, the data for the remaining demand for the final 3 to 6 days is not considered. Also, some information could still be on-processing, been just missing or simply wrong. To mitigate the risk of blindly trusting this data and being misled to wrong estimations, Trust Rate (TR) represents how much participants trust on-chain data.

The main goal is to find a reasonable formula to mostly use the data shared on ledger while still partially relying on the traditional process.

The final forecasting will be given by:

$$TR * DLT\_BASED\_FORECASTING + (1 - TR) * TRADITIONAL\_FORECASTING \tag{4.3}$$

Where:

- TR represents the Trust Rate.
- $DLT\_BASED\_FORECASTING$ represents the figures of the forecasting using demand data.
- $TRADITIONAL\_FORECASTING$ represents the forecasted figures by the traditional means, or in other words, the ones used before this solution.
- $0 \leq TR \leq 1$

4.2 Testing Scenarios

This section explores various demand scenarios designed to test the simulation model under different market conditions. The chosen scenarios represent a diverse collection of market configurations, from stable and predictable environments to others affected by high variability and complexity. Each scenario has an identic starting point and contains the same historical data. The goal of these tests is to discuss how effectively the proposed solution can be to mitigate the Bullwhip Effect and enhance forecasting accuracy across the supply chain when compared with a traditional approach.

Each scenario consists of 36 periods of demand, following a unique pattern that mimics real-world supply chain challenges. The goal of these scenarios is to test how the system behaves under various conditions, such as steady-state operations, seasonal fluctuations, and abrupt market disruptions. This analysis is crucial for determining if this proof of concept enables supply chain participants to perform better forecasting activities, improve stock management, and ultimately reduce the frequency and impact of stock disruptions when compared with the approach used by default.

Examining the outcomes generated from each scenario provided meaningful conclusions about the effectiveness of the proposed approach.

4.2.1 Continuous Growth

This testing scenario represents a stable market with consistent, gradual growth. It tests the system's ability to handle consistent demand increases without major fluctuations. It's ideal for understanding how the simulation responds to predictable growth and helps in evaluating the impact of long-term growth on stock management. The table 4.5 depicts this scenario.

Table 4.5 - Demand for testing scenario Continuous Growth

Period	Demand	Period	Demand	Period	Demand
1	1000	13	2200	25	3400
2	1100	14	2300	26	3500
3	1200	15	2400	27	3600
4	1300	16	2500	28	3700
5	1400	17	2600	29	3800
6	1500	18	2700	30	3900
7	1600	19	2800	31	4000
8	1700	20	2900	32	4100
9	1800	21	3000	33	4200
10	1900	22	3100	34	4300
11	2000	23	3200	35	4400
12	2100	24	3300	36	4500

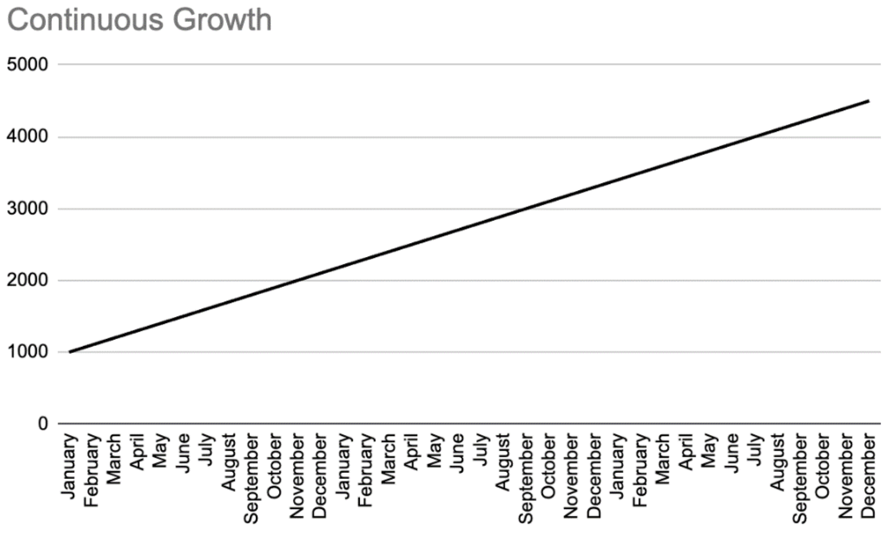

Figure 4.3 - Demand for testing scenario Continuous Growth

4.2.2 Hard Peak

This scenario simulates an unexpected surge in demand, followed by a return to normal levels. It helps in assessing how well the system can handle sudden increases in demand. The table 4.6 depicts this scenario.

Table 4.6 - Demand for testing scenario Hard Peak

Period	Demand	Period	Demand	Period	Demand
1	800	13	850	25	800
2	850	14	800	26	850
3	900	15	1000	27	900
4	950	16	5000	28	950
5	1000	17	4900	29	1000
6	5000	18	4800	30	5000
7	4900	19	4700	31	4900
8	4800	20	1000	32	4800
9	4700	21	950	33	4700
10	1000	22	900	34	1000
11	950	23	850	35	950
12	900	24	800	36	900

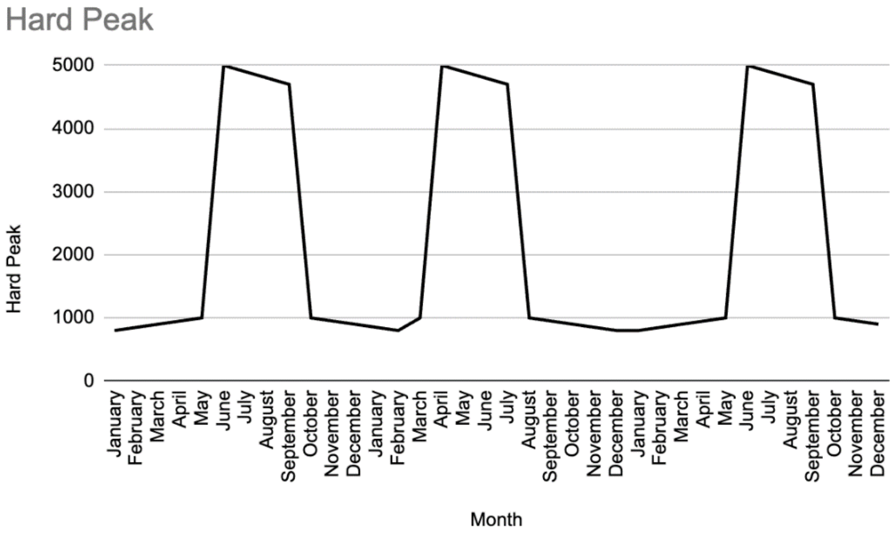

Figure 4.4 - Demand for testing scenario Hard Peak

4.2.3 Declining Demand

This scenario tests how the system reacts to a gradually declining market. The table 4.7 depicts this scenario.

Table 4.7 - Demand for testing scenario Declining Demand

Period	Demand	Period	Demand	Period	Demand
1	4000	13	1600	25	300
2	3800	14	1400	26	280
3	3600	15	1200	27	260
4	3400	16	1000	28	240
5	3200	17	900	29	220
6	3000	18	800	30	200
7	2800	19	700	31	180
8	2600	20	600	32	160
9	2400	21	500	33	140
10	2200	22	450	34	120
11	2000	23	400	35	100
12	1800	24	350	36	80

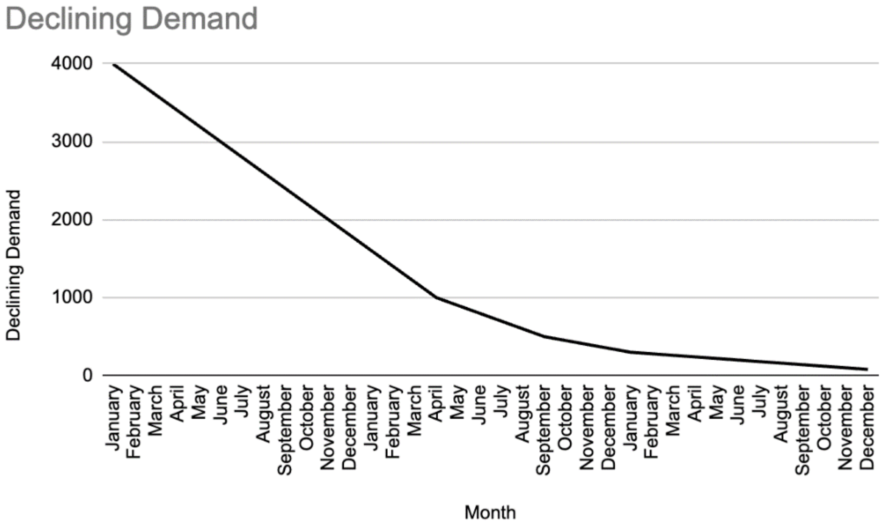

Figure 4.5 - Demand for testing scenario Declining Demand

4.2.4 Cyclical

This scenario represents markets where demand follows a cyclical pattern over longer periods. It tests the ability to forecast and manage stock in markets where demand is influenced by longer business cycles. The table 4.8 depicts this scenario.

Table 4.8 - Demand for testing scenario Cyclical

Period	Demand	Period	Demand	Period	Demand
1	1000	13	3000	25	5000
2	1500	14	2500	26	4500
3	2000	15	2000	27	4000
4	2500	16	1500	28	3500
5	3000	17	1000	29	3000
6	3500	18	1500	30	2500
7	4000	19	2000	31	2000
8	4500	20	2500	32	1500
9	5000	21	3000	33	1000
10	4500	22	3500	34	1500
11	4000	23	4000	35	2000
12	3500	24	4500	36	2500

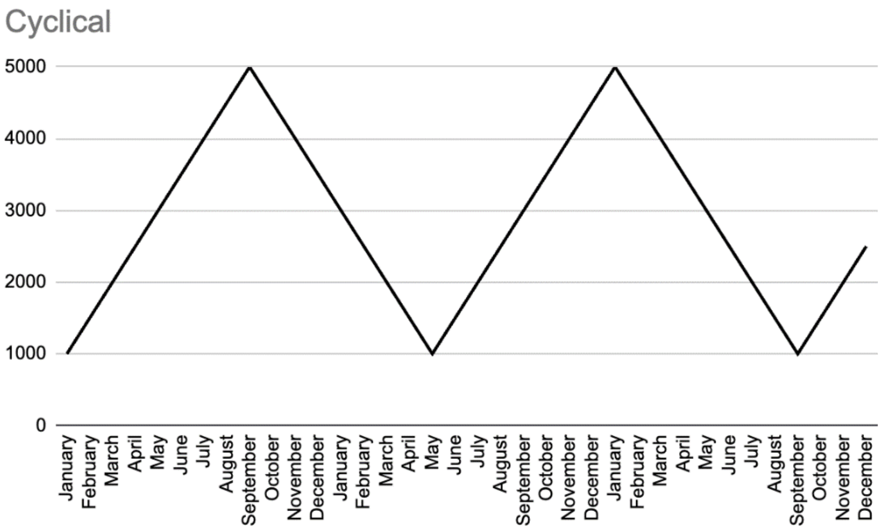

Figure 4.6 - Demand for testing scenario Cyclical

4.2.5 Random Fluctuation Demand

This scenario simulates demand with random fluctuations, which is useful for understanding how well the system can handle unpredictability without any clear pattern. It's valuable for stress-testing the robustness of forecasting models under conditions of randomness and uncertainty. The table 4.9 depicts this scenario.

