Hochschule Neubrandenburg
University of Applied Sciences

Hochschule Neubrandenburg

Landscape Sciences and Geomatics

Study Course: Geomatics

Development of a prototype of a centralised supply chain track and trace system for the food and agriculture industry

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Master Thesis

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Date of submission: April 21, 2023

URN: urn:nbn:de:gbv:519-thesis 2022-0266-7

Abstract

Due to the complexity of the food supply chain, it is difficult to ensure food safety and traceability, endangering the health and safety of consumers. There is an increasing demand for efficient supply chain traceability systems to ensure the safety and quality of food items from farm to table. In the food supply chain, using a monitoring and tracing system can aid with product recalls, cut down on food waste, find the source of contamination, and boost customer confidence.

Modern tracking and tracing systems use cutting-edge technology like RFID, barcodes, and IoT sensors to offer real-time data on the location, status, and condition of things, whereas traditional supply chain management systems rely on human paper-based recordkeeping and information sharing. However, even these cutting-edge technologies encounter a number of challenges that might restrict their efficacy, including data interoperability, data accuracy, data security, and data privacy. The efficient tracking and tracing of products from farm to fork are further complicated by the absence of standards and coordination across the many systems and supply chain participants.

The development of an integrated, traceable, and transparent supply chain system using blockchain technology has become a viable response to these problems. However, there aren't many blockchain apps available for use in supply chain management, and a lot of companies don't know much about the technology. Many questions about the direction and impact of blockchain on business and technical advancement remain unanswered, including whether blockchain will be profitable and who would earn the most, particularly in the context of supply chain management.

Therefore, the goal of this thesis is to assess the state of existing supply chain management systems and create a prototype for a tracking and tracing system that provides complete visibility and transparency across the food supply chain. The study will look at the methods and procedures used by supply chain management and tracking systems now in use, and it will create a prototype of a system that can track and trace products along the supply chain using a centralised database and QR codes.

With the help of this study, we can better understand the possibilities of centralised tracking and tracing systems in supply chain management and provide businesses with useful advice on how to make their supply chains more secure and transparent. The findings of this study can assist business professionals, government decision-makers, and researchers in enhancing the effectiveness, sustainability, and safety of the food supply chain.

Acknowledgements

This master thesis is based on my research and practical work within the joint project called “MaltFungiProtein” in the Visutronik GmbH (Automation Technology & Computer Service). This work has been created with the generous and sincere support of many people. To everybody who helped make this research possible, I would like to extend my deepest appreciation. First and foremost, I want to express my gratitude to my spouse, who supported me through the most difficult phases of writing this paper, and to my parents and family, who have always had faith in me.

To my supervisors, my teacher Prof. Dr.-Ing. Andreas Wehrenpfennig and my boss Master of Science Ralf Kietzmann, I would like to express my deep and eternal gratitude. They not only provided me with mental support, but they also always guided me and prevented me from getting discouraged. I appreciate the support and assistance of my supervisors, who not only guided me to complete my thesis but also encouraged me to explore a variety of interesting topics, contributing to my development as a qualified professional. Additionally, I would like to thank my colleagues Christian Riebe, Daniel Bennin and Lutz Hamann for their help and patient support with my programming learning process during the practical part of the research.

Furthermore, my sincere appreciation is expressed to each and every Visutronik GmbH colleague for the welcoming and enjoyable environment. I also want to express my gratitude to Visutronik GmbH for giving me the chance to do an internship there while I was working on my master's thesis.

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List of Abbreviations

SC	**S**upply **C**hain
SCM	**S**upply **C**hain **M**anagement
FSCM	**F**ood **S**upply **C**hain **M**anagement
SCV	**S**upply **C**hain **V**ulnerability
SCA	**S**upply **C**hain **A**gility
SCR	**S**upply **C**hain **R**esilience
IoT	**I**nternet **o**f **T**hings
RFID	**R**adio **F**requency **I**dentification
ESCG	**E**nvironmental**, S**ocial and **C**orporate **G**overnance
GPS	**G**lobal **P**ositioning **S**ystem
GTIN	**G**lobal **T**rade **I**tem **N**umber
DBMS	**D**atabase **M**anagement **S**ystem
SHA	**S**ecure **H**ash **A**lgorithm
UI	**U**ser **I**nterface
HTML	**H**yper**T**ext **M**arkup **L**anguage
CSS	**C**ascading **S**tyle **S**heets
PHP	Hypertext Preprocessor
AJAX	**A**synchronous **J**avaScrip**t** **a**nd **X**ML

1 Introduction

The modern food industry's supply chain is complicated and includes a number of different participants, including farmers, manufacturers, distributors, and retailers. Despite significant advancements over the years, the food supply chain still faces various difficulties, including food safety and traceability, which endanger the health and safety of customers. Therefore, there is a growing need for effective supply chain traceability solutions that can guarantee the safety and quality of food products on their way from farm to table. Using a tracking and tracing system in the food supply chain can improve product recalls, decrease food waste, help find the source of contamination, and increase consumer confidence. Stakeholders may track items using this system, which also provides accurate and up-to-date information about the products' manufacture, distribution, and place of origin.

Modern tracking and tracing systems use cutting-edge technology like RFID, barcodes, and IoT sensors to offer real-time data on the location, status, and condition of objects while traditional systems rely on human paper-based documentation and information sharing. However, even these modern systems face multiple difficulties such as data interoperability, data accuracy, data security, and data privacy, which can limit their effectiveness. The seamless tracking and tracing of products from farm to fork is further complicated by the absence of coordination and standards among the many systems and players in the supply chain.

In recent years, blockchain technology has gained popularity with the aim of creating an integrated, traceable and transparent supply chain systems. The supply chain industry stands to gain greatly from the use of blockchain technology, but there is still a considerable gap between the technology's potential and its actual application. Despite its potential, few blockchain apps are readily accessible for use in supply chain management, and many businesses have a poor understanding of the technology. While some businesses and researchers are looking into deploying blockchain to support their business goals, a thorough analysis of the technology's effects on the supply chain is still difficult. As a result, there are still many unanswered concerns regarding the direction and effect of blockchain on business and technological progress. For example, when blockchain will generate profits and who will profit the most, particularly in the context of supply chain management, are still unknowns.

The purpose of this master's thesis is to examine the current state of supply chain management systems and develop a prototype of a tracking and tracing system to provide end-to-end visibility and transparency in the food supply chain. The study will concentrate on the investigation of the existing practices and approaches for supply chain management and tracking systems and the development of the prototype of the system which can provide tracking and tracing of the product along the supply chain using centralised database and QR-codes. At the same time, given the practical nature of this work, in the sections describing the technical requirements and characteristics of the system, it was decided to take into account not only scientific articles, but also sources of information from practitioners. The system will be created to overcome the difficulties, that the present tracking and tracing techniques confront, and offer a more dependable and effective supply chain management solution. This study will enhance the knowledge of the potential of centralised tracking and tracing systems in supply chain management and offer suggestions for the creation of reasonable solutions that businesses can employ to increase the safety and transparency of their supply chains. The result of this study can help practitioners in business, decision-makers in government, and researchers to enhance the efficiency, sustainability, and safety of the food supply chain.

1.1 Motivation

Supply chain management has evolved into a more complicated process in recent years as a result of globalization, just-in-time manufacturing, and rising transparency and sustainability demands. Several businesses are using tracking and tracing technologies that can give them real-time visibility into their supply chains to address these issues. However, putting these systems into place can be expensive, and there is a lack of industry standardization, which causes problems with interoperability.

With the growing demand for supply chain transparency and sustainability, this research is especially relevant. This prototype has the potential to enhance consumer trust, decrease waste and fraud, and improve supply chain efficiency by offering a solution that is both affordable and scalable. This thesis also seeks to add to the body of knowledge on supply chain management by examining the difficulties and advantages of putting into place a tracking and tracing system.

1.2 Objectives

The objective of this master's thesis is to develop a prototype tracking system that can be easily integrated into existing supply chain management processes. This master's thesis is part of the «MaltFungiProtein»[1] project and meets the main requirements of the project's customers, namely the creation of a centralised traceability system for the supply chain. The

[1] „MaltFungiProtein" – is a joint project of nine German companies, goal of which is a development of recycling-oriented processes for the conversion of previously unused side streams of the food industry (brewer's grains) into protein-containing foods, combined by a digital tracking & tracing platform (Retrieved from the Internal Project Concept).

goal of this study is to create a working prototype for a tracking and tracing system that makes use of QR codes and a central database. Real-time tracking and tracing of items will be possible with the use of QR codes and a central database, assuring the integrity of the supply chain from the beginning to the end.

The creation of such a system has the potential to completely transform the food business by enhancing supply chain accountability and transparency, ultimately resulting in a safer and more sustainable food system. The successful design and execution of this prototype system will offer new opportunities for supply chain management by demonstrating the viability of using centralised databases and QR codes in tracking and tracing systems. This work is composed of the following tasks:

1. Conduct a literature review on current state-of-the-art traceable systems in the food industry.
2. Investigate existing tracking and tracing systems and identify their limitations and challenges.
3. Analyse the advantages and disadvantages of a centralised approach to tracking and tracing systems in comparison to decentralised approaches.
4. Design a system architecture for the tracking and tracing prototype, specifying the components and their interactions, including the centralised database and QR-code scanning functionality simulation.
5. Develop a user-friendly interface for the prototype, enabling users to view product information, as well as add new products to the database.
6. Implement a prototype using appropriate programming languages and tools, ensuring that the system functions as intended and meets all necessary requirements.
7. Test and validate the developed prototype system in a simulated food supply chain environment.
8. Document the design, development, testing, and evaluation processes in a clear and concise manner, including detailed descriptions of the prototype system and its components, as well as the methods of testing and evaluation.
9. Draw conclusions based on the results of the evaluation of the system, identifying strengths and weaknesses of the prototype and suggesting areas for further improvement and research.

The development of this work has been supported by the Visutronik GmbH Automation Technology & Computer Service. The prototype system has been developed using the HTML, CSS, JavaScript, PHP, and a MySQL database.

1.3 Thesis Outline

The remaining parts of this paper are arranged as follows: the next chapter offers a thorough analysis of the state-of-the-art in supply chain management and contemporary methods and current requirements for supply chain traceability systems. The software architecture is examined in chapter 3 along with issues related to access control, centralised and decentralised databases, and methods for creating unique values that can be used to generate unique values for a token, which is a digital representation of a QR code. The practical part of this work is outlined in chapter 4, where we created a user interface and a central database to monitor products along the supply chain and verify the system's functionality. Finally, in chapters 5, the conclusions and future work are presented.