Table 4.9 - Demand for testing scenario Random Fluctuation Demand

Period	Demand	Period	Demand	Period	Demand
1	1200	13	1600	25	1900
2	400	14	3200	26	4500
3	3000	15	1400	27	2100
4	700	16	2200	28	1600
5	1600	17	400	29	3200
6	1200	18	3000	30	1400
7	1000	19	700	31	2200
8	3400	20	1600	32	400
9	800	21	1200	33	3000
10	1900	22	1000	34	700
11	4500	23	3400	35	1600
12	2100	24	800	36	1200

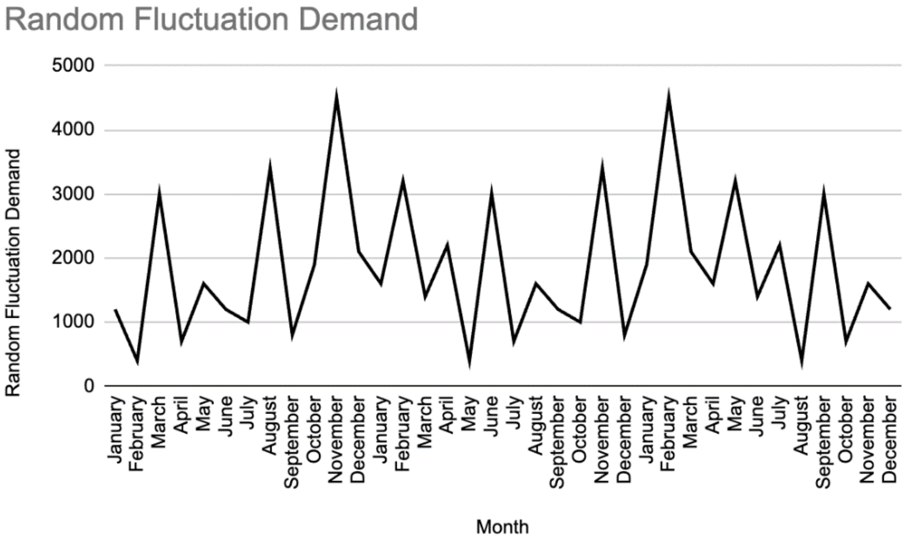

Figure 4.7 - Demand for testing scenario Random Fluctuation Demand

4.2.6 Stable

This scenario represents a market with consistent demand, with very minimal fluctuations over time. It simulates a product with steady consumption, where forecasting is straightforward, and there is minimal risk of stockouts or overstock. The table 4.10 depicts this scenario.

Table 4.10 - Demand for testing scenario Stable

Period	Demand	Period	Demand	Period	Demand
1	1500	13	1500	25	1500
2	1500	14	1500	26	1500
3	1500	15	1500	27	1500
4	1500	16	1500	28	1500
5	1500	17	1500	29	1500
6	1500	18	1500	30	1500
7	1500	19	1500	31	1500
8	1500	20	1500	32	1500
9	1500	21	1500	33	1500
10	1500	22	1500	34	1500
11	1500	23	1500	35	1500
12	1500	24	1500	36	1500

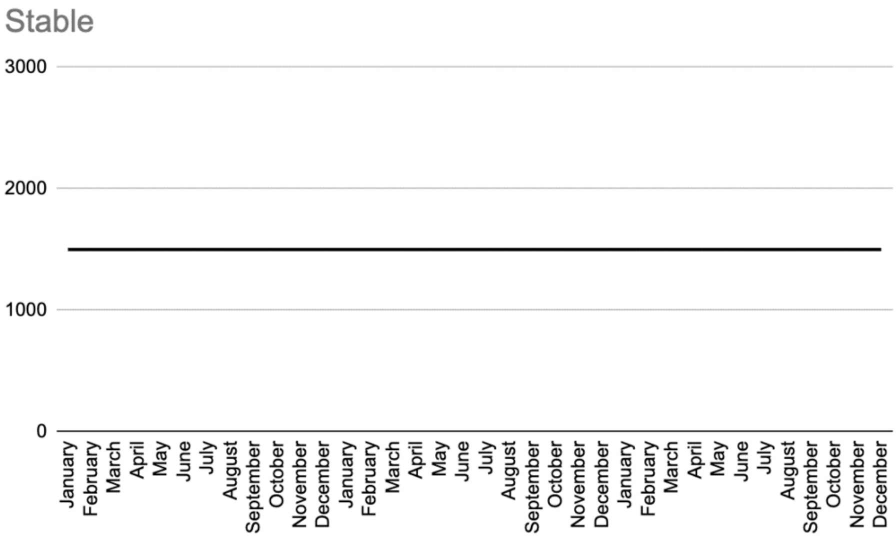

Figure 4.8 - Demand for testing scenario Stable

4.2.7 Seasonal

The seasonal scenario reflects a market with predictable, periodic fluctuations in demand. This allows us to assess how well the supply chain anticipates and prepares for regular cycles, such as those driven by seasonal consumer behavior or production cycles. The table 4.11 depicts this scenario.

Table 4.11 - Demand for testing scenario Seasonal

Period	Demand	Period	Demand	Period	Demand
1	550	13	550	25	560
2	600	14	600	26	550
3	620	15	620	27	600
4	700	16	700	28	620
5	1000	17	1000	29	700
6	2000	18	2000	30	1000
7	3000	19	3000	31	2000
8	2500	20	2500	32	3000
9	1500	21	1500	33	2500
10	1000	22	1000	34	1500
11	750	23	750	35	1000
12	560	24	550	36	750

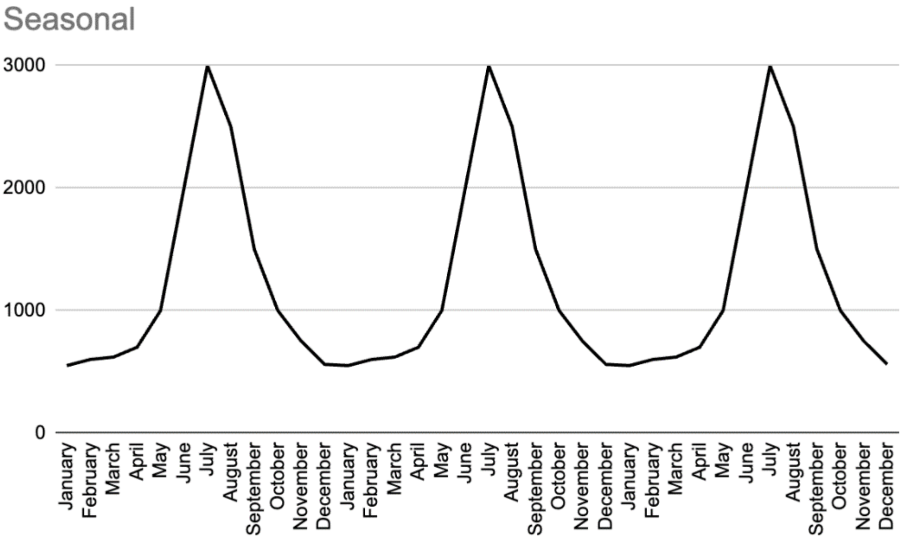

Figure 4.9 - Demand for testing scenario Seasonal

4.2.8 High Growth

In this scenario, we simulate a market with rapidly increasing demand. This is designed to test the supply chain's scalability and ability to manage sharp growth. The table 4.12 depicts this scenario.

Table 4.12 - Demand for testing scenario High Growth

Period	Demand	Period	Demand	Period	Demand
1	500	13	4500	25	9400
2	700	14	4900	26	9800
3	900	15	5200	27	10000
4	1200	16	5500	28	10500
5	1500	17	6000	29	11000
6	1800	18	6400	30	11500
7	2100	19	6700	31	12000
8	2500	20	7000	32	12500
9	2900	21	7500	33	13000
10	3300	22	8000	34	13500
11	3700	23	8400	35	14000
12	4000	24	9000	36	15500

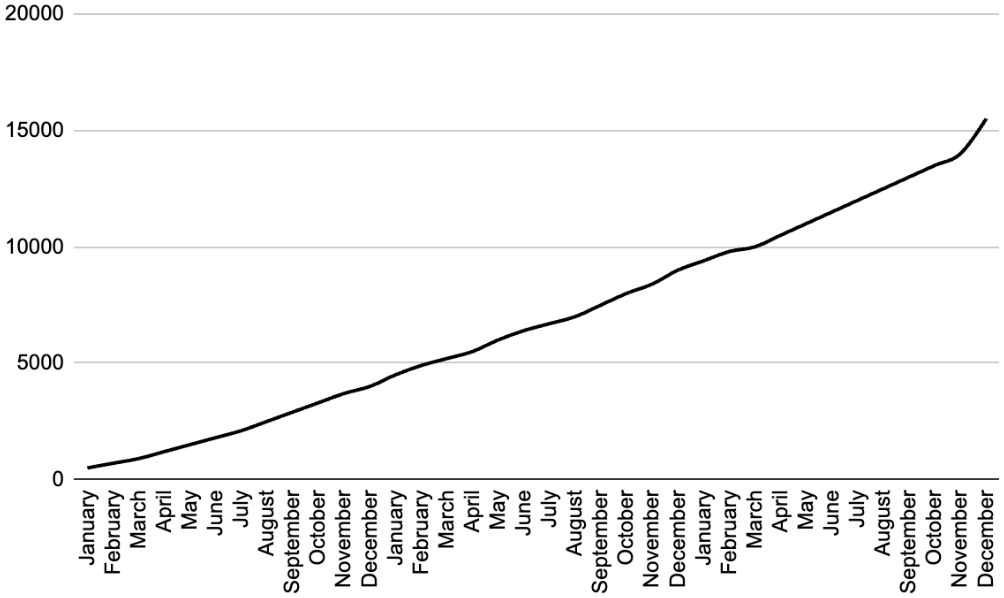

Figure 4.10 - Demand for testing scenario High Growth

4.2.9 Disruptive

This scenario represents a supply chain environment characterized by significant and frequent fluctuations in demand. These fluctuations include sudden spikes and drops in demand, creating challenges for inventory management and forecasting. The table 4.13 depicts this scenario.

Table 4.13 - Demand for testing scenario Disruptive

Period	Demand	Period	Demand	Period	Demand
1	500	13	545	25	540
2	1000	14	625	26	1000
3	3000	15	640	27	3000
4	3200	16	715	28	3200
5	3800	17	1200	29	3800
6	4000	18	1800	30	4000
7	3800	19	3200	31	3800
8	3000	20	3000	32	3000
9	2000	21	1450	33	2000
10	2000	22	900	34	2000
11	1000	23	700	35	1000
12	523	24	530	36	500

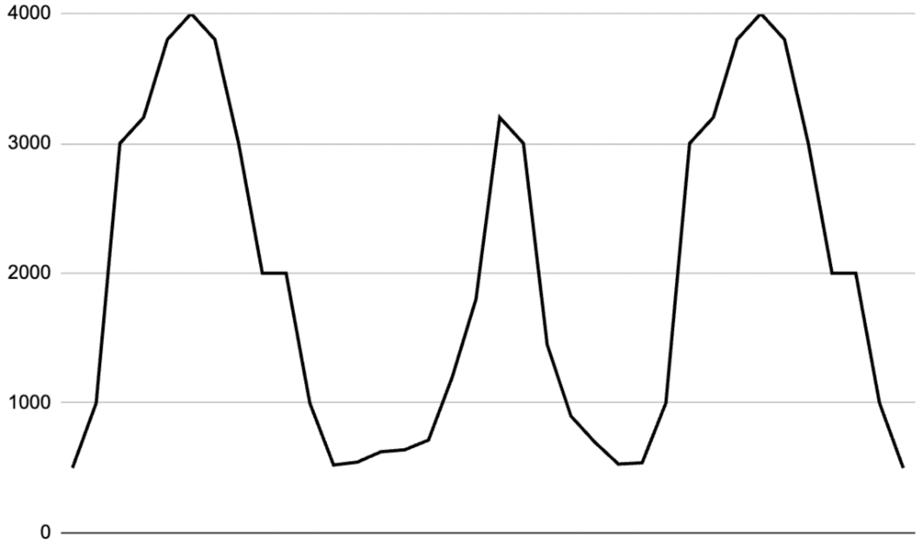

Figure 4.11 - Demand for testing scenario Disruptive

4.3 Limitations

The simulation including CC and DLT, faces a considerable set of limitations that must be outlined.