2. A Comprehensive Definition and Overview of Supply Chain Management

A supply chain is a complex network of relationships, whose objective is to produce value in the form of products and services for the customers. These networks are linked through upstream and downstream relationships of the suppliers and other participants as well as their activities (Winter & Knemeyer, 2013). Simply put, a supply chain is a huge mechanism which allows companies to move their product from the source place to the final point of consumption. A typical supply chain consists of the suppliers, factories, warehouses and the flow of products (or resources) from one point to another until it gets to the final customer (Watson et al., 2017).

Each supply chain consists of multiple members who provide diverse processes to make this supply chain run in proper way. The food supply chain is no exception to the rule and therefore the characteristics of its main members are largely similar to those of supply chain members in any other industry (Figure 2. 1).

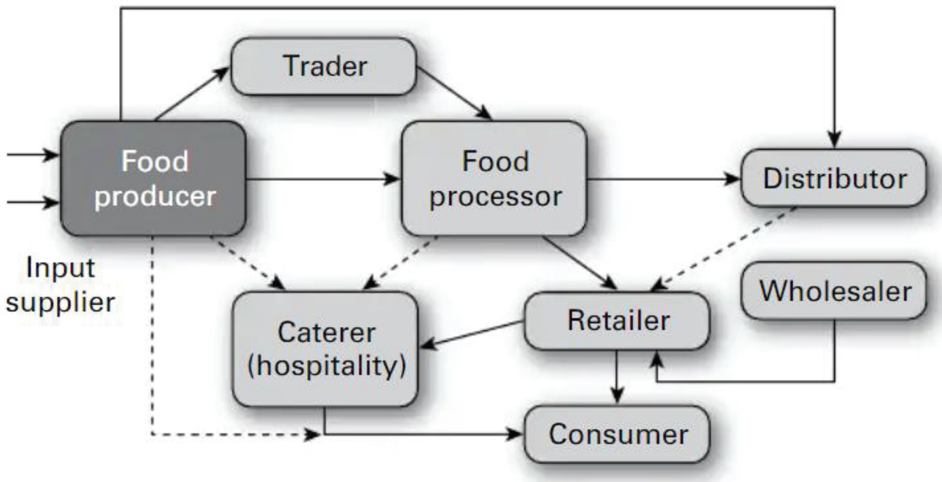

Figure 2. 1 Actors in Food Supply Chain (from Dani, 2015, p.2)

Typically, the food supply chain begins with a producer (or supplier), which is an agricultural business that cultivates or raises crops and livestock. After that, the producer sells the raw materials to processors (manufacturer) who turn them into consumable food products. Moving food from one stage to another is an important function of logistics and transportation businesses (distributor) in the food supply chain. They make sure that food is transported effectively and safely, and they take precautions to preserve its quality while in transit. Distributors, wholesalers, and retailers are additional players in the food supply chain who are in charge of getting food to different establishments including supermarkets, restaurants, and other food service outlets. There is also an intermediary actor between processor or producer and customer, called Hospitality Sector, which plays a crucial role in the food supply chain. Although it is not a retailer or distributor, catering establishments, hotels, restaurants and takeaways purchase raw materials and transform them to meet consumer requirements. The hospitality sector is made up of small- and medium-sized enterprises, some of which are one-person organisations, that provide high-quality services within the food system. Additional actors in the supply chain are also regulatory bodies that set rules and regulate the process of manufacturing, delivery, sales, and so on. The final beneficiaries of the meal are the end user, who are also in charge of preparing and eating it (Dani, 2015, Wang et al., 2019).

An example of a typical food supply chain can be seen in the supply chain diagram of the «MaltFungiProtein» project (Figure A. 1). This chain starts with the brewing process which has malt, barley, and hops as direct inputs, and the beer and treber (or the spent grains which are produced during the mash when the crushed malt is heated with water). Also, water and electricity can be considered as inputs for this process as they are resources used to make this process work. A goal of the "MaltFungiProtein" is the non-waste system, and the main focus is on the production of protein-based products, particularly using spent grains from the brewing process. The next step is fermentation where the water, mushrooms, and spent grains (treber) are used as inputs and as result peptones and produced. After this process separation follows with using the previously produced peptones as an input and producing so-called wet fungi mycelium. Before the next-step process, the product of separation should be delivered to the next producer as it shown in Figure A. *1*. Part of the product is used for the extraction, the result of which is the protein-isolate, and part is for drying of these wet fungi mycelium. The protein-isolate is drying as well as wet mycelium. After it both the dry fungi mycelium and dry protein-isolate are grinded in powder. Both fungi powder and protein powder then are used for producing food products such as sausages, meat, and other protein-containing foods. A generalised diagram of this SC can be depicted as in Figure 2. 2.

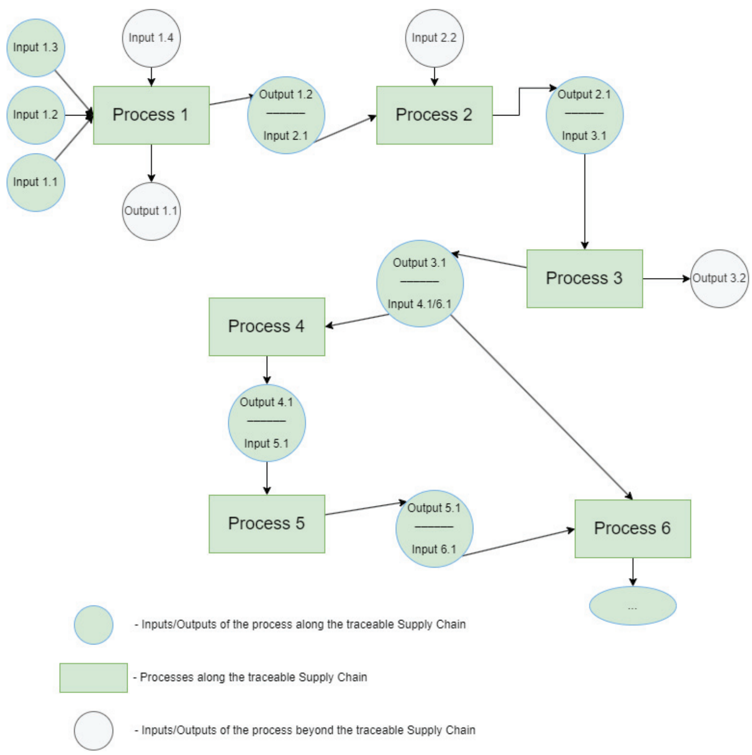

Figure 2. 2 Generalized sample of the Supply Chain

In order to administer and control activities of all members of the supply chain companies provide "Supply Chain Management", which is an important process of systematic coordination of components such as production, purchasing, sales, logistics and so on (Basuki, 2021, p. 9).

Supply Chain Management has a strategic influence on the result of business performance in total. Using well-designed and professionally managed supply chain domestic firms, for instance, can compete with international competitors by offering their products worldwide (Heckmann, 2016, p. 20).

The term `supply chain` was first used in 1980s exactly in this meaning. Since then, many specialists and researchers have been seeking to improve the coordination of supply chain workflow, optimize the activities across the entire chain and enhance its overall competitiveness. Although supply chain management has evolved since last century, there are still gaps and areas that should be improved (Nasrin et al., 2016).

Speaking of improvements still needed in the Supply Chain (SC), these include the problem of disruptions which are frequently occur in supply chain management. Experts believe that the larger and more complex the SCs become, the more disruptions tend to happen, and more exposed companies become to the risks associated with these disruptions (Jafarnejad Chaghooshi et al., 2018). While globalization become more common phenomenon of our normal life and the complexity of global supply chains is promptly increasing, some geopolitical events and unexpected incidents can cause disruptions and losses for all the members of supply chains. According to Svensson (2002) such exposure to serious disturbance, which can arise both from risks within the supply chain and from outside, is defined as Supply Chain Vulnerability (SCV). Higher SCV leads to a higher probability of disruptive events with severe consequences (Radhakrishnan et al., 2018). Li et. al. (2021) in their research emphasizes the impact of centrality on vulnerability in the SC. Their model showed that higher centrality leads to higher vulnerability of each node in a supply network.

However, disruptions can occur not only due to some external factors but also because of some internal (operational) risks, which can take place for example in manufacturing companies. These internal and external factors can cause interruptions in work not only of one specific organization but make a great impact on all other down- and upstream partners. However, a supply chain network can be vulnerable to it not only because of direct impact, but also due to so called "ripple effects" (Dolgui et al., 2017). Many researchers call this phenomenon also a "domino effect" and it means spreading of disruption causes to the neighboring supply chain "nodes" (Wieteska, 2018, p. 496).

As the examples of such "ripple effect" we can consider the hurricane Katrina that hit oil refineries in New Mexico. It caused the price increases not only in USA, but all over the world. This tragedy that took a lot of lives, made it clear in terms of SC, that reliance on a single source of energy, supply actor or even one country can have a great impact in case of emergency or disruption (Chow & Elkind, 2005, Eskew, 2004). One of the latest global examples of such phenomenon was the COVID-19 pandemic, which caused severe disruptions and the impact of these disruptions on upstream and downstream participants all over the world and even some external players like competitors. Another recent example is the Russian invasion of Ukraine: due to military actions, sea routes to and from Ukraine were blocked, seaports were closed for trade or any ship calls, unloading, etc. This caused significant disruptions in export of oil, grains and other products, which Ukraine exported and imported, and which are important for manufacturing in different supply chains. Additionally, Ukraine exports about 50% neon gas and 40% of the world's krypton gas, which are used in the production of electronic chips (Nguyen, 2022). These and other examples demonstrate, that each time manufacturers, affected by some disruption event, face problems of reaching components or product, difficulties to deal with component shortages, production delays and increasing price of raw materials.

However, one firm`s disruption may not necessarily cause another company`s disruption. The rate of possible diffusion of disruption in a supply chain is conducted by different factors, like:

- The nature of the disruption, which includes the type, severity and duration.

- The level of dependency of the customer of the supplier. When a customer buys components purely from one supplier, he tends to be more vulnerable and easily disrupted by this supplier.
- Customer`s resilience capacity. When customer is highly resilient, e.g., he has good enough SC visibility, sufficient safety stock etc., he becomes less vulnerable to supplier`s disruptions (Li et al., 2021).