- Every non-functional requirement is taken out of scope, as well as any implementation that could resemble the usage of real data or targeted by a real integration in existing systems as this study did not consider real data.
- In case of a disruption, the operation continues, and the consequent orders are processed. This has been defined to maintain the focus on the forecasting and not in the disruptions.
- Confidential Computing is not implemented as it is very resource consuming.
- The blockchain network is not implemented as in a production grade environment, meaning less resources were used.
- Moreover, some components are simulated given the need of proper infrastructure and elevated costs.

It is relevant to emphasize that this is a deterministic use case, meaning that the expected output for a given input is the same despite the environment where it runs, as every functional aspect is considered. Therefore, the forecasted figures resultant of the execution of this simulation when leveraging DLT and CC would be the exact figures when running them under the same inputs and same configuration in a non-simulated setting.

4.4 Technological Stack

This chapter lists the specific technologies leveraged in this research. Each of these technologies brings certain capabilities and advantages, facilitating the development and deployment of such system.

- **Hyperledger Fabric** - Hyperledger Fabric is an open-source blockchain framework designed for enterprise use. It provides a modular architecture that allows organizations to create customizable blockchain networks. This technology is Further explained in detail throughout the next sub-chapter. This technology is used for the DLT + CC scenario. Appendices L and M contain the code implemented to be used in the Hyperledger implementation.

- **HTML** - is the standard markup language used to create web pages. It is the foundation of web content, structuring and presenting text, images, and other elements on the web.
- **CSS** – (Cascading Style Sheets) is a stylesheet language used to describe the presentation and design of web pages, including layout, colors, and fonts. It works alongside HTML to control how the content is displayed.
- **JavaScript** - High-level, dynamic, and interpreted programming language that is one of the core technologies of the web, alongside HTML and CSS. It enables interactive web pages and is an essential part of web applications. JavaScript is versatile and can be used for client-side as well as server-side development. Appendices J and K contain the Javascript code developed for this simulation.
- **Node.js** - Open-source, cross-platform runtime environment that allows developers to run JavaScript on the server-side. Appendices J, K, L and M
- **Catalyst Blockchain Manager** - Catalyst Blockchain Manager is a comprehensive platform that provides tools and services for deploying, managing, and maintaining blockchain networks. It offers an interface to simplify the complex tasks associated with blockchain development, such as node management, smart contract deployment, and network monitoring. For this simulation this software was used to facilitate the creation of the blockchain networks. Appendices A, B, C, D, E, F, G, H and Iand display screenshots of the usage of this software upon the configuration of different components.

4.5 Representative Blockchain Architecture – Hyperledger Fabric

This platform introduces its own specific terminology and components for implementing the foundational concepts of blockchain discussed in Chapter 3. (https://hyperledger-fabric.io). These components are:

- **Certificate Authorities (CAs)** - Certificate Authorities is the name given to the components used by HLF to issue digital certificates. With these, participants can authenticate and identify themselves and their resources and be able to identify other counterparties.
- **Digital Certificates -** Each certificate stores the basic information of its owner identity. When a participant identify itself by showing their certificate, other participants can validate their identity by checking the CA’s digital signature on the certificate.

- **Membership Service Provider (MSP)** – MSPs are one of the main components in HLF. In a nutshell, it provides the necessary means to authenticate and authorize participants using on their certificates, ensuring that only recognized identities can perform operations on the blockchain. When a participant holds another participant's MSP, it means that participant knows the other. Also, every component by any participant has to have a link to its MSP, which brings transparency to the network.
- **Orderer Nodes** - These are responsible for ensuring the consistency of the blockchain ledger across the network. They manage the ordering of transactions into blocks and deliver these blocks to peer nodes. The orderer nodes form the backbone of the consensus mechanism in Hyperledger Fabric. They collect transactions from various participants, order them chronologically, bundle them into blocks, and then distribute these blocks to peer nodes for validation and addition to the blockchain.
- **Peer Nodes** - are the main entities in Hyperledger Fabric that maintain the blockchain ledger and execute smart contracts (chaincode). Peers validate transactions, execute the code defined in smart contracts, and update the ledger state. They also store a copy of the entire blockchain and the current state of the ledger. Peers can be endorsing peers (which simulate transactions and sign the results) or committing peers (which validate and commit the transactions to the ledger).

Figure 4.12 summarizes these components for a participant overview.

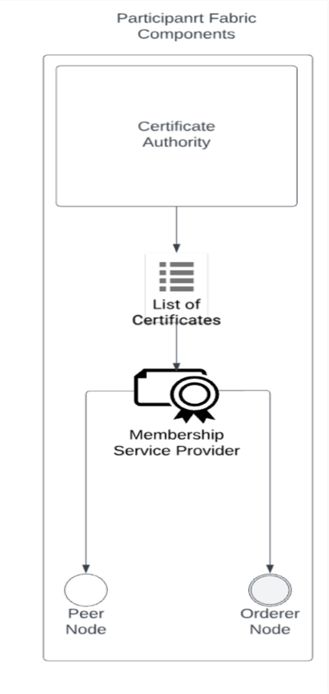

Figure 4.12 - Participant Fabric Components architecture diagram

- **Oracle Nodes -** An oracle in blockchain is a trusted entity or system that provides external data or computation results to the blockchain. Unlike traditional nodes, oracles bridge the gap between the blockchain and the external world, allowing smart contracts to interact with data or services outside the blockchain environment. When combined with confidential computing, oracles play a crucial role in securely processing sensitive data before it is relayed to the blockchain. For the implementation of this proof of concept an Oracle is a fundamental component given that the blockchain network has to be deterministic, meaning no external computation should alter the state of the ledger unless initiated by a network member. For forecasting and exchange of demand data, it must remain confidential yet transparent, accessible, and processed by a trusted and identifiable party. Therefore, an oracle node provides the connection between blockchain participants and the secure confidential computing enclave (Zhang et al, 2016).

- **Application Channel** - In Hyperledger Fabric, a channel acts as a private "subnetwork" that enables confidential communication between specific network members. This setup is designed for conducting private transactions. A channel is characterized by its member organizations, anchor peers for each member, the shared ledger, chaincode applications, and ordering service nodes. Transactions are carried out on a channel, and each participant must be authenticated and authorized. Every peer joining a channel is assigned an identity by a MSP, ensuring secure authentication among channel peers and services.

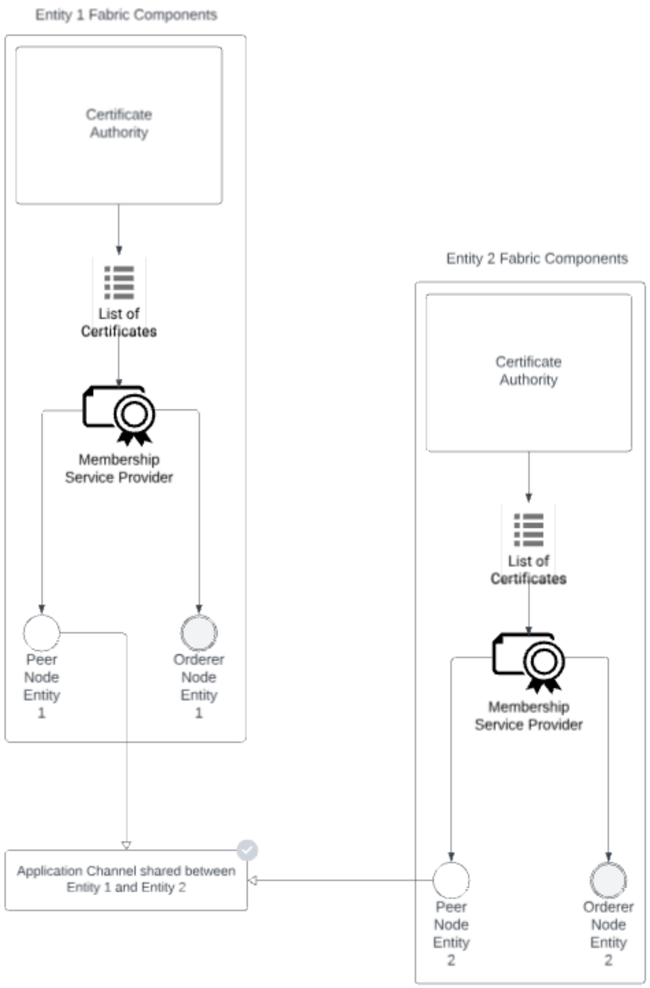

Figure 4.13 - Application channel overview

To establish a new channel, a client invokes the configuration system chaincode, referencing properties like peers and member organizations. This process generates a genesis block for the channel ledger, storing configuration details about channel policies, members, and anchor peers. When integrating a new member into an existing channel, the genesis block or the latest reconfiguration block is shared with the new participant.

The application channel is where the entities connect to towards the execution of smart contracts. To participate in each use case, entities must be connected to the same channel.

4.6 Confidential Computing by Intel SGX

Confidential Computing is a technology (or family of technologies) designed to protect data in use by performing computation in a hardware-based Trusted Execution Environment. This approach helps ensure that data remains secure not only when stored (at rest) and during transmission (in transit) but also while it is being processed. CC environments, such as Intel SGX (Software Guard Extensions), provide assurances that the data and the computation are protected from external threats and potential data breaches.

Intel SGX in specific is a set of security-related instruction codes that are built into modern Intel CPUs. SGX allows applications to create private regions of memory, called enclaves, which are designed to be protected from processes running at higher privilege levels, such as the operating system. The main goal of Intel SGX is to enhance the security of applications by shielding sensitive data from unauthorized access or modification, even if the system is compromised. Enclaves are highly secure and isolated environments that can run code and process data in a manner that ensures confidentiality and integrity (Costan, 2016)

Implementing a confidential computing mechanism will be simulated on the DLT and CC implementation, due to the high costs and resource requirements associated with such technologies. These environments demand significant investment in specialized hardware and software, which is not unavailable for the current scope of this project. However, it is important to note that the core objective of this proof of concept is to validate the functionality and effectiveness of the proposed solution, which in case of indicates that data privacy would be enhanced in a full-scale implementation.

4.7 Network Deployment through Catalyst Blockchain Manager

Catalyst Blockchain Manager is a tool designed to simplify the deployment, management, and scaling of blockchain networks. It provides an intuitive interface and a suite of tools that enable organizations to quickly set up and manage their blockchain infrastructure without the need for deep technical expertise. This manager supports various blockchain frameworks, including Hyperledger Fabric (https://catalyst.intellecteu.com/)

Catalyst Blockchain Manager serves several critical functions, some of them are

- **Simplified Deployment:** It automates the deployment of blockchain networks, reducing the complexity and time required to set up nodes, channels, and smart contracts.
- **Resource Management:** It provides tools for managing the resources needed by different entities in the blockchain network, such as compute, storage, and networking resources.

- **Monitoring and Maintenance:** It includes features for monitoring network performance, health, and security, and provides tools for regular maintenance and updates.

This proof-of-concept leverages Catalyst Blockchain Manager as it can speed-up the development and provide the technical resources while abstracting the whole technological configuration burden that is not relevant for the scope of this thesis. The HLF network has been configured following CAT-BM's official developer docs (https://docs.catalyst.intellecteu.com/fabric/release-notes).

4.8 Traditional Solution Architecture overview

This architecture aims to represent a traditional approach – where no DLT or CC technologies were put in place.

By default, each participant performs its forecasting activities based on the history of the previous demand they received. As they perform in a siloed manner, each participant manages its own system that together simulate the processing of orders from retail to raw material suppliers. Each system is represented by a stand-alone NodeJs application. The way they interact is through HTTP requests that are received, processed and sent by/to each server.

To provide the user with interactions, The UI/UX client application implemented serves as the front-end interface where orders are initiated by the user (acting as a customer). It is a standalone HTML and JavaScript application that submits demand orders via HTML requests to the Retail Backoffice.

Figure 4.14 - Traditional solution architecture Diagram

The code block 4.1 contains a pseudocode that reflects how each participant process demand in the default approach.

```
Algorithm processDemand
Input: demand, Demand for month m
Output: orderedUnits, Purchase Order for month m

Begin
    demand[m] ←demand
    // Calculate level, trend and seasonal equations
    lt[m] ← calculateLT(m)
    tt[m] ← calculateTT(m)
    st[m] ← calculateST(m)
    forecast[m+1] ← calculateForecast(lt[m], tt[m], st[m])
    // Calculate the safety stock based on the standard deviation of demand vs forecast
    stdDev ← calculateStdDev(demand, forecast)
    safetyStock[m+1] ← calculateSafetyStock(stdDev, confConst)
    // Update stock levels
    stock[m] ← stock[m-1] – demand + ordered[m-1]
    // Calculate order needs and obtain real orders after ceiling to next provider units
    orderNeeds ← forecast[m+1] + safetyStock[m+1] – stock[m]
    ordered[m] ← ceiling (orderNeeds, nextLevelUnitsConst)
    return ordered[m]
End
```

Code Block 4.1 - processDemand pseudocode

4.9 DLT and CC Solution Architecture overview

The core of this architecture consists in a HLF blockchain network to which five different participants connect to, each representing a specific node in the supply chain. The participants interact with each other through dedicated Backoffice environments, and the overall system is built to simulate the processing of orders from retail to material suppliers.

Each participant has its own Backoffice system responsible for processing incoming orders and submitting new orders to the next participant in the chain. These are developed as NodeJs applications and serve as each participant Backoffice.

The architecture also includes an Oracle Setup, which simulates an external entity responsible for processing demand data in a confidential manner. This setup simulates an environment designed to be run in a confidential computing enclave, all the other Hyperledger Fabric components required for a participant, including a peer. In this case the peer is enrolled in the two application channels.

- **Global Application Channel** – Stores the demand written by the Orcale node ensuring complete confidentiality. Each participant can access this channel to read data.
- **Demand Application Channel** – Used exclusively by the Retail participant and the Oracle setup. In this channel, the Retail Merchant system shares demand data in real-time with the Oracle for confidential processing. The other participants do not have access to this channel, ensuring privacy until the processed data is shared via the Global Application Channel.

The UI/UX client application is the same as the one used by the traditional solution.

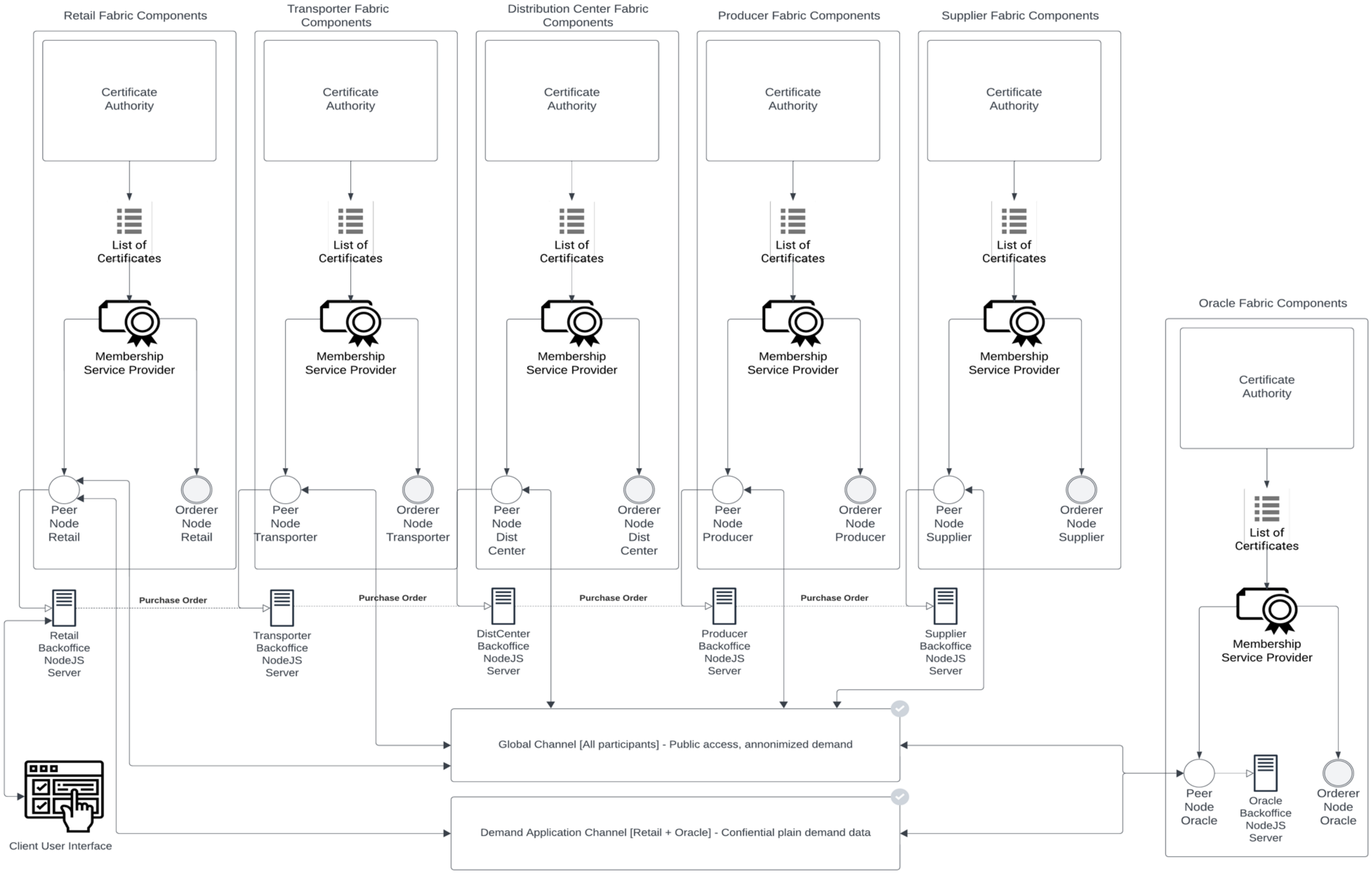

Figure 4.15 – DLT and CC Solution architecture diagram

Participants perform the same forecasting as in the traditional scenario described in the code block 4.1. However, once able to access the shared ledger at the end of the period of 36 months, participants correct their forecasted figures by looking at the data shared on ledger. The new figures are calculated by summing 80% of the demand (on equivalent units) plus 20% from the default forecasting. The code block 4.2 illustrates this operation.

```
Algorithm updatetForecasting
Input: ledgerData, demand on ledger in its raw form (cola bottles) for month m

Begin
    // calculate new forecasting using correct units
    convertedDemand ← convertToManagedUnits(ledgerData)
    forecast[m] ← forecast[m] * 0.2 + convertedDemand * 0.8
    // Calculate order needs and obtain real orders after ceiling to next provider units
    orderNeeds ← forecast[m] + safetyStock[m] – stock[m-1]
    ordered[m] ← ceiling (orderNeeds, nextLevelUnitsConst)
End
```

Code Block 4.2 - updateForecasting pseudocode

The data shared on ledger is written and read through specific smart contracts run inside the Global Channel and Demand Application Channel. Code blocks 4.3 illustrates how the demand is stored on ledger to make it available to all participants.

```
Algorithm writeDemand
Input: demand, demand figures written on retail units (cola bottles)

Begin
    // Update demand on ledger for month m and increment month
    demandVec[m] ← demand
    m = m + 1
End
```

Code Block 4.3 - writeDemand smartContract - Demand Application Channel

Code block 4.4 shows what the readDemand function available in the Global Application is supposed to do In order to fetch the demand shared on ledger for a given month.

```
                         Algorithm readDemand
             Input: m, month to which the demand is queried
       Output: demand for month m in Retailer units (Cola bottles)

Begin
    // Fetch demand for month m
    Return demandVec[m]
End
```

Code Block 4.4 - readDemand smartContract - Global Channel

For the implementation of the architecture displayed on Figure 4.15, the Technological stack refered to as in 4.4 has been used, attending to every aspect mentioned in cgapoter 4.

4.10 Results and analysis

This chapter systematically examines the outcomes of the different demand scenarios tested in the simulation model defined along chapter 4. The goal of analyzing such scenarios is to assess the impact of the blockchain-based approach on mitigating the bullwhip effect, reducing stock disruptions, and improving overall supply chain efficiency, in a comparison with a traditional approach.

To understand the magnitude of effectiveness of the proposed solution, it has to be compared against a traditional approach.

The analysis focuses mostly on key metrics such as forecast accuracy comparison, stock levels, the frequency of disruptions, and the overall performance of the supply chain under each scenario. Once these results are compared against a traditional forecasting approach, the emphasis is to highlight the advantages and potential drawbacks of the blockchain-enhanced approach.

4.10.1 Forecasting methods comparison – Forecasting Error Difference

The table 4.14 highlights the Forecasting Error differences between the traditional scenario and the scenario incorporating blockchain technology. Forecasting accuracy plays a crucial role in minimizing stock discrepancies and improving operational efficiency. For each scenario the improvement ratio results of dividing the difference between the figures of the error of the traditional forecasting and the Blockchain Informed Forecasting by the Blockchain Informed Forecasting for each participant.

Table 4.14 - Forecasting methods comparison – Forecasting Error Difference

Scenario	Transporter			Distribution Center			Producer			Supplier			Network Total (in cola bottles)		
	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio
Continuous Growth	3631	2191	65.72%	777	458	69.65%	18419	630	2823.65%	21007	569	3591.92%	12767400	540150	2263.68%
Hard Peak	4712	3556	32.51%	1189	705	68.65%	2702	1266	113.43%	3368	956	252.30%	2353550	940150	150.34%
Declining Demand	6583	3394	93.96%	672	590	13.90%	1081	1046	3.35%	1350	1149	17.49%	1109075	924725	19.94%
Cyclical	5658	3251	74.04%	1085	781	38.92%	2143	1779	20.46%	1924	1329	44.77%	1669950	1219650	36.92%
Random Fluctuation	5187	4121	25.87%	1782	606	194.06%	2886	976	195.70%	2682	630	325.71%	2302425	734775	213.35%
Stable	2016	1201	67.86%	314	246	27.64%	455	402	13.18%	437	437	0.00%	406525	355900	14.22%
Seasonal	4561	2743	66.28%	776	741	4.72%	1242	1040	19.42%	1142	889	28.46%	1046775	847200	23.56%
High growth	8292	4651	78.28%	1247	758	64.51%	2394	1598	49.81%	4202	2081	101.92%	2693300	1485650	81.29%
Disruptive	4561	2919	56.25%	776	697	11.33%	1242	981	26.61%	1142	815	40.12%	1046775	798100	31.16%

4.10.2 Forecasting methods comparison – Stock Management Difference

The table 4.15 shifts the focus to the amount of stock managed in both scenarios. For each scenario the improvement ratio results of dividing the difference between the managed stock figures of the traditional forecasting and the Blockchain Informed Forecasting by the Blockchain Informed Forecasting for each participant.