These factors can be applied vice versa to backward direction of a supply chain (from customer to supplier). For example, when a supplier has only one main source of income from exactly one customer, he becomes more likely to be disrupted when his customer meets disruption. At the same time, it is also important to realize that dependencies in the "supplier-customer" projection and the " customer -supplier" projection mostly have different scales and should be mostly considered as being asymmetric. As an example, we can cite the dependence of a small farmer (supplier) and a large supermarket chain (customer), where the supermarket is mostly not dependent from this supplier, but in opposite, a small farmer can suffer, if his customer would be disrupted.

Considering all these factors above, it becomes clear that while designing the supply chain (or its part) the individual needs, the environment, and other factors should be considered to make it sustainable and resilient.

2.1. Characterization of Disruptions in the Supply Chain

In general, specialists distinguish five most important external triggers of disruptions (according to the Supply Chain Risk Initiative of the World Economic Forum): natural disasters, extreme weather conditions, political turmoil, terrorism and demand shocks (Risk Response Network, 2013). According to these triggers, we can emphasize the following types of disruptions (Heckmann, 2016):

1 Environmental Disruptions

According to the Centre for Research on the Epidemiology of Disasters (CRED) International Disaster Database (EM-DAT), the long-term trend of increasing frequency and economic impact of disasters worldwide began in 1950 and has intensified since then. Certainly, this development has been influenced by population growth, the proliferation of valuable assets and improved reporting. However, the exponential increase in frequency and magnitude cannot be explained by these factors alone (Coleman, 2006). The outlook for the future of supply chains is clear: supply chains remain vulnerable to disruptions caused by natural and epidemics disruptions.

2 Economic Disruptions

Changes or disruptions in the economic system are difficult to predict, but unfortunately, they continue to affect global supply chains.

As known, the supply chain, functioning as a globally branched one and connecting countries around the world with its networks, deals with different currency zones. Exchange rate fluctuations between procurement, production and distribution locations can potentially erode margins. Furthermore, export and import restrictions or delays at the border caused by customs regimes, quota systems, security concerns and so on evoke the vulnerability of cross-border movements (Risk Response Network, 2011). These and other economic risks are often unpredictable and have an adverse impact on supply chains.

3 Socio – Geopolitical Disruptions

When the law is violated and the political situation is no longer stable, problems arise with many negative consequences, including disruption of transportation, supply and production. The Russian invasion in Ukraine in 2022 caused disruptions not only in local chains of production and distribution, but also forced global giants in the food, textile and various other goods markets to stop deliveries due to the danger that appeared on the horizon. Likewise, the war in Iraq has disrupted global traffic flows: Singapore Airlines flying over the Middle East were forced to take more southern routes, reducing their capacity for goods originating in Singapore (Craighead et al., 2007). There is no evidence to point to future global, sustainable political stability. Current unrest situations in Middle East, Taiwan and Ukraine make scientists all over the world assume that uncertainties in this field will continue to exist in future.

4 Technological Disruptions

Information Technologies (IT) are extremely useful for manufacturing and supply industries. Real-time control software, tracking and tracing and other innovation tools and possibilities can deal not only with information interchange but also with transportation processes, inventory, financial workflow and many other sides of production and distribution. Nevertheless, IT infrastructures are constantly under risk of cyber-attacks and various injections from outside which can lead to disruptions and other troubles in different stages of a supply chain. Nowadays, many countries establish national institutions to counteract to hacker software and defend companies from cyber-attacks. As well as big corporates develop security frameworks for ensuring the integrity of the network and reduce number of attacks (The Open Group Trusted Technology Forum, 2011). For example, in 2011 Germany set up National Cyber Defence Centre (Cyber-AZ) as the central information and coordination platform for cyber threat prevention (Cyber Security Strategy for Germany, 2021). Anyway, even accidental IT failure can affect efficiency of workflow, because even a small IT-failure could have a tremendous impact on the complete chain (Heckmann, 2016). Therefore, we should consider these technologies as possible triggers of disruptions as well.

Summarizing all above it seems to be clear, that disruptions can occur at each of step in the chain. The three major locations are: supplier, warehouse and production plant (Sonar et al., 2017). Underestimating all possible risks and their effects can lead to unpredictable severe consequences.

While disruptions are not daily phenomena and normally don`t happen every day, the decisions and actions within the strategies of supply chain – so called "risk drivers" – that can lead to these disruptions, are actually provided on everyday basis. For example, when company develops the strategy of increasing the overall efficiency by using the approach of pure cost minimization, it reduces excess capacity and inventory, which could make up for production losses caused by disruptions (Heckmann, 2018, p. 20). In the meantime, when efficiency is a sole objective of the strategy, very little reserves for recovery from supply chain disruptions has occurred remain (Heckmann, 2018, p. 23).

To stay afloat and compete in today's fast-changing world, companies must react quickly to all innovations, be agile and remain resilient to any changes (Jafarnejad Chaghooshi et al., 2018, p. 136). The amount and variety of uncertainties, as was mentioned before, is increasing with the supply chain complexity and size, and is reflected in partners, competitors, upstream suppliers and downstream customers (Zhu et al., 2021).

2.2 Agile and Resilient Supply Chains

The existence of an agile supply chain is one of the most important aspects of coping with risks in the supply chain networks. Therefore, consideration of all the possible risks and uncertainties while designing the supply chain network and planning its strategy is critical when a company is eager to create a resilient supply chain (Snyder et al., 2006). It is important to comprehensively understand the internal and external relationships as well as up- and downstream ones. The match between flexibility and uncertainties can be considered as a good approach to deal with environmental uncertainties and cooperate with members all over the supply chain. The supply chain flexibility is defined by scholars as ability to respond cost-effectively and quickly to uncertain environment challenges. Flexibility from the organizational point of view means an ability to manage the relationships among participants and coordinate the workforce to meet customer requirements (Zhu et al., 2021).

Another point emphasized by business experts and scientists in recent years is the need of a systematic analysis of vulnerability, resiliency and security of the supply chain. Among other possible ways to prevent disruption causes, a company can include in its strategy different locations for stock and/or alternative suppliers for its products. For example, in the event of a disruption, the company should be able to find an alternative supplier that has not been affected by the disruption (Sonar et al., 2017). According to an analysis of Li, Chen et al. it was revealed, that mitigation actions are different for forward and backward disruption propagations. For instance, to mitigate forward disruption propagation companies should work with safety stock and backup supply, but to manage the backward one they should pay attention to make operations more flexible and cope with demand management (Li et al., 2021).

Another aspect, which still needs more improvements, is the effectiveness of both the customer service levels and the internal operating efficiencies of the supply chain participants. The customer service level is considered as consistently high order-fill rates, on-time delivery rates and low product return rates. The rate of investment returns and optimizations of operating and sales expenses belong to the internal efficiency level of a supply chain management (Hugos, 2018).

According to the studies of Cui and Lee (Cui et al., 2016), the transportation expediting is one of the key factors in a reduction of supply chain risks. They summed up, that the company`s strategy of optimal risk reduction is sensitive to its ability to expedite the transportation. It can be explained from the point of view of the challenges, which fall on inventory management due to, for example, demand uncertainties, when delivering takes long and uncertain lead times. Therefore, facility location design should be integrated into inventory management, so spatial inventory distribution and transportation can be balanced. Their mathematical model demonstrated that, in terms of a small number of suppliers and a low demand level, it is necessary to use more expedited services. At the same time a purely increasing of inventory positions for keeping the service quality becomes de facto worthless. Nevertheless, with increasing demands, regular shipments become increasingly important. Then, in the same model, we can notice the increasing and dropping of different indices, according to which the authors summarized as follows: the growth of regular shipment delay causes a decrease in inventory locations and, accordingly, expedited service quality.

Kleindorfer & Saad (2005) formulated a set of ten principles that companies could implement in order to be able to increase SC robustness, mitigate disruption propagation and make their chains more agile. These principles are following:

1. Internal optimization should precede any inter-companies' manipulations. It comes from fact that SC consists of main subsystems: Supplier Relationship Management (SRM), Internal Supply Chain Management (ISCM), and Customer Relationship Management (CRM).

2. This principle follows one of the main principles in finance - portfolio diversification, which reduces investor`s risks. That means, when a facility applies this approach to diversify locations, sourcing options, products provided, processes and so on, it increases its chance of risk minimization to be reached.

3. The weakest link in the chain undermines the profitability of the whole chain. The vulnerability should be identifying across the entire supply chain, otherwise a disruption of one weak partner can destroy the workflow of the complete system.

4. Investments in risk assessment to define vulnerabilities and possible worst cases are crucial in disruption risk management.

5. The trade-off between SC "resilience" to disruptions and the overall supply chain efficiency in normal operations should be found in order to mitigate risks.

6. Considering traditional way to increase SC resilience, the use of redundancy and back-up systems can help in process improvements.

7. Collaboration and cooperation are important to handle disruptions. Additionally, non-cooperative strategies don`t allow partners along the SC to find and enhance the weak link (what was mentioned in the second principle).

8. It is important to provide risk assessment with linkage to weak parts of the chain and a quantification of risks. It helps to consider all the risks not only in a general probabilistic way, but also take into account real factors like the most cost-effective tools of mitigating expected and worst-case scenarios.

9. Paying attention to flexibility and agility in supply chain designing. It refers to risks that appear, for instance, in global SC when it comes to a currency exchange volatility or regional demands. In this case it is important to include components, products, as well as suppliers, which can be fungible.

10. Applying Total Quality Management tools can help to achieve higher security, performance and to reduce disruptive risks.

According to their authors, these 10 principles must be implemented in a comprehensive and coherent way.

The term “supply chain” covers various processes like manufacturing, distribution, storing and recycling of the product, the effectiveness of the supply chain indicates the effectiveness of business performance. Nowadays fast-changing industrial enviroment requires the companies to constantly review their supply chain structure to make them more flexible, up-to-date and agile. The supply chain agility is regularly discussed in both academic and practical levels. It is considered in the context of the needs of the integrated supply chain in dealing with uncertainty and contributing positively to organizational performance (Sağbaş, 2021).