Table 4.15 - Forecasting methods comparison – Forecasting Error Difference

Scenario	Transporter			Distribution Center			Producer			Supplier			Network Total (in cola bottles)		
	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio
Continuous Growth	4540	4220	7.58%	800	481	66.32%	17786	1350.5	1216.99%	17650	10	176400.00%	11378750	567125	1906.39%
Hard Peak	3570	2810	27.05%	800	585	36.75%	1949	900.5	116.44%	2830	0	N.A.	N.A.	N.A.	N.A.
Declining Demand	4860	2750	76.73%	698	601	16.14%	902	779	15.79%	1100	20	5400.00%	934000	421250	121.72%
Cyclical	6370	4600	38.48%	982	702	39.89%	1536.5	1157	32.80%	1210	10	12000.00%	1242625	583500	112.96%
Random Fluct.	3510	2900	21.03%	1594	417	282.25%	2207	591.5	273.12%	2150	10	21400.00%	1844250	328375	461.63%
Stable	2350	2180	7.80%	229	230	-0.43%	236	297.5	-20.67%	320	20	1500.00%	295000	193875	52.16%
Seasonal	1460	1470	-0.68%	144	130	10.77%	156.5	141.5	10.60%	130	0	N.A.	N.A.	N.A.	N.A.
High growth	10300	10500	-1.90%	1168	1118	4.47%	1724	1383.5	24.61%	1890	0	N.A.	N.A.	N.A.	N.A.
Disruptive	3430	2300	49.13%	457	539	-15.21%	675.5	863	-21.73%	1142	1066	7.13%	797125	807750	-1.32%

4.10.3 Forecasting methods comparison – Disruptions

The table 4.16 examines the number of disruptions recorded in each scenario. Disruptions occur when a participant fails to meet demand due to insufficient stock or other logistical issues. For each scenario the improvement ratio results by applying dividing the difference between the figures of the number of disruptions of the traditional forecasting and the Blockchain Informed Forecasting by the Blockchain Informed Forecasting for each participant.

Table 4.16- Forecasting methods comparison - Disruptions

Scenario	Transporter			Distribution Center			Producer			Supplier			Network Total (in cola bottles)		
	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio	Traditional Forecasting (ERR)	Blockchain Informed Forecasting (ERR)	Improvement Ratio
Continuous Growth	0	4	-100.00%	3	6	-50.00%	4	6	-33.33%	4	2	100.00%	11	18	-63.64%
Hard Peak	4	5	-20.00%	4	4	0.00%	3	5	-40.00%	3	1	200.00%	14	15	-7.14%
Declining Demand	2	2	0.00%	4	4	0.00%	5	4	25.00%	3	3	0.00%	14	13	7.14%
Cyclical	5	11	-54.55%	6	6	0.00%	4	5	-20.00%	4	2	100.00%	19	24	-26.32%
Random Fluct.	4	4	0.00%	1	3	-66.67%	3	3	0.00%	4	2	100.00%	12	12	0.00%
Stable	3	6	-50.00%	4	4	0.00%	3	5	-40.00%	4	3	33.33%	14	18	-28.57%
Seasonal	3	4	-25.00%	2	3	-33.33%	1	2	-50.00%	2	1	100.00%	8	10	-25.00%
High growth	7	9	-22.22%	3	7	-57.14%	4	4	-22.22%	3	1	200.00%	17	21	-23.53%
Disruptive	3	4	-25.00%	2	4	-50.00%	2	3	-33.33%	2	1	100.00%	9	12	-33.33%

4.10.4 Analysis

Following the execution of the scenarios outlined for this proof-of-concept in Chapter 4, several significant findings emerged, highlighting the comparative effectiveness of the blockchain-based model over the traditional approach.

In regards of the forecasting accuracy, the blockchain approach demonstrated a significant improvement. This enhancement can be attributed to the model's inherent ability to reduce the distance between actual orders and forecasted figures as it can provide a glance on what is going on in the retail level not available in the traditional approach. This improvement was evident even under highly volatile conditions, such as those in the Disruptive, High Peak, and Random Fluctuation scenarios. It is important to note that participants are not aware of their clients' stock levels or the safety stock policies implemented by them, which directly affects the quantity of units ordered as each processes its own data under its siloed environment.

In terms of stock management efficiency, the simulation revealed a noticeable reduction in the average amount of stock managed by participants across most scenarios. However, in the Disruptive Scenario, increased volatility in demand led to a rise in the amount of stock managed. This was primarily due to the high variability and its impact on estimations and safety stock levels.

Lastly, an overall increase in the number of disruptions was observed across all scenarios. This occurred primarily due to the improved accuracy of demand forecasts, which reduced excess stock but increased vulnerability during sudden demand spikes, as safety stock levels were smaller and consequently more susceptible of being disrupted. This finding underscores the classic trade-off between stock levels and availability, with implications for both cost management and service reliability. The choice of stock management policy ultimately depends on the product and market context; in some cases, companies may even prioritize minimizing inventory over meeting all customer demands. Additionally, this effect could have been mitigated if the safety stock policy had been adjusted to be more dynamically responsive to sudden changes in demand by approximating the stock amount to informed forecasting figures.

Overall, these results emphasize that there is a potential advantage of incorporating blockchain technology to significantly enhance supply chain management. By leveraging real-time data, these advanced methods could further refine and optimize supply chain operations, leading to more accurate and responsive outcomes.

5 Conclusions and Recommendations

5.1 Conclusions

Supply chain management is confronted with numerous challenges, including globalization, material disruptions, regulatory compliance, product safety and quality standards, technological advancements, and demand variability. Among these, demand variability is becoming increasingly critical due to its profound impact on operational management. In a world characterized by volatility, uncertainty, complexity, and ambiguity (VUCA), only companies that can implement flexibility and agility survive in this highly competitive landscape.

To navigate these challenges, supply chain participants must enhance their forecasting capabilities to manage stocks and operations as efficiently as possible. The goal is to avoid stock disruptions while minimizing inventory levels. Poor stock management and inaccurate forecasting in scenarios of high variability of customer demand can lead to the bullwhip effect, a scenario where fluctuations in consumer demand cause increasingly larger variations in orders placed with upstream suppliers. This effect not only disrupts the supply chain but also inflates costs and complicates inventory management.

Blockchain technology offers a solution by providing a platform where companies can share trustworthy, tamper-proof, and auditable data. Additionally, confidential computing, particularly through Intel SGX, creates a secure environment where data can be processed without exposure, ensuring privacy even during computation. The integration of these two technologies allows supply chain participants to share anonymous yet reliable real-time data, enhancing traditional forecasting methods. As a result, companies within the supply chain can optimize their operational management, leading to reduced costs, improved inventory management, and fewer demand disruptions.

By leveraging distributed ledger technologies and confidential computing, organizations can significantly enhance their forecasting capabilities, ultimately preventing and mitigating the effects of the Bullwhip Effect in the supply chain.

5.2 Suggestions for future research

Given the findings and conclusions of this research, several avenues for further exploration are proposed:

- **Exploring Alternative Forecasting Methods:** While this study employed the Triple Exponential Smoothing method under the defined architecture, future research could evaluate the performance of other forecasting models such as machine learning-based algorithms, neural networks, or other advanced statistical models, especially one that could integrate real-time data.
- **Dynamic Safety Stock Calculation:** This research focused on a relatively static approach to safety stock calculations. Future studies could investigate a dynamic approach that adapts in real-time based on fluctuating demand data recorded on the blockchain ledger. This will improve the solution as less demand is propagated through the network, as most likely less disruptions would take place given that purchase orders would contain fewer units.
- **Exploring Additional Use Cases:** While the current research focused on demand forecasting and the bullwhip effect, the same architecture (integrating blockchain and confidential computing) could be leveraged for other supply chain challenges such us food tracking, carbon credit certificates and many others in the access to shared trusted data could benefit.

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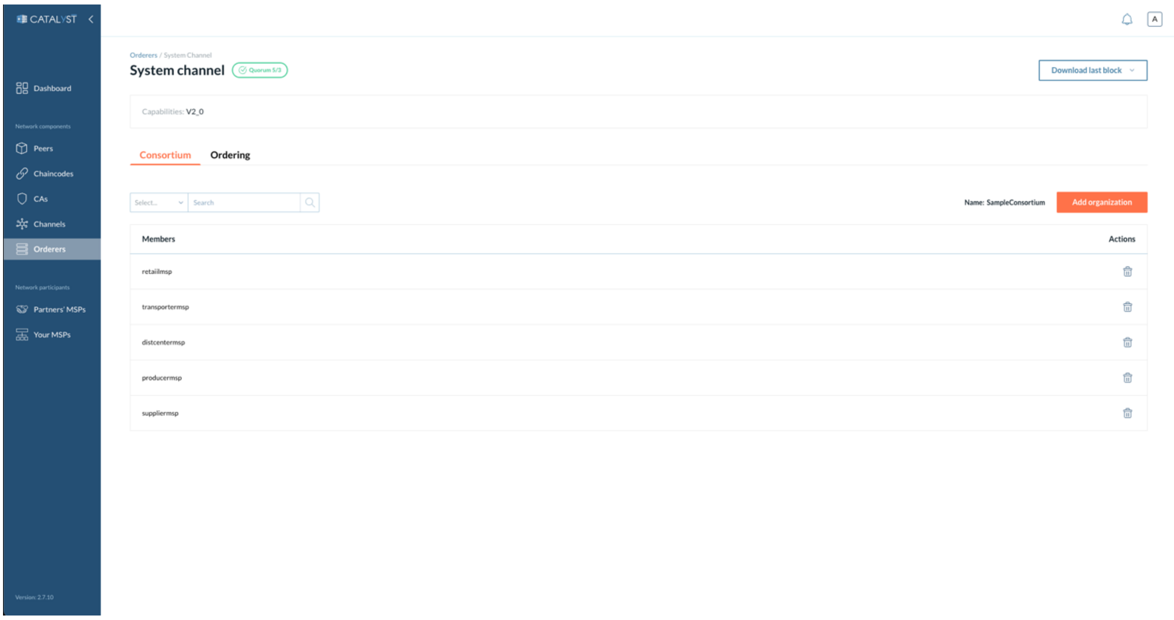
Appendices

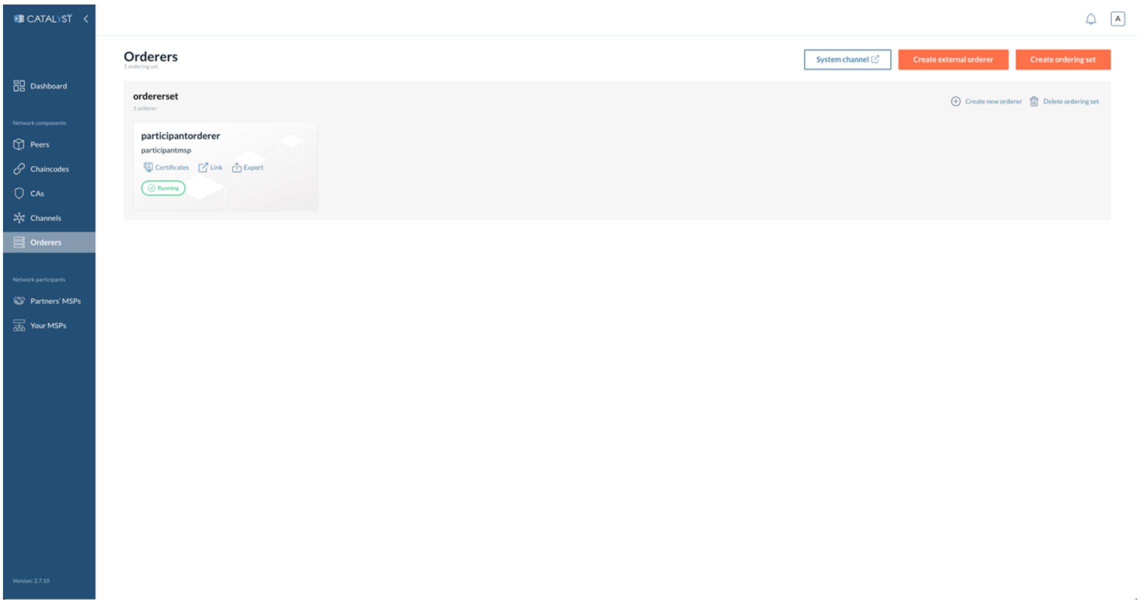


Capabilities: V2_0

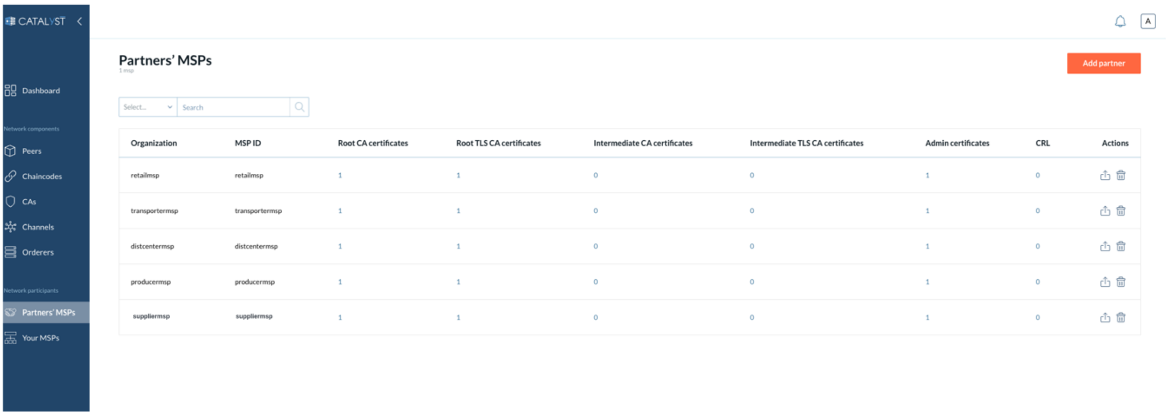
Name: SampleConsortium

Members	Actions
retaiilmsp	🗑
transportermsp	🗑
distcentermsp	🗑
producermsp	🗑
suppliermsp	🗑