Supply Chain Agility (SCA) refers to the capacity to maintain a flexibility, resilience and responsiveness to temporary changes in market conditions throughout the supply chain processes (Sağbaş, 2021). At the same time, scientists distinguish another term: Supply Chain Resilience (SCR) - which refers to the supply chain's ability to cope with the repercussions of unavoidable incidents of risk in order to return to its original operating state or to move to a new, more desirable state following a disruption (Radhakrishnan et al., 2018). These two terms are mostly used together to describe the supply chain’s ability to manage risks. Previous research papers have argued that some companies pursue only one of these two strategies: either agility or resilience strategy (Carvalho et al., 2012). But the latest studies argue that organisations are more eager to implement both strategies by developing capabilities for ambidexterity (Aslam et al., 2018). Ambidexterity refers to an organization's ability and capacity to perform two opposing things well simultaneously, like exploration and exploitation or, in this case, agility and resilience. As long as ambidexterity is supposed to improve long-term firm performance and survivability, by deploying it, they increase their chances of exploring new opportunities and gain competitive advantages by using available resources (Vahlne & Jonsson, 2017, Aslam et al., 2018).

Sheffi (2005) believes, that the combination of the flexibility and redundancy can be seen as two important approaches to building resilience. Redundancy can be achieved by building up additional inventory (thus preventing shortages) or by ensuring that suppliers have excess capacity. In addition, having multiple sources of supply or a geographically dispersed business can also increase the amount of redundancy and therefore reduce the likelihood of risk and cope with interruptions (Christopher & Peck, 2004; Ole-Hohenstein et al., 2015). Another equally important factor is high visibility of SC, because clear view of upstream and downstream partners, understanding of demands and conditions are significant for resilient functioning of the chain.

Due to the growing complexity of global supply chains, the lack of standardization of supply chain data, and the rise of e-commerce and omnichannel retail, the issue of visibility in supply chains is a significant challenge for organizations. Due to these circumstances, it is challenging for firms to track and monitor goods in real time, which results in delays, inventory shortages, and other supply chain issues. Businesses need to invest in new technology and procedures that promote more visibility and collaboration throughout the supply chain in order to handle this challenge (Christopher & Peck, 2004, Ahmed Saqib et al., 2020). Today's businesses must have visibility into their supply chains in order to succeed. When individuals are not fully aware of all supply chain activities, there can be a lack of synchronization in task performance. Enhancing visibility and transparency along the entire supply chain fosters cross-departmental collaboration and idea sharing. Visibility can provide a return on investment and assist organizations in achieving long-term objectives by lowering risks and costs, enhancing performance, and detecting issues. Collaboration and information exchange among partners can also boost performance as a whole. Utilizing cutting-edge infrastructure and technology can support a manufacturing system and increase supply chain visibility, which ultimately boosts a company's development and standing (Ahmed Saqib et al., 2020).

As was mentioned above, there are multiple ways to prevent and cope with disruption, hence, to enhance the SCR. Among all other approaches specialists emphasize the usage of Internet of Things (IoT) or other technologies for cargo tracking. IoT connects real-world objects to the internet so they can share and gather data. IoT sensors can be attached to goods, machines, and vehicles in the context of supply chain tracking in order to gather information about their position, temperature, humidity, and other variables. S.I. Al-Ayed and A. A. Al-Tit explored the impact of SC risk management and the mediating role of IoT in this impact on supply chain resilience. According to their results, the hypothesis that SC risk management fully influences supply chain resilience was rejected, as it works in parallel with IoT to influence supply chain resilience. Additionally, considering other research papers (e.g., Jia et al., 2012, Parteek, 2019, Golpira et al., 2021, İsmail, 2022), significance of IoT in the context of supply chain risk management can be recognized also by the impact of IoT on SC visibility, as well as information sharing, SC tracking, location detection, duplication avoidance, supply and demand matching, and inventory control. The term 'Internet of Things' encompasses a range of devices that can connect and communicate with one another through wireless technology. The concept of the Internet of Things emerged as a result of the introduction of information and communication technologies into everyday objects people use at home, work etc. This was driven by the need to label and track physical objects, which was made possible using inexpensive radio frequency identification (RFID) devices (İyigün, 2022).

According to the same research work, S.I. Al-Ayed and A. A. Al-Tit declare, that there is no further value in research works which not taking into account nowadays digital solutions in SC risk mitigation investigation. However, digital solutions are not only IoT, but also a lot of other types of smart technologies which can be used to improve SC efficiency (Al-Ayed & Al-Tit, 2023).

2.3 Sustainable Supply Chain

In today`s reality, supply chain should be not only resilient and flexible, but also it should operate in line with sustainability requirements. Climate change affects all over the world and we can observe its consequences each year even more. In 2015, various countries around the world signed a historic agreement known as the Paris Agreement to limit global temperature rise to below 2 degrees Celsius and pursue efforts to limit the increase to 1.5 degrees Celsius. Part of the European Union's (EU) commitment is to reduce greenhouse gas emissions by 55% by 2030 compared to 1990 levels. The EU has also taken steps towards achieving sustainable development by introducing the European Green Deal. The goal of this agreement is to achieve carbon neutrality by 2050. The EU believes that renewable energy is the key to achieving sustainable development by reducing dependence on fossil fuels, which are the main contributor to global warming, and thus curbing climate change. (Savaresi, 2016, Sikora, 2020, Vasylieva et al., 2019).

The push for sustainable and transparent supply chains results in cost increases and companies need to find a way to achieve sustainability while keeping costs in check. Essential factors in creating sustainable supply chains are a collaborative mindset throughout the chain and monitoring both the origin and end-use of products. This involves working directly with lower-level suppliers and bypassing intermediaries when necessary. A good example of this is Starbucks' partnership with coffee bean farmers through the Coffee and Farmer Equity (C.A.F.E.) initiative which provides certification, training, and financial aid (Choi & Linton, 2011).

In academic literature, the term "sustainable supply chain management" has been used interchangeably with various other terms such as "corporate social responsibility," "green supply chain management," "environmental purchasing," "value chain management," and "ethical purchasing". These terms, however, are frequently used vaguely and lack precise definitions. Dani (2015), therefore, refers to the three main aspects - economic, social and environmental - as sustainable supply chain management.

When designing a supply chain and how they interact with one another during the fulfilment process, it is essential to take into account all three Bottom lines. This means that in addition to economic factors like cost reduction and profit maximization, sustainable supply chain management should also consider social factors like fair labour practices and community development as well as environmental factors like lowering carbon footprint and minimizing waste generation. The effects of each choice on the environment, society, and economy must be taken into account when designing a supply chain as well.

For instance, a company may decide to use sustainable materials made in accordance with all environmental and humanitarian principles in its production process, thereby reducing its environmental impact and increasing its social responsibility by encouraging ethical sourcing practices. To reduce the environmental effect of food production, a food distributor could decide to collaborate with farmers that involve sustainable farming methods, such as regenerative farming. By collaborating with surrounding farmers and producers, the distributor may also place a higher priority on local sourcing and cut down on transportation emissions. This distributor may also use traceability systems that track the place of origin of their goods and guarantee food safety, encouraging responsibility and transparency across the supply chain. Another illustration might be a grocery store that collaborates with food banks or other charity groups to distribute extra food, so minimizing food waste and benefiting the neighbourhood. By making thoughtful decisions regarding their sourcing, shipping, and donating methods throughout the food supply chain, the businesses in both situations are moving in the direction of sustainability and social responsibility. This can then result in cost savings and improve the financial performance of the business (Dani, 2015). Therefore, sustainable supply chain management is an integrated strategy that seeks to balance the three bottom lines. Companies that use sustainable supply chain management strategies can benefit both themselves and society at large in the long run. They can improve their reputation, minimize risk and contribute to sustainable development by meeting the needs of the present without compromising the ability of future generations to meet their own needs.

According to an analysis of the State of Supply Chain Sustainability (2021) conducted by the MIT Centre for Transportation and Logistics and the Council of Supply Chain Management Professionals, companies are increasingly integrating sustainability into their practices (Figure 2. 3). The most typical ones are supplier collaboration, sustainability standards and certification, increased visibility and traceability, supplier audits, supply chain mapping exercises, supplier benchmarking, third-party verifications, supplier training programs, and partnerships with NGOs and other third parties.

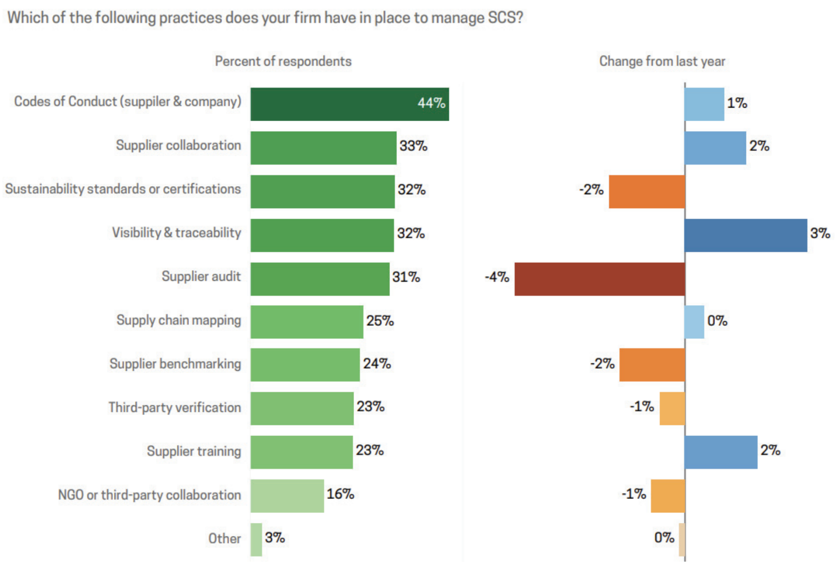

Figure 2. 3 Practices in 2020 and year-over-year change from 2019 to 2020 (from Bateman et al., 2021)

To calculate and determine whether a supply chain is sustainable, many indicators need to be taken into account. The number of indicators increases many times over when considering farm-to-fork mapping, as this network has many processes and heterogeneous inputs and outputs (for instance, use of pesticides in farming, fertilizers and so on). The implementation of a sustainable supply chain has been made even easier by the use of IT technologies such as IoT, data analytics, blockchain and so on, which provide a framework for collecting data and communicating information related to material changes and transfers of ownership (Min et al., 2019).

2.4 Contemporary Approaches and Standards for Efficient and Effective Supply Chain Management

As many different industries and diverse companies exist in the world, so do different supply chains. As previously stated, the creation and successful operation of supply chains is a widely researched topic by numerous scholars and experts in the field.

In literature, traditional supply chain issues primarily focus on location and allocation choices, demand forecasting, planning for distribution channels, forming strategic partnerships, developing new products, outsourcing, choosing suppliers, setting prices, and establishing network structures at the strategic level. On the tactical level, the focus is on managing inventory, coordinating production and distribution, streamlining order and freight processes, handling materials, choosing equipment, and designing layouts. Finally, at the operational level, attention is given to routing and scheduling vehicles, scheduling workforce, maintaining records, and packaging (Min & Zhou, 2002). The complexities of FSCM (Food Supply Chain Management) set it apart from other supply chains such as those in furniture logistics and traditional supply chain management. The prioritization of food quality, safety, and freshness within limited time constraints adds an additional layer of difficulty to the management of the supply chain (La Scalia et al., 2016).

Food traceability has been a common practice for many years with numerous applications. Despite its widespread use, there is limited information available on a comprehensive framework for implementation. Karlsen et al. (2013) observed that a standardized framework leads to consistent traceability and more streamlined implementation processes. Multiple publications have adopted technical specifications, such as RFID (Radio-Frequency Identification) for identification, WSN (Wireless Sensor Network) for data acquisition, and EPC (Electronic Product Code) for product coding (as noted by Corrado et al., 2013; Supriya and Djearamane, 2013; Jamal et al., 2013). These solutions store product information in a centralised database hosted in the cloud and can be accessed through the internet. However, these solutions don`t take into account technological advancements and the diverse array of identification and sensing methods. They also typically provide inadequate insight into how to integrate product data with other datasets or existing systems within the traceability framework (Bougdira et al., 2019).

According to Phadnis et. al. (2022), modern SCs are being shaped by 4 major drivers:

1) Global

Globally, modern supply networks are becoming more interconnected and integrated. It follows that businesses are acquiring raw materials and parts from all over the world, and that a worldwide consumer base is being served by the sales and distribution of goods. The development of communication and transportation technology has made it simpler and more affordable to transport goods throughout the world, which has enabled the globalization of supply chains. The ambition of businesses to access new markets and benefit from cheaper labour and manufacturing costs in other regions of the world has also been a driving force (Phadnis et. al., 2022, Meixell & Gargeya, 2005). However, because of this interconnectivity, there are also new risks and challenges, such as complex logistics management, trade laws, and geopolitical tensions. Companies also need to be prepared to handle supply chain disruptions brought on by natural disasters or political unrest. Companies must therefore continue to be flexible and nimble in order to succeed in the international supply chain environment.

2) Digital

The impact of digital technologies like blockchain, the Internet of Things, augmented reality, Big Data, etc. is undoubtedly considered revolutionary, but there is still debate and uncertainty about which of the current developments in digitalization will become truly integral to the supply chain of the future and which will remain at the level of niche uses (Phadnis et. al., 2022). Blockchain is a technology that holds great promise for transforming supply chain practices. With blockchain, companies can create a digital ledger of transactions that are stored in a shared database that is secure from deletion, tampering, and revision. Currently, a typical supply chain invests a significant amount of time and resources into verifying transactions that take place from raw material suppliers to end customers as value is added throughout the chain (Iansiti and Lakhani 2017).

The dark side of growing digitalization is the greater vulnerability that comes from the networks on which companies increasingly rely. For example, in 2021 Colonial Pipeline Company[2] had to shut down an oil pipeline, which transported fuel from Texas to New York, due

[2] Colonial Pipeline - is the largest refined products pipeline in the United States.

to a ransomware attack. This resulted in fuel shortages and panic buying in multiple states along the way (Phadnis et al., 2022, Turton & Mehrotra, 2021). A Blockchain is typically considered of as a secure technology because of its cryptography capabilities, but it is vulnerable to cybersecurity attacks. Only the attacks on cryptocurrencies (except other types of Blockchain technology) have been identified by researchers, making the total about 500 and costing $9 billion in losses. Decentralization and openness of blockchain make it difficult to defend against these dangers (Alabdulkarim, 2023).

3) Focused on environmental, social and corporate governance (ESCG)

ESCG, or environmental, social and corporate governance, is a framework that businesses use to assess and communicate their social and environmental impact. Investors use ESCG criteria to assess a company's sustainability and ethical standards and decide whether to make a long-term investment in it.

More and more companies are becoming involved in ESCG, concerning global warming issues, clean energy, slavery and forced labour, racial inequality, etc. To implement these ESCG rules, the supply chain should, at least, increase its visibility. However, most companies' visibility remains only at the level of the first-tier supplier (those whom they pay directly for materials and components) and does not extend further (Phadnis et al., 2022).

4) Demanding customers

This driver refers to the tendency for consumers to want more from the businesses they do business with. Due to the development of social media and the growth of informational resources, consumers have higher expectations for the products and services they buy. Customers are looking for companies that value transparency, sustainability, and moral behaviour, and demand a seamless, personalised purchase experience. To remain competitive and meet the changing needs of their customers, this factor is pushing companies to prioritise customer satisfaction, innovation and adaptability. A lot of large retailers are offering increasingly favourable services to their clients. For instance, Amazon offers free two-day delivery for most products, setting high customer service expectations and putting pressure on retailers to make strategic decisions about how they serve their customers.

The above factors have become crucial for companies to remain competitive in today's dynamic business environment, while satisfying customer needs and mitigating environmental impact. A comprehensive approach to supply chain management that integrates these factors and leverages modern tools and technologies is paramount to optimising operations and increasing efficiency. To succeed in supply chain management, organisations must be able to adapt to changing market conditions, embrace new ideas and apply a holistic approach to supply chain management.

2.4.1 Evolution of Supply Chain Management from the Turn of the Century to Present Day

The origin of study and research of supply chain management is believed to have commenced in the latter part of the 20th century, specifically in the 1990s. A conceptual framework of SCM was developed within the activity of the research centre, that was set up to create a concept and establish a scientific basis for the supply chain management (Lambert & Enz, 2017). The framework consisted of three steps: first – determining the essential supply chain participants to connect processes with; second – identifying the processes to be implemented with each of the key supply chain members. It was recognized that a standardized approach to supply chain processes is crucial for achieving inter-company process integration effectively. Variances in the number of processes, definitions of processes, or activities within each process may cause communication issues, thus emphasizing the need for standardization. Third step was to identify the proper degree of integration and management for each process connection. The research team determined nine management elements to be incorporated during implementation: Product Flow (which contains different processes as production, purchasing, logistics, marketing, R&D etc.), Customer Relationship Management, Customer Service Management, Demand Management, Order Fulfilment, Manufacturing Flow Management, Procurement, Product Development and Commercialization, Returns (Lambert & Cooper, 2000). Although each of these components has been updated and changed since then, they remain relevant today.

Later, it was investigated and determined that the definition of the supply chain established at that time did not mention the terms "relationship", "partnership", "network of organizations" etc. There was a need to create a new framework that would appeal specifically to the partnership type of interaction within the supply chain. In response, the Partnership Model was developed by Lambert et al. in 1996. The authors did not anticipate the significant role this model would play in the future development of the Supply Chain Management concept. To further aid collaboration between organizations, the Collaboration Framework was introduced by Lambert, Knemeyer, and Gardner in 2010. This framework is suitable for use in either the establishment of new relationships or in situations where significant joint business is involved, and a joint plan is required. The Collaboration Framework provides a systematic approach for creating product and service agreements with key customers and suppliers as part of the customer and supplier relationship management processes. The Collaboration Framework consists of six steps: 1) evaluating the drivers for each company; 2) synchronizing expectations; 3) creating action plans; 4) crafting product and service agreements; 5) evaluating performance; and 6) reassessing drivers.

The above-mentioned concepts created to organize successful supply chain management are the basis for modern theoretical research and practical applications. Nevertheless, there is still a need for a framework that addresses key requirements, including those relevant to this research paper: 1) minimizing risks in the supply chain, and 2) promoting sustainability initiatives within supply chain management (Lambert & Enz, 2017).

2.4.2 Political, social and scientific requirements to SCM

According to Lambert and Cooper (2000, p. 65), at the time of writing their article there has been a lack of academic guidance in the field of Supply Chain Management, which has generally been reactive to, rather than proactive in, business practice. However, it is evident that numerous external factors, including social pressures, consumer demands, regulatory requirements, and technological advancements, have forced supply chain stakeholders to continuously reassess and improve their strategies and tools to effectively manage their supply chains. In order to create a secure and transparent food supply chain, numerous regulations have been developed over the years at various international and national levels to govern the supply chain. These regulations are aimed at ensuring that food is produced, processed and transported in accordance with strict safety and quality standards, and that transparency and traceability are maintained throughout the supply chain. By complying with these regulations, food sector organisations can build trust with consumers and gain a competitive advantage in the marketplace (Dani, 2015). For instance, in order to ensure a high level of protection for consumer interests and human health in relation to food while preserving the efficient operation of the internal market, Regulation (EC) No 178/2002 of the European Parliament and of the Council (2002) establishes common principles and responsibilities, ways to provide a solid scientific foundation, and effective procedures. Except for primary production for private home use and domestic preparation, handling, or storage of food for private domestic use, the law is applicable to all phases of the production, processing, and distribution of food and feed. Additionally, it creates the European Food Safety Authority and outlines procedures for matters impacting food and feed safety.

Although there are regulations related to various parts of supply chain management, we are interested in the part of traceability requirements. According to ISO 9000:2015, traceability is an ability to trace the history, application or location of an object. In case of product or service traceability, it relates to the origin of materials and parts, the processing history and its location after delivery (ISO, 2015). According to CAC/GL 60-2006, traceability refers to the capacity to track the path of a food item as it progresses through specific stages of production, processing, and distribution. Traceability is important for ensuring food safety and quality, but many industry actors are not willing to bear the burden of implementing end-to-end traceability without regulatory requirements. The recently finalized Food Traceability Rule in the US is a step forward for traceability, defining recordkeeping requirements and a traceability framework for all food commodities, including imported ones. However, the rule is just one of many traceability schemes used worldwide, highlighting the need for alignment on definitions and standards for traceability in the global food industry (Bratager, 2022).