Appendix A - Catalyst System Channel



Appendix B - Catalyst Orderer

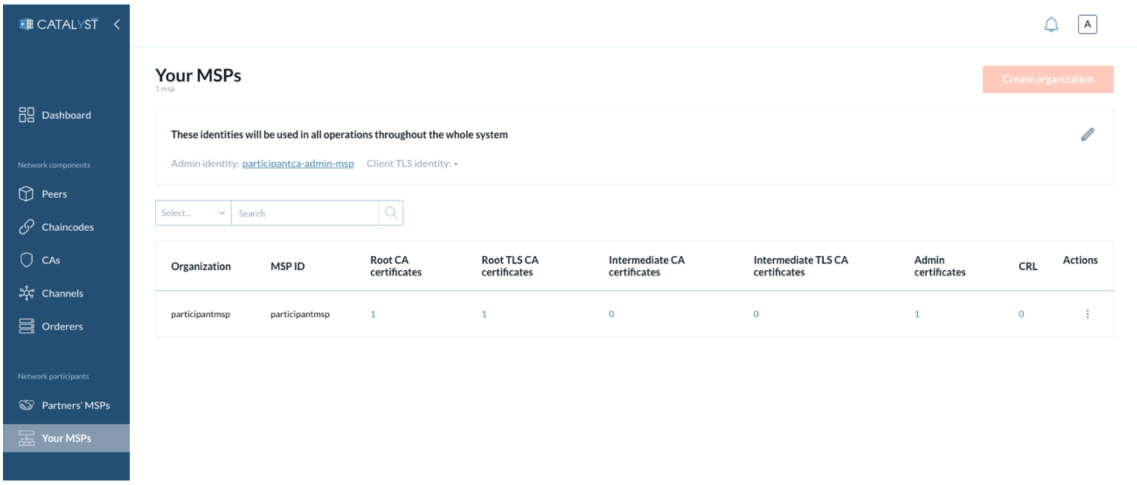


Partners' MSPs

1 msp

Organization	MSP ID	Root CA certificates	Root TLS CA certificates	Intermediate CA certificates	Intermediate TLS CA certificates	Admin certificates	CRL	Actions
retailmsp	retailmsp	1	1	0	0	1	0	
transportermsp	transportermsp	1	1	0	0	1	0	
distcentermsp	distcentermsp	1	1	0	0	1	0	
producermsp	producermsp	1	1	0	0	1	0	
suppliermsp	suppliermsp	1	1	0	0	1	0	

Appendix C - Catalyst Parnter MSPS



Your MSPs

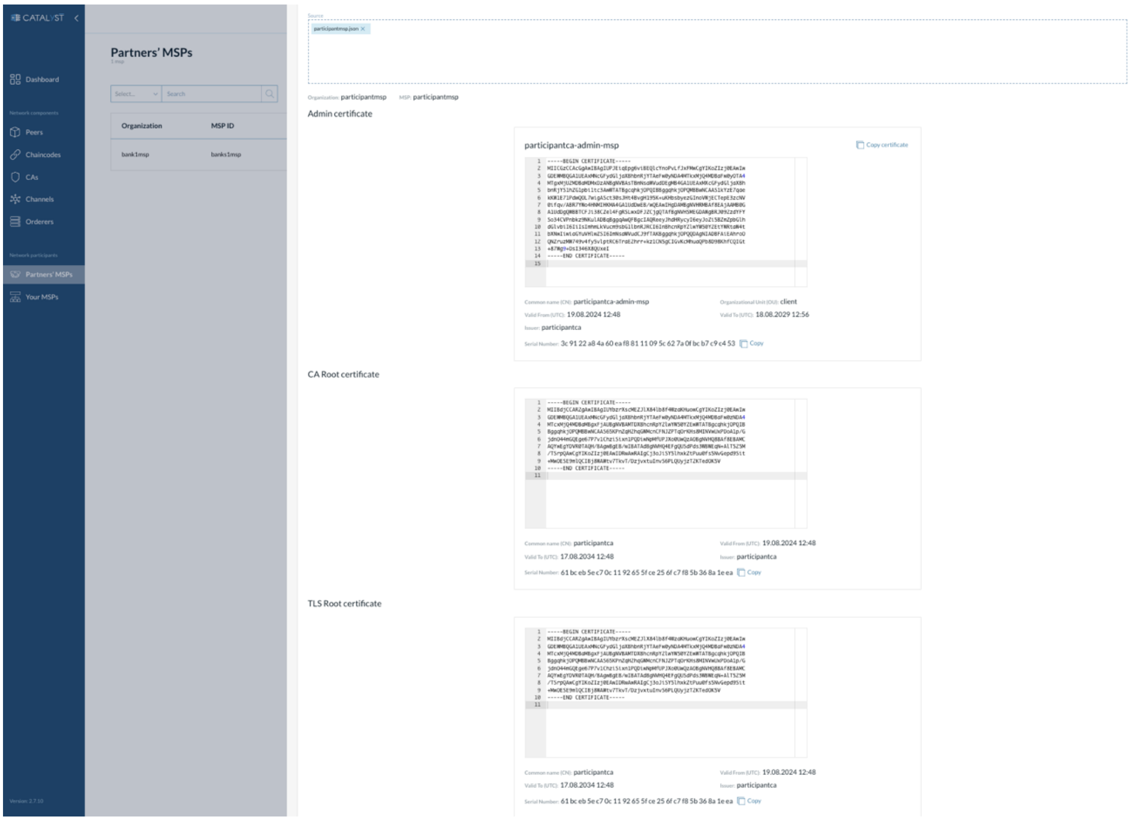
1 msp

These identities will be used in all operations throughout the whole system

Admin identity: participantca-admin-msp Client TLS identity: -

Organization	MSP ID	Root CA certificates	Root TLS CA certificates	Intermediate CA certificates	Intermediate TLS CA certificates	Admin certificates	CRL	Actions
participantmsp	participantmsp	1	1	0	0	1	0	⋮

Appendix D - Catalyst My MSP



Organization	MSP ID
bank1msp	banks1msp

Organization: participantmsp MSP: participantmsp

Admin certificate

participantca-admin-msp

Common name (CN): participantca-admin-msp
Organizational Unit (OU): client
Valid From (UTC): 19.08.2024 12:48
Valid To (UTC): 18.08.2029 12:56
Issuer: participantca
Serial Number: 3c 91 22 a8 4a 60 ea f8 81 11 09 5c 62 7a 0f bc b7 c9 c4 53

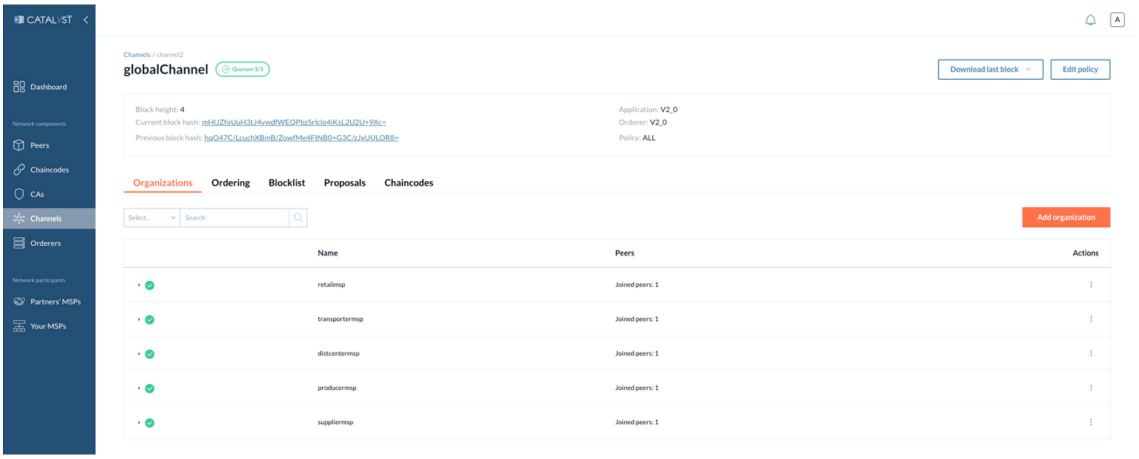
CA Root certificate

Common name (CN): participantca
Valid From (UTC): 19.08.2024 12:48
Valid To (UTC): 17.08.2034 12:48
Issuer: participantca
Serial Number: 61 bc eb 5e c7 0c 11 92 65 5f ce 25 6f c7 f8 5b 36 8a 1e ea

TLS Root certificate

Common name (CN): participantca
Valid From (UTC): 19.08.2024 12:48
Valid To (UTC): 17.08.2034 12:48
Issuer: participantca
Serial Number: 61 bc eb 5e c7 0c 11 92 65 5f ce 25 6f c7 f8 5b 36 8a 1e ea

Appendix E - Catalyst MSP View

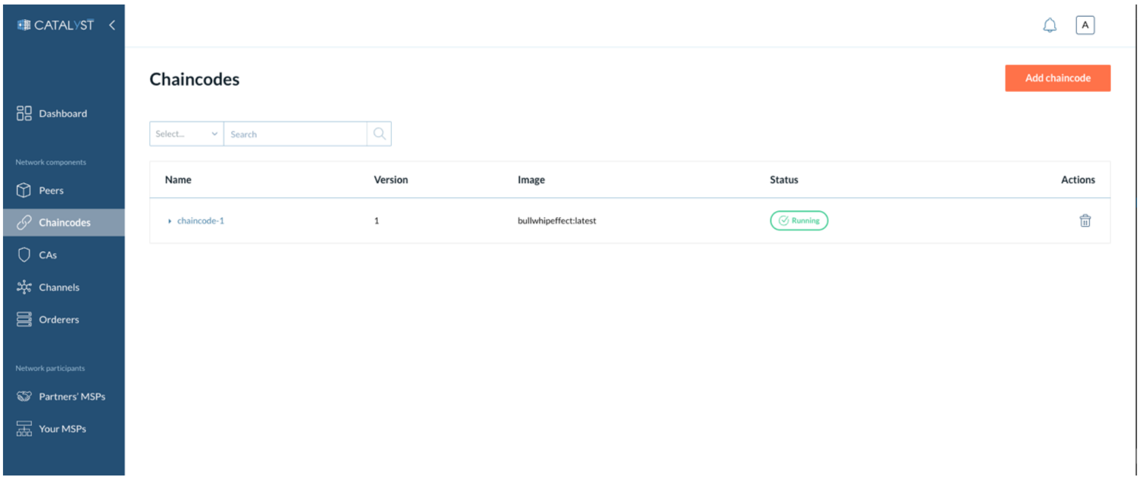


globalChannel

Block height: 4
Current block hash: mHIJZfoUuH3tJ4vwdfWEQPbzSrlclo4iKsL2U2U+9Xc=
Previous block hash: hqO47C/LcuchXBmB/ZowfMe4FINB0+G3C/zJxUULOR8=
Application: V2_0
Orderer: V2_0
Policy: ALL