Considering definitions provided in both the ISO 9000:2015 and the CAC/GL 60-2006 standard, it can be concluded that a link between the product and supply chain participants is essential element of any traceability system to track products as they move through the supply chain. The amount of information needed may vary based on the sector and product type, and different methods, such as paper forms, barcodes, or computer software, can be used to keep records. Most countries now require the "one step back - one step forward" traceability requirement (for example, Article 18 of Regulation (EC) No 178/2002) in their national legislation as a fundamental requirement for effective traceability in any production field and for any product type (The World Bank et al., 2019). However, Regulation 178/2002 does not regulate the form and structure of traceability systems and procedures. Precise information related to the food items of animal origin is regulated by Regulation (EU) No 931/2011. According to Article 3 of this Regulation, information must be documented, stored on, and made available upon request by a business operator who receives the food or a responsible authority. This is in addition to the fundamental information that Regulation (EC) No 178/2002 requires. The required information includes a detailed description of the food, its volume or quantity, the name and address of the food business operator who dispatched it, the owner's name and address if they are different from the operator who dispatched it, the name and address of the food business operator who received it, the owner's name and address if they are different from the operator who received it, and a reference designating the lot, batch, or consignment as appropriate.

Internal traceability is the practice of monitoring the ingredients and parts of a final food product inside the organization and the production process. While not required by EU law, it is recommended for effective food traceability and production management. Internal traceability can improve production by controlling stocks, identifying trustworthy sources, and precisely targeting withdrawals as necessary (The World Bank et al., 2019).

2.4.3 Tracking and tracing in Food Supply Chain

As was mentioned multiple times before, traceability is a vital factor in modern supply chains, particularly in the food and agriculture sectors. At the beginning of the century, Stefansson and Tilanus (2001) noted the significance of traceability and the vital role tracking systems play in supply chain management. They act as a bridge between information systems and the physical material flow in the supply network. The absence of such tracking systems can hinder efficient coordination of logistic flows, making it difficult to ensure seamless operations across the supply chain, especially when it comes to agriculture or other food field.

According to latest Eurostat data (2022), there were 9.1 million agricultural holdings in the EU in 2020 and the food supply chain employed 21.5 million people in 2019 (Food Drink Europe, 2022). Ensuring food safety is crucial for many industries, but meeting customer demand while maintaining safety can be challenging. The responsibility for it falls on both food producers and governments. Achieving full supervision of food safety throughout the supply chain is essential, as food products go through various stages from farms to consumers' tables, making the process time-consuming and complex (Pawar & Mali, 2020). The WHO Global Strategy for Food Safety 2022–2030 acknowledges that the increasingly extended and complex nature of global supply chains has given rise to new challenges in ensuring effective traceability and recalls in the food supply chain. As the global food system becomes more interconnected, it becomes more difficult to track the movement of food components and products, particularly in the event of a recall or other food safety incident.

Furthermore, in traditional supply chain systems, each enterprise records its data on local centralised ledger. This localized nature of the ledger can lead to distrust among enterprises, as the recorded information may not always align with the interests of the enterprise, resulting in private falsification of data. As a result, communication costs between enterprises increase, and the inconsistency of information between supply chain nodes can lead to disruptions in the product traceability process (Wang et al., 2019).

Effective traceability in food systems requires three main prerequisites: depth of traceability, breadth of traceability, and precision in measuring tracked attributes. Depth of traceability refers to how far upstream and downstream the food components can be traced, meaning the ability to trace the origins of the food components as well as its entire journey through the supply chain to the final product. Breadth of traceability, on the other hand, refers to the number of variables or attributes of the food that are tracked. This includes information such as production dates, origin, processing methods, and transportation history, which are all essential in identifying potential food safety risks and managing food recalls. Finally, precision in measuring these attributes is crucial to ensure accurate and reliable tracking of the food products throughout the supply chain. This includes the use of standardized record-keeping systems, reliable data collection and communication methods, and consistent adherence to traceability protocols (Dani, 2015).

To meet the essential requirement of traceability and establish an effective system, gathering and utilizing appropriate data is crucial, but it requires significant efforts and investments. Thus, finding a balance between costs and benefits for the company becomes a top priority.

Traceability can be conditionally divided into two categories: mandatory and voluntary, based on the level of obligations imposed on food market operators to implement a traceability system. Mandatory traceability refers to requirements imposed by regulatory bodies that mandate food and feed businesses to keep records and identify the source of all food and ingredients, as well as provide the basis for further monitoring throughout the supply chain. This type of traceability is a legal requirement and is enforced through regulatory guidelines, such as the General Food Law Regulation (EC) No. 178/2002 in the European Union. Voluntary traceability, on the other hand, is not mandatory but is a higher level of traceability that can provide a more detailed and comprehensive record of a food product's journey from farm to table. Food businesses currently often voluntarily implement this type of traceability to meet consumer expectations for transparency and accountability in the food supply chain. Accredited organizations to coordinate and promote the application of the standards, including AFNOR Association in France[3], BSI in the UK[4], and UNI in Italy[5], may provide oversight for it. Additionally, to regulations mentioned in previous section, there is also one of important ones - ISO 22000:2005, which includes a specific voluntary traceability standard. Among key elements along the supply chain regulated by this ISO are interactive communication, system management, prerequisite programmes and Hazard Analysis and Critical Control Point (HACCP) principles. The GS1 Global Traceability Standard is a complement to international standards that helps companies understand how they can meet the various requirements defined in such standards. GS1 offers a standard for the traceability process that is independent of the choice of technology (Data, 2015).

Various methods are available to attain traceability and transparency across the food supply chain, with some systems designed to track food extensively from retailers to the source supplier, while others focus on key points in the supply chain. Traceability systems may collect

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[3] AFNOR: https://www.iso.org/member/1738.html
[4] BSI: https://www.iso.org/member/2064.html
[5] UNI: https://www.iso.org/member/1823.html

data only for tracking food to the point of production or logistics trajectory, while others may gather only general information, such as location (Zhong et al., 2017). The diverse nature of these approaches emphasizes the need for customized solutions that account for the unique characteristics of each supply chain.

Yaoqi et al. (2018) developed a QR-code based tracing method of checking a pork quality in cold supply chain. Although, in a certain way, their work is of some interest to this study, the use of QR codes in their work is limited to tracking the temperature of meat, but there is no information on tracking the entire history of meat movement through the supply chain, which is the object of current study.

In practice, there are many tools for tracking, such as GPS, GTIN, RFID, and barcodes, but they often offer only partial solutions and lack a unified architecture. Real-time tracking of an object's location is made possible through the use of a satellite network and GPS tracking technologies. In addition to tracking goods throughout the supply chain, GPS tracking may be utilized in many other situations. Real-time location information is provided, which can support enterprises in streamlining their processes. Yet, because of the potential for privacy problems, it is crucial to make sure that it conforms with all applicable laws. A GTIN (Global Trade Item Number) is a special number that the manufacturer assigns to each product. It is compatible with several tracking systems, including barcoding and RFID, and is used to identify items in the supply chain. RFID involves sending data through radio waves from a reader to a tag attached to a product. Compared to barcodes, RFID tags can track items in real time and provide more precise and in-depth information. On the other hand, barcodes are commonly used since they are affordable, simple to read, and do not need any specialized tools (Dani, 2015). Similar to barcodes, but with more data storage, are QR codes. These can be scanned with a smartphone to get product details or find out where it is in the supply chain. To solve nowadays problems, modern technologies such as IoT, an industrial internet platform, and trackers are needed for a sustainable production process. These tools must be cost-effective and provide the necessary data. (Helo & Shamsuzzoha, 2020). In recent years, there has been growing interest in the potential use of blockchain technology for tracking and tracing items through the supply chain.

The blockchain is essentially a distributed ledger that records transactions in a secure and transparent way, with each block in the chain containing a unique digital fingerprint that can be used to verify the authenticity and integrity of the data. The use of blockchain technology could potentially enhance traceability in the supply chain by providing a tamper-proof and immutable record of all transactions, thereby increasing transparency and reducing the risk of fraud or error. However, while the potential benefits of blockchain are significant, there are also challenges to consider, such as scalability, cost, and compatibility with existing systems (Helo &

Shamsuzzoha, 2020). On the other hand, centralised infrastructure may cause such problems as data integrity or tampering.

Despite all advantages described for IoT, there are still some disadvantages such as potential for security vulnerability, risks of cyber-attacks and data breaches (Sarmah et al., 2017). A lot of IoT devices have limited security features, which may make them sensitive to unauthorized access, especially with increase of the devices number. Furthermore, privacy concerns arise due to the collection and transmission of personal data by many IoT devices. Users may not be aware of the extent of data collection or who has access to their data. This can lead to misuse of personal information, such as identity theft or unauthorized profiling. In addition, IoT can create new environmental hazards due to their toxic components, as well as contribute to environmental issues such as carbon emissions and climate change due to constant energy consumption (Parteek, 2019).

According to Shahbazi and Byun (2020) the development of IoT technology in the food industry has made traceability more complex and time-consuming. Authors believe that in addition to the challenges of IoT, the current traceability system can be limited by lack of access for consumers to check product information and make informed decisions about quality and shelf life. The blockchain system has a potential solution by offering a low-cost approach to food traceability, but there are limitations to its ability to utilize raw data and establish trust within the supply chain network. Although blockchain system has the potential to track and trace products, its primary focus on cryptocurrency means that it may not be a comprehensive enough solution for the complexities of the supply chain network. Therefore, there is a necessity for further research and development in order to determine the most effective and efficient traceability system.

Innovative Solutions in Today's Supply Chain: Real-World Applications

The author considers it as crucial to examine practical cases related to supply chain management, especially when it comes to traceability issues, to meet the scientific objective of this paper. A noteworthy scientific and practical case worth considering is the implementation of the blockchain-based approach designed by Pincheira, Ali, Vecchio, and Jaffreda and described in their paper. Pincheira et al. (2018) developed and assessed a decentralised, blockchain-based traceability solution for managing the Agri-Food supply chain. It integrates IoT sensor devices and relies on either the Ethereum[6] or the Hyperledger Sawtooth[7] blockchain implementations. The system produces and consumes valuable information from the IoT devices along the supply chain and stores the data in its underlying blockchain, providing transparent and auditable traceability of assets.

However, as the primary focus of this paper is not the examination of modern practical cases, the author has decided to limit the scope of their analysis to the following criteria: a) innovative solutions relevant to supply chain traceability, b) a limited number of solutions from top companies globally, and c) solutions for which information was readily available. Among chosen supply chains to examine are Amazon, Walmart, Cargill, Unilever and P&G.

Amazon

Amazon is a global leader in e-commerce and cloud computing, and the largest online retailer in the United States. The company offers a wide range of products, including books, electronics, furniture, food, jewellery and more, sold through its online sites in countries around the world, including the United States, Canada, China, West Europe and so on. Amazon saves storage costs by integrating inventories from distribution centres and partner warehouses. The location of distribution centres is determined based on the proximity to customers and tax levels. Within the distribution centres, Amazon uses different processing equipment depending on the product type, with more automated equipment for easier-to-handle products and lower-level automation for irregularly shaped products *(Yu et al., 2016)*.

For inter-city transportation, Amazon uses transportation hubs located in areas with high customer concentration. Orders are first integrated at distribution centres, then sent to the hubs using either less-than-truckload or truckload shippers. This approach helps to save on overall transportation costs as the unit mile costs for these shippers are relatively low *(Yu et al., 2016)*. Mainly, Amazon uses a combination of its own delivery network, third-party logistics providers, and technology-driven platforms. It provides its delivery using air, ocean, rail, and trucking services to move goods between cities, and to provide the "last mile" delivery from the warehouse to the customer's doorstep, it partners with local delivery service providers. Last years, Amazon implemented advanced technologies like machine learning, artificial intelligence, and automation to optimize routes, reduce delivery times, and improve overall efficiency (Quaker, 2023).

[6] Ethereum - is a decentralised platform that enables communication without the need for a centralised authority, the development of decentralised apps, and the transfer and storage of assets. More information: https://ethereum.org/en/

[7] HyperLedger – is a collaborative effort that aims to advance blockchain technology across various industries. It is an open-source project that involves leaders in banking, finance, supply chain, and technology, among others. The project is hosted by the Linux Foundation. More information: https://www.hyperledger.org/

As mentioned on Amazon's official website, traditional SCs still use paper based or/and disengaged data systems, which cause difficulties in providing tracking products. Lack of transparency leads to delays, disruptions and increased costs and it is actual challenge for industry (*Blockchain for Supply Chain: Track and Trace*, n.d.-b). To solve this problem Amazon provides its own solution for supply chain – Amazon Managed Blockchain.

The Amazon Managed Blockchain is a fully managed service that simplifies the process of creating and managing both private and public blockchain networks using Hyperledger Fabric and Ethereum. The traditional process of setting up a blockchain network is complex and requires manual provisioning of hardware, software installation, access control, and constant monitoring. Therefore, Amazon offers to its customer the managed service for creating the network with other organizations much easily. For businesses seeking privacy and control in a decentralised network, private Hyperledger Fabric blockchains are considered more than sufficient for use cases such as supply chain data sharing (*Amazon Managed Blockchain*, n.d.).

There are a number of benefits and drawbacks to Amazon's approach to supply chain management using Amazon Managed Blockchain. As businesses may use blockchain technology without investing in their own hardware, one advantage is the reduction of infrastructure expenses. Another benefit of using the fully managed service is how simple it is to set up and manage. Moreover, by producing an unchangeable and auditable record of all transactions and data changes, blockchain technology enhances security for supply chain management (Ameeruddin, 2022). In addition, Hyperledger Fabric and Ethereum, two well-liked blockchain frameworks in business contexts, are supported by Amazon Managed Blockchain.

Walmart

Walmart is world's largest retailer which pay attention to customer needs through optimizing the SCM system. Its supply chain efficiency was attributed to automated distribution centres and computerized inventory systems. These factors not only reduced checkout times but also enabled transaction recording, which is crucial for predicting and addressing demand. Walmart implemented innovative changes in its power distribution system to reduce lead time, minimize paperwork, and increase efficiency in supply chain management. They used barcodes to track inventory levels and strategically aligned the movements of products to reduce time and costs. The company had an effective distribution system that educated drivers on supply chain responsibility and utilized cross-docking to increase efficiency (Francis, 2020).

Walmart partnered with IBM to create a blockchain-based food traceability system for its decentralised food supply chain. They use IBM Blockchain which is built on Hyperledger Fabric. The system was tested with mangoes sold in Walmart stores in the US and pork sold in Walmart stores in China, which reduced the time needed to trace provenance from 7 days to

2.2 seconds. Walmart now uses the system to trace over 25 products from five different suppliers, including produce, meat, dairy, and packaged foods. The company plans to roll out the system to more products and categories in the future and require all suppliers of fresh leafy greens to use the system. Walmart may also use the system to trace sustainability data in the future (Hyperledger Foundation, 2022). The use of automation, computerised inventory systems, and an efficient distribution system in Walmart's supply chain management strategy has increased productivity, reduced costs, and improved customer satisfaction. However, implementing such technologies can be costly, and convincing suppliers to use new procedures and technologies can be difficult. In addition, blockchain technology may raise security and data privacy issues.

Cargill

Cargill Incorporated is a worldwide conglomerate that provide its activity in agricultural field by trading, purchasing and distributing grain, palm oil, glucose syrup, cocoa, vegetable oils and fats used in plenty of processed foods. The company considers traceability of its SC as important component and in order to enhance it to 100% by 2030 (as Cargill declared it in its outline) company is developing various of tools and applications. It operates in the field of supply chain traceability, conditionally dividing its activities into three dimensions:

1. Obtain and record origin information.
2. Link characteristics of sustainable development to previously obtained information.
3. Transfer traceability data along the SC.

Within first dimension, which is directly connected to the traceability challenge, Cargill is implementing two main components: supply chain mapping and first mile traceability. Supply chain mapping involves mapping the supply chain to the farm level, using GPS farm polygon maps to verify partner farmers against environmental measures. First-mile traceability, on the other hand, involves tracking the source farms and farmers from which cocoa enters the direct supply chain, initially through third-party certifications (such as Fairtrade International, Rainforest Alliance etc).

Cargill believes that the value of traceability lies in linking origin data with sustainability characteristics (second dimension), such as agricultural practices, social conditions, and proximity to protected forests. These linkages enable Cargill to identify risk areas and tailor interventions accordingly (Stoop et al., 2021a). Cargill's monitoring and evaluation system, CocoaWise Insight, tracks and monitors progress in achieving sustainability goals, including detailed data on tree density, cultivation methods, and replanting activities, as well as information on farming families and their communities. Cargill uses a set of tools, including CocoaWise eFinance, CocoaWise ProFarm, and CocoaWise ProCoop, to increase transparency and traceability while enhancing cocoa farming practices and community well-being. CocoaWise eFinance is a mobile money solution that ensures fair and secure payments, while CocoaWise ProFarm provides digital tools to support farmers in making informed decisions based on agronomy and market information. Finally, CocoaWise ProCoop manages first-mile traceability and supports farmer cooperatives to be more professional in how they sell and manage their cocoa (Uittenbogaard, 2021).

Within the third dimension, Cargill has multiple tools and applications to transfer and verify traceability and sustainability data in their supply chain. They have launched CocoaWise Portal for customers to access sustainability data easily. CocoaWise gathers information from various digital tools that Cargill uses to enhance cocoa farming practices and community well-being and compiles it in a centralised data platform called CocoaWise 360. This platform enables Cargill to layer data from different sources to get a clearer picture of what's happening on the ground, assess interventions, and identify areas where impact can be increased.

Cargill works directly with cooperatives and buying centres in its direct supply chain, supporting them to build their capacity with traceability systems and targeted sustainability programs. In the indirect supply chain, Cargill maps its suppliers and engages with them to address identified risks through a due diligence system. Physical segregation has limitations, so Cargill aims to understand not only where cocoa is sourced, but also under what conditions it was produced to design targeted sustainability interventions. Cargill provides supply chain transparency to customers by knowing the origin of all cocoa bought (Stoop, 2021a, Stoop, 2021b).

The traceability and sustainability-focused supply chain strategy adopted by Cargill has the potential to address the environmental and social problems related to agriculture production. Using digital tools like CocoaWise Insight and CocoaWise eFinance may make decision-making and risk assessment more transparent and efficient. Direct interaction with cooperatives and buying centres may aid in capacity development and improve the lives of farmers and their communities. Responsible sourcing is demonstrated by Cargill's approach of due diligence for controlling risks in indirect supply chains, which may also increase supplier accountability. Physical segregation, however, may provide obstacles to complete traceability and monitoring, making this system vulnerable to these issues. For first-mile traceability, relying entirely on third-party certification could not fully account all environmental and socioeconomic considerations. It can be difficult to scale up traceability and sustainability throughout Cargill's broad and complicated supply chain, particularly in areas with poor infrastructure or technical capabilities. (Stoop, 2021b).

UniLever

Unilever is a global consumer goods company founded in 1930 and based in the Netherlands and the UK. It produces food, beverages, cleaning agents, and personal care products, and targets 2.5 billion people in 190 countries. The company has a sustainability plan to improve its products and services with the help of partners, NGOs, and consumers (Notta & Reimoo, 2018).

Unilever works with direct suppliers to increase transparency and traceability of materials, requiring them to undertake supply chain mapping and provide details of production facilities and agricultural supply areas. Direct suppliers are also required to have effective control mechanisms in place to trace materials and share traceability data and attributes of the agricultural supply area with Unilever. The company declares that it only buys materials that comply with its policy and is committed to verifying compliance independently or with the help of stakeholders (Sustainable Sourcing, Procurement Department of Unilever, 2020).

Unilever is using a digital crowdsourcing platform provided by partner Premise to gather information and photos of collection points and ramps in the palm oil supply chain in Aceh, Indonesia. The pilot recruits involve contributors to take photos and videos of palm oil collection points and upload them to a digital platform, and the data is run through Premise's quality control system to verify its credibility. This effort has led to the identification and documentation of over 5,000 collection points, which provides a better understanding of where the oil palm that supplies Unilever is being grown (Unilever Plc., 2022).

Direct communication with suppliers and the application of digital technology to improve traceability and transparency are key components of Unilever's supply chain management strategy. This strategy may have various benefits, such as increased sustainability and social impact, better supply chain efficiency, and increased supplier responsibility. There are, however, also restrictions and difficulties, such as possible restrictions of digital platforms and the requirement for continuous review and development to guarantee the success of sustainability initiatives. Overall, Unilever's strategy is a positive move toward more accountable and sustainable supply chains, but more work and advancements are still required to handle the numerous difficulties involved.

P&G

Procter & Gamble (P&G) is a global leader in consumer products with more than 100 supply chains. Supply chain risk management has been a P&G board initiative since 2000, and it was firmly embedded in the corporate approach to risk management by the time Hurricane Katrina devastated many local businesses in 2005. Thanks to well-documented and practiced business continuity and crisis response plans, P&G's Folgers coffee plant returned to full production two months after the hurricane.