Name	Peers	Actions
retailmsp	Joined peers: 1	⋮
transportermsp	Joined peers: 1	⋮
distcentermsp	Joined peers: 1	⋮
producermsp	Joined peers: 1	⋮
suppliermsp	Joined peers: 1	⋮

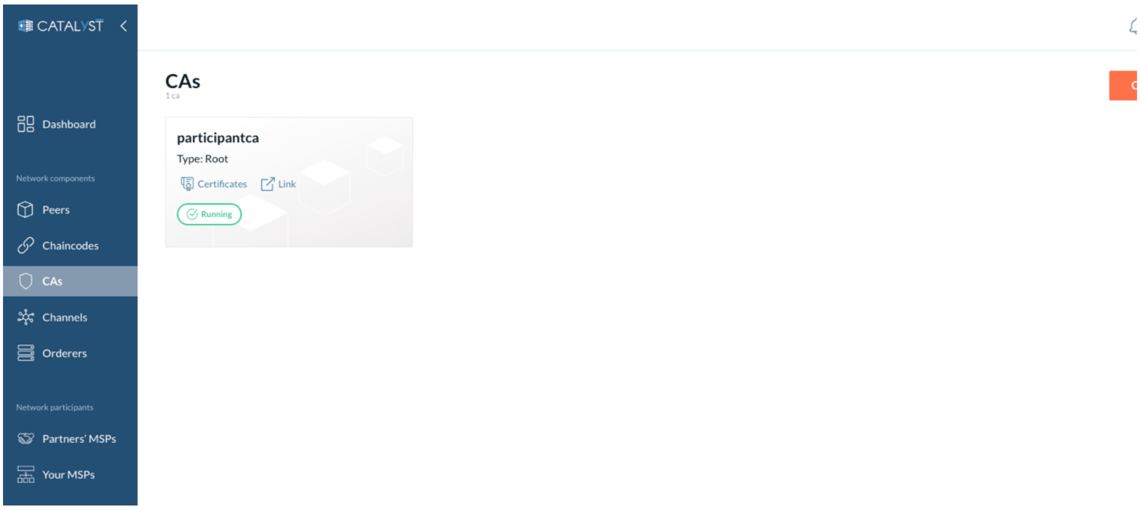
Appendix F - Catalyst Global Channel



Chaincodes

Name	Version	Image	Status	Actions
chaincode-1	1	bullwhipeffect:latest	Running	

Appendix G - Catalyst Chaincodes



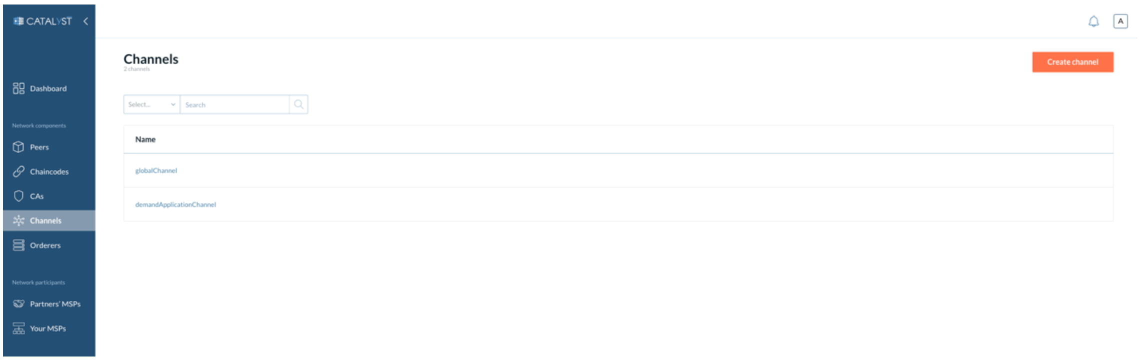
CAs

1 ca

participantca

Type: Root

Appendix H - Catalyst CA

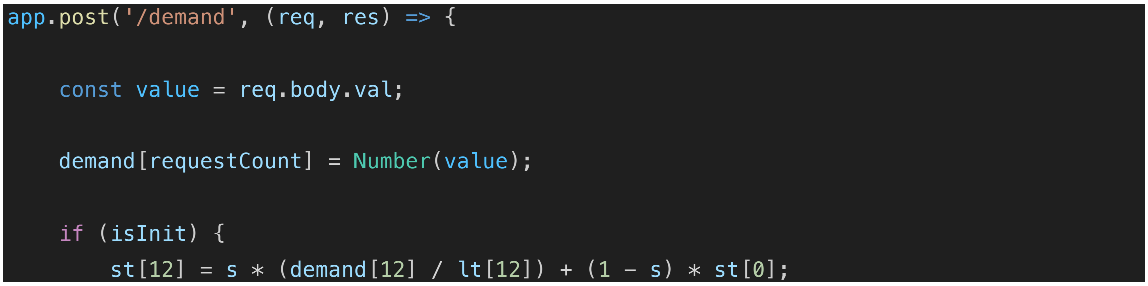


Channels

2 channels

Name
globalChannel
demandApplicationChannel

Appendix I - Catalyst Channels



```
app.post('/demand', (req, res) => {

    const value = req.body.val;

    demand[requestCount] = Number(value);

    if (isInit) {
        st[12] = s * (demand[12] / lt[12]) + (1 - s) * st[0];
```

```
        forecast[13] = (lt[12] + tt[12]) * st[requestCount - 12];
        isInit = false;

    }

    lt[requestCount] = a * (demand[requestCount] / st[requestCount - 12]) +
        (1 - a) * (lt[requestCount - 1] + tt[requestCount - 1]);
    tt[requestCount] = b * (lt[requestCount] - lt[requestCount - 1]) + (1 - b) *
tt[requestCount - 1];
    st[requestCount] = s * (demand[requestCount] / lt[requestCount]) + (1 - s) *
st[requestCount - 12];

    // Calculate forecasting figures
    var defaultFC = (lt[requestCount] + tt[requestCount]) * st[requestCount - 11];
    if (defaultFC > 0) {
        forecast[requestCount + 1] = (lt[requestCount] + tt[requestCount]) *
st[requestCount - 11];
    } else
        forecast[requestCount + 1] = 0;

    var averageDemand = calculateAVGLast3Months(demand, requestCount);
    var stadevDemand = calculateStandardDeviationLast3Months(demand, requestCount);
    if (requestCount == 13) {

        stock[requestCount] = 668;
        safetystockVec[requestCount] = 0;
        safetystockVec[requestCount + 1] = stadevDemand * safety_stock_confidence;
        orderUnitsVec[requestCount] = 650;
        orderBoxesVec[requestCount] = 26;
        receivedUnitsVec[requestCount] = 0;
        receivedBoxesVec[requestCount] = 0;

    } else {

        //Imporved SS Calculation
        if (requestCount >= 16) {
            stadevDemand = calculateStandardDeviationErrorLast3Months(demand, forecast,
requestCount);
        }


        receivedUnitsVec[requestCount] = orderUnitsVec[requestCount - 1];
        receivedBoxesVec[requestCount] = receivedUnitsVec[requestCount] /
units_in_a_box;

        var stockRaw = stock[requestCount - 1] - demand[requestCount] +
receivedUnitsVec[requestCount];
        if (stockRaw <= 0)
            stock[requestCount] = 0;
        else
            stock[requestCount] = stockRaw;

        //safetystockVec[requestCount]=safetystockVec[requestCount-1];
        safetystockVec[requestCount + 1] = stadevDemand * safety_stock_confidence;
```

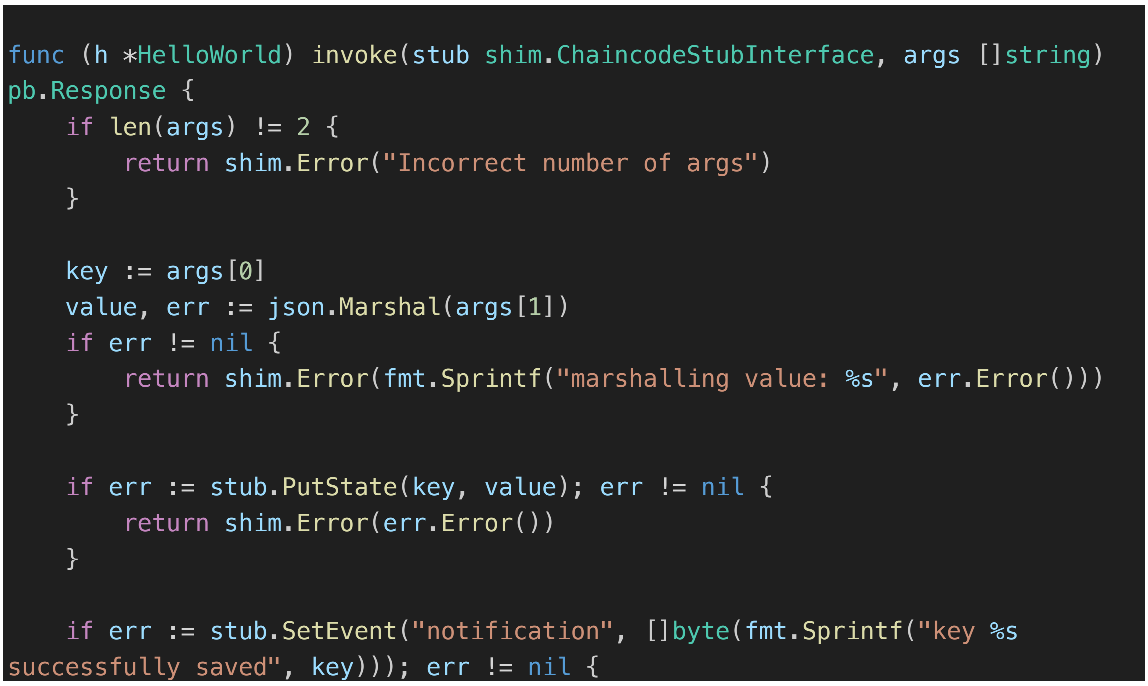
```
        var orderRaw = forecast[requestCount + 1] + safetystockVec[requestCount + 1] -
stock[requestCount];

        if (orderRaw < 0)
            orderUnitsVec[requestCount] = 0;
        else
            orderUnitsVec[requestCount] = ceiling(orderRaw, units_in_a_box);

        orderBoxesVec[requestCount] = orderUnitsVec[requestCount] / units_in_a_box;

    }



    if (value != 0 && !value) {
        return res.status(400).send('Demand parameter is required');
    }

    res.json({
        demand: demand[requestCount],
        stockUnitsDefault: stock[requestCount],
        stockUnitsFinal: stock[requestCount],
        hasDisruption: (demand[requestCount] > stock[requestCount - 1] +
receivedUnitsVec[requestCount]),
        disruptionSize: 0,
        safetyStock: safetystockVec[requestCount],
        safetyStockNextMonth: safetystockVec[requestCount + 1],
        orderedUnits: orderUnitsVec[requestCount],
        orderedBoxes: orderBoxesVec[requestCount],
        receivedUnits: receivedUnitsVec[requestCount],
        receivedBoxes: receivedBoxesVec[requestCount],
        forecastedNextMonth: forecast[requestCount + 1],
        error: Math.abs(forecast[requestCount] - demand[requestCount]),
    });

    requestCount++;

});

app.listen(port, hostname, () => {
    console.log(`Retail server running at http://${hostname}:${port}/`);
});
```

Appendix J – JS Code to process demand at the retail

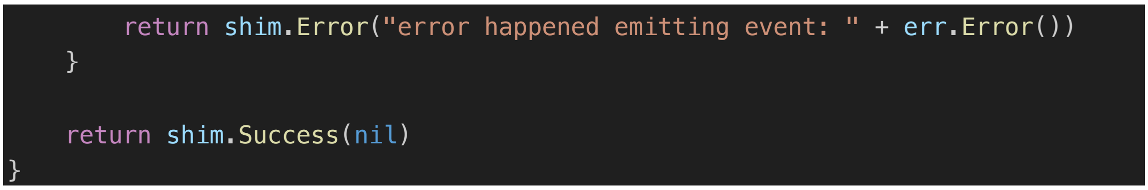
```
//@POST - Update demand based on ledger data
app.post('/updateBlockchainForecast', async (req, res) => {
    const value = req.body.val;
    const newDemand = value;
    var valueOnBc = await callReadDemand();
    //update with 80% weight on shared data
    forecast[requestCount] = Math.ceil(forecast[requestCount] * 0.4 +
valueOnBc / 25 * 0.6);
```

```
    //also update order request taking into account 80% weight on shared data
as demand is continuous and not uniform
    var orderRaw = forecast[requestCount] + safetystockVec[requestCount] -
stock[requestCount - 1];

    if (orderRaw < 0)
        orderUnitsVec[requestCount - 1] = 0;
    else
        orderUnitsVec[requestCount - 1] = ceiling(orderRaw, units_in_a_box);

    orderBoxesVec[requestCount] = orderUnitsVec[requestCount] /
units_in_a_box;

    var orderedUnitsRes = orderUnitsVec[requestCount - 1];
    var orderedBoxesRes = orderBoxesVec[requestCount - 1];
    var forecastRes = forecast[requestCount];

    if (value != 0 && !value) {
        return res.status(400).send('Demand parameter is required');
    }

    res.json({
        orderedUnits: orderedUnitsRes,
        orderedBoxes: orderedBoxesRes,
        forecast: forecastRes,
    });

});
```

Appendix K – JS code to update forecasting with ledger data

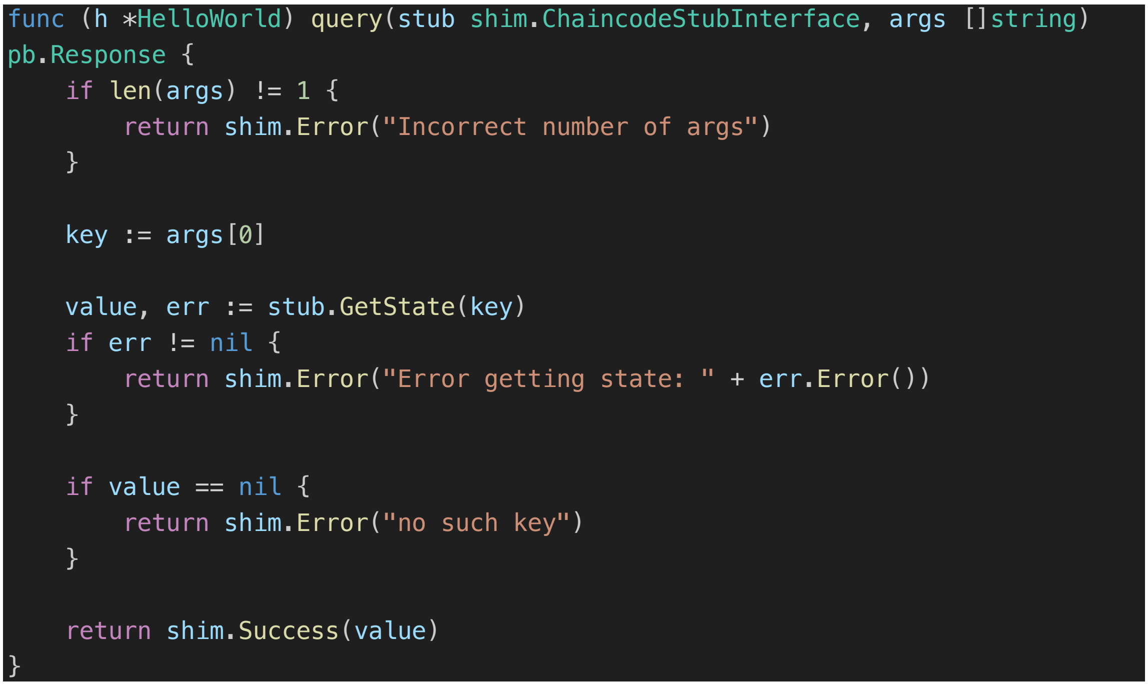


```
func (h *HelloWorld) invoke(stub shim.ChaincodeStubInterface, args []string)
pb.Response {
    if len(args) != 2 {
        return shim.Error("Incorrect number of args")
    }

    key := args[0]
    value, err := json.Marshal(args[1])
    if err != nil {
        return shim.Error(fmt.Sprintf("marshalling value: %s", err.Error()))
    }

    if err := stub.PutState(key, value); err != nil {
        return shim.Error(err.Error())
    }

    if err := stub.SetEvent("notification", []byte(fmt.Sprintf("key %s
successfully saved", key))); err != nil {
```



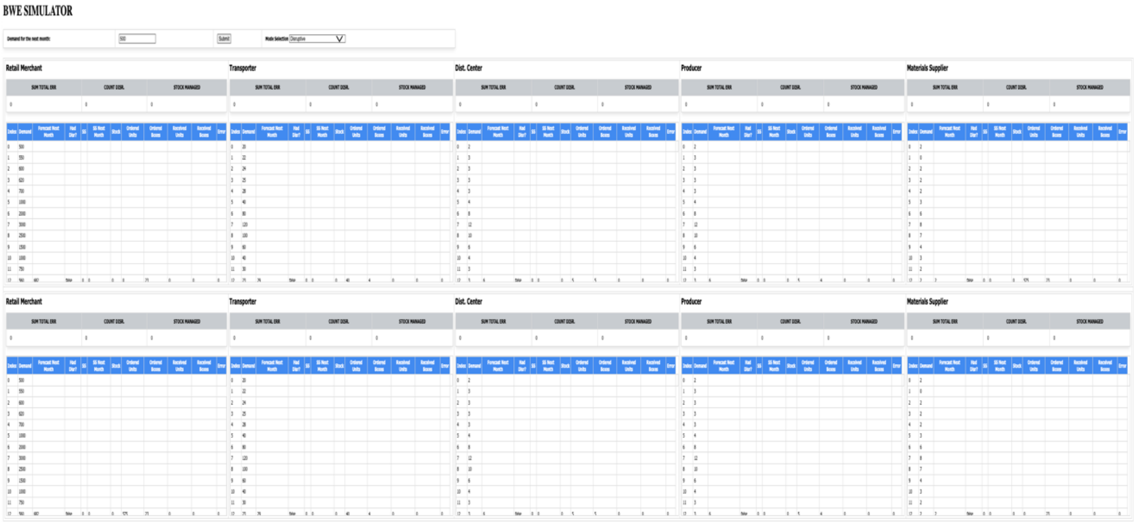
```
        return shim.Error("error happened emitting event: " + err.Error())
    }

    return shim.Success(nil)
}
```

Appendix L - Chaincode Smartcontract in go - Write Data



```
func (h *HelloWorld) query(stub shim.ChaincodeStubInterface, args []string)
pb.Response {
    if len(args) != 1 {
        return shim.Error("Incorrect number of args")
    }

    key := args[0]

    value, err := stub.GetState(key)
    if err != nil {
        return shim.Error("Error getting state: " + err.Error())
    }

    if value == nil {
        return shim.Error("no such key")
    }

    return shim.Success(value)
}
```

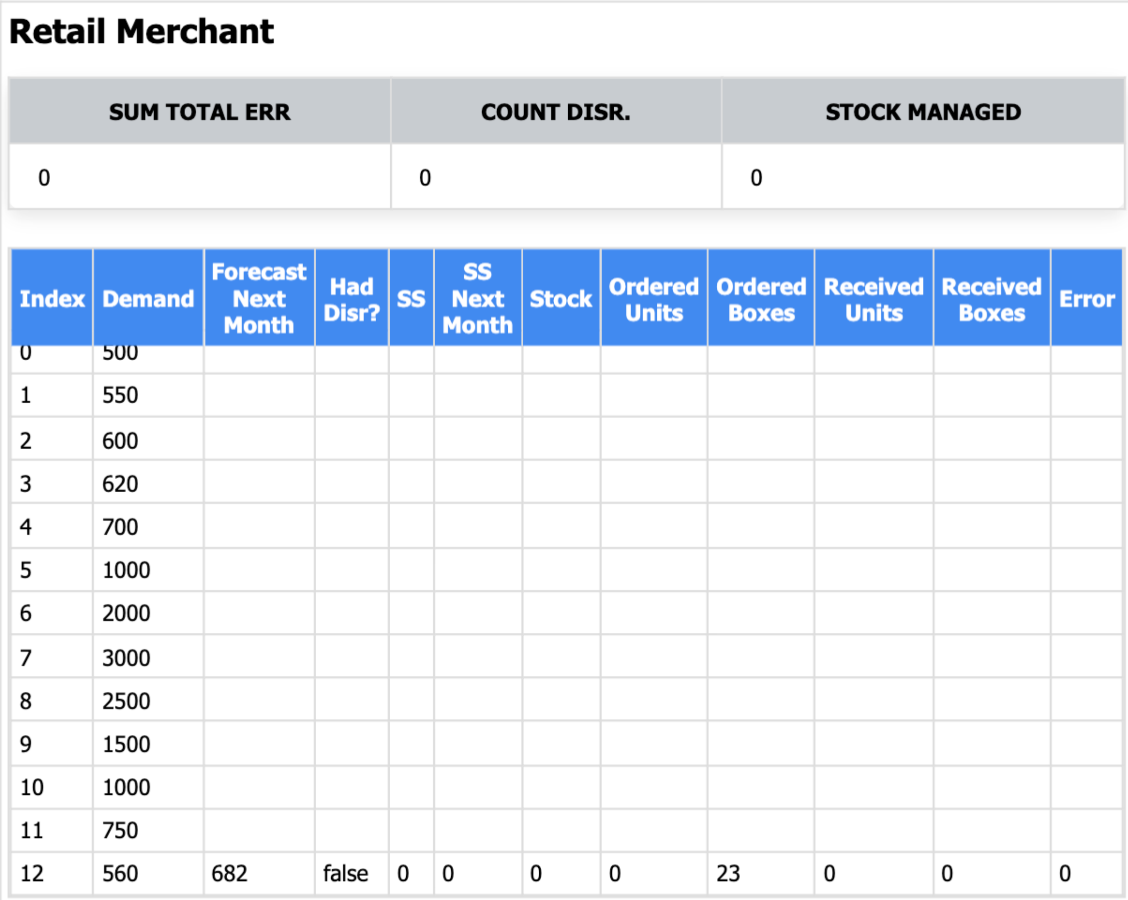
Appendix M - Chaincode Smart contract in go - Read data



Appendix N - BWE UI APP Screen Shot

Demand for the next month: 500 Submit **Mode Selection** Disruptive

Appendix O - Interaction console



Retail Merchant

SUM TOTAL ERR	COUNT DISR.	STOCK MANAGED
0	0	0

Index	Demand	Forecast Next Month	Had Disr?	SS	SS Next Month	Stock	Ordered Units	Ordered Boxes	Received Units	Received Boxes	Error
0	500										
1	550										
2	600										
3	620										
4	700										
5	1000										
6	2000										
7	3000										
8	2500										
9	1500										
10	1000										
11	750										
12	560	682	false	0	0	0	0	23	0	0	0

Appendix P - Sample Participant Dashboard