The company is unique in that it sources ingredients from a global network of suppliers, but the final products are typically shipped locally from their factories. This makes them vulnerable to global risks in the ingredient supply chain, but only to a more limited set of local risks associated with production and delivery to retailers. This contrasts with other large corporations that have to manage risks for their inbound shipments to factories and outbound shipments to customers over much longer distances (Babcock, 2015). With a number of projects, Procter & Gamble (P&G) is working toward achieving end-to-end visibility in its supply chain. Using digital technology, such as radio frequency identification (RFID), to monitor goods and commodities across the supply chain is one of its strategies. Moreover, P&G works with its suppliers to enhance transparency and traceability and mandates that they adopt ethical sourcing procedures. Moreover, the business has a risk management program that regularly evaluates how well suppliers comply with P&G's requirements for sustainability and social responsibility. Moreover, P&G collaborates with other agencies to audit and validate its supply chain. By 2025, P&G wants to have full end-to-end visibility throughout its supply chain (P&G & EY, 2022). The benefits of P&G's strategy include improved risk management, better openness, and a dedication to sustainability; however, there are also disadvantages, including a possible difficulty in reaching end-to-end visibility and a greater dependence on digital technology.

2.4.4 Blockchain approach for Supply Chains

Blockchain is a relatively new distributed peer-to-peer ledger technology that uses interconnected blocks of data and has become extremely popular and implemented in various fields over the past few years (Wang et al., 2019, Li et al., 2018). The technology organizes data into 'blocks' each block is connected to the previous block through a hash value, forming a ‘chain’. The header of each block contains various information such as the block's version number, timestamp, and previous block hash, which helps to create a connection between blocks. The main idea of Blockchain is depicted in Figure 2. 4. Unlike traditional electronic databases or paper ledgers, blockchain stores not only current data but also a complete history of transactions, allowing users to trace the chain from the first to the last block to determine the current set of data (Verhoeven et al., 2018). This cryptographic connection between blocks ensures data integrity and eliminates the possibility of data tampering inherent in centralised systems.

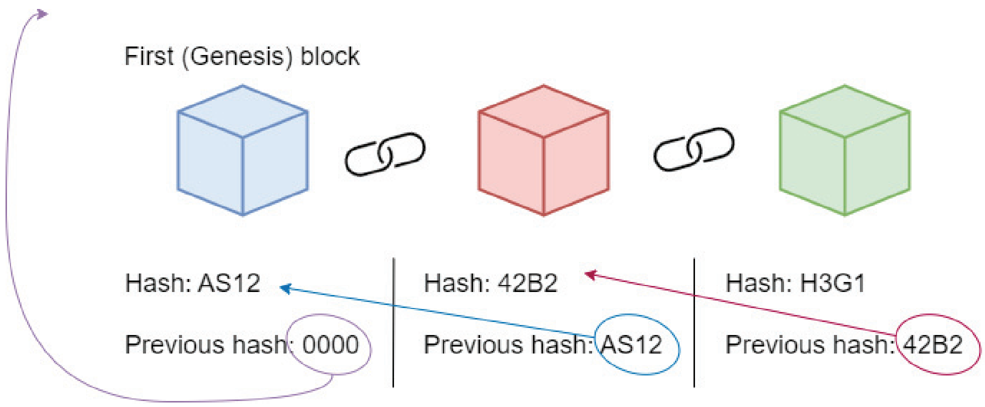

Figure 2. 4 Blockchain algorithm of work

There are public, private and consortium blockchains. Public blockchains are decentralised networks that are open to everyone (like Bitcoin and Ethereum), while private blockchains restrict access to a select group of users (Hyperledger Fabric). Consortium blockchains are a hybrid of both public and private blockchains (like IBM Blockchain), formed by a group of organisations that share blockchain data and transaction history (L. Wang et al., 2021).

When it comes to supply chains, blockchain technology has recently become one of the most popular solutions for achieving efficient and transparent management in this area. It is believed that the combination of BT and the Internet of Things (IoT) increases the efficiency of SCM (Francisco & Swanson, 2018). Among all the existing blockchains, many companies are choosing Ethereum because it enables companies to create and deploy their own smart contracts to manage and track the movement of goods and information throughout the supply chain. Smart contracts are software programs that operate similarly to scripts that run on non-blockchain applications. They can be programmed to perform automated actions based on pre-defined rules that cannot be changed by anyone. To write a smart contract on Ethereum, developers use a low-level bytecode language that is executed by the Ethereum Virtual Machine (EVM). The EVM code is unique to Ethereum and is stored in the blockchain in binary form. However, developers can also write smart contracts in high-level programming languages such as Solidity, and then compile them into EVM code. The Ethereum Virtual Machine is at the core of the Ethereum platform, and it can execute code with arbitrary algorithmic complexity, making Ethereum a Turing-complete system. Developers can deploy tokens and create contracts and various decentralised applications (DApps) on the Ethereum Virtual Machine using existing programming languages such as Java and Python (Ethereum, n.d.). A token is a conventional unit of count that represents a value, similar to real-world units like coins, points, or some assets like gold or property. They can be used for a variety of purposes such as means of payment or exchange for goods and services, a representation of ownership, or a way to encourage users to perform certain actions within a decentralised application (Lesavre et al., 2021).

Despite its immense potential, there is still a lack of knowledge among supply chain professionals regarding its use, however, to solve this issue, Sunny et al., (2020) as well as Verhoeven et al., (2018) investigated in their works the existing use cases of blockchain-based solutions for supply chain in different kinds of scenarios and application fields. Anyway, the relative novelty of BT in the market makes it difficult to accurately forecast its performance outcomes in the long-term (Francisco & Swanson, 2018). Nevertheless, Blockchain technology currently is gaining popularity in numerous industries, including food supply chains. There are several examples describe the cases of implementation of this technology. Rejeb (2018) described theoretical implementation of distributed approach with using IoT, RFID and Hazard Analysis and Critical Control Points (HACCP) in halal FSC in order to reduce the risks related with halal market. Salah et al. (2019) provided their practical solution for traceability of soybean SC using Ethereum public blockchain. They developed rather general framework which could be applied with modifications for other fields.

Despite the use of established cryptographic technologies, blockchain is not immune to cybersecurity threats. Consensus protocol weakness is one of the main cyber vulnerabilities to blockchain. Consensus protocols are used to add new blocks, and flaws in these protocols might give attackers influence over the blockchain network and the ability to force their will on consensus decisions. Attackers may gain control over the blockchain network, for instance, through a majority attack (51%), selfish mining, or both.

The invasion of privacy and confidentiality provides another concern. Blockchains are transparent by nature, and users may exchange data from which hackers may be able to infer private or sensitive information. Organizations must carefully assess how they use blockchain technology and make sure that only authorized data is shared, preventing the exposure of sensitive or private data. Another serious threat to blockchain is the compromise of private keys. These keys are used for the identification and authentication, and if they are stolen, attackers can take over those accounts and the related resources. Attackers can compromise private keys or take advantage of flaws in blockchain client software using a variety of techniques, including phishing and dictionary attacks. Finally, a significant risk to blockchain security are smart contract flaws, which can be used as means of attack. For instance, a hacker stole about $60 million from the Decentralised Autonomous Organization in 2016 by taking advantage of a smart contract vulnerability. Therefore, in order to address potential flaws and comply with business and legal requirements, smart contracts must be assessed and properly tested (Alabdulkarim, 2023, Horizen Academy, 2023).

Among other disadvantages of Blockchain technology, specialists emphasize several (Strebko & Romanovs, 2018):

a) High energy consumption, which is needed for keeping a real-time ledger and verifying the transactions (Fauvel, 2018, Blockchain Technology, 2016).

b) Scalability, conducted by the growing of transactions number, which could lead to a slower time of the next transactions and higher costs.

c) There is still the problem of legal regulation because governments around the world still figuring out how to provide regulation on the blockchain. It could lead to legal and compliance risks for businesses (Blockchain Technology, 2016).

d) Complexity of this technology requires significant technical expertise to implement it to an own use case.

Furthermore, the current throughput of Bitcoin is limited to around seven transactions per second, which could be increased to about 66 without affecting security (Gervais et al., 2016). In contrast, centralised systems like Visa can handle more than 50,000 transactions during peak periods. The choice to use a blockchain system should consider the trade-off between decentralization, which scales well for a large number of writers without mutual trust, and throughput, which determines the number of states updates the system can handle within a given time frame (Wüst & Gervais, 2018).

Although supply chain management (SCM) solutions can be improved, it is not clear why blockchain is the appropriate solution. For instance, Skuchain – is a one of the companies who use IBM's Hyperledger Fabric as its blockchain backend along with its wide range of consensus options. (*Skuchain: Currency Agnostic Blockchain for Global Trade*, 2021). However, Skuchain admitted that for most SCM features, a single source of truth would suffice, and a single trusted database should meet most business needs (Wüst & Gervais, 2018).

2.4.5 Centralised Database for Real-Time Tracking and Tracing of The Products In SC

In industries like logistics and transportation, centralised tracking systems are commonly used to monitor goods and shipments in real-time. For instance, a logistics company might use such a system to improve delivery routes, manage inventory levels, and give customers accurate delivery estimates. Unfortunately, these centralised tracking systems have some weak points. Since the database is controlled by one entity, it's prone to data manipulation or tampering. Furthermore, if the central database is hacked or goes interrupted, the whole system will be affected and disruptions in the supply chain could occur. To tackle these issues, some businesses are looking into decentralised tracking systems enabled by blockchain technology, as was described above (Tian, 2016, Shahid et al., 2020).

To keep track of products, a system is needed that tracks and traces their path throughout the supply chain. Since the supply chain is interconnected, Maouchi et al. believe that it's hard to introduce a centralised system managed by a third party, where a large amount of trust is required. Due to the lack of trust, separate systems have been put in place, making it difficult to achieve traceability across the whole supply chain.

Nevertheless, the objective of this study is to develop a centralised supply chain tracking system, thus demonstrating the possibility of using not only decentralised technologies, which gain a huge popularity over the last years, but also an alternative solution to the problem of traceability and transparency of supply networks.

2.5 Requirements for the System to be Developed

Examining the relevant specifications for the result of this work is essential in order to develop an effective and efficient traceability system for the food supply chain. Since the master's thesis is being completed as part of the "MaltFungiProtein" project, it's critical to give the project-specific needs first priority in this situation. Furthermore, extensive research which has been conducted previously for managing contemporary supply chains and ensuring product traceability throughout these chains should be taken into account when designing a supply chain system, as well as international guidelines.

2.5.1 "MaltFungiProtein" Project-Based Requirements

The system requirements set out in the project can be divided into several segments:

Supply Chain Structure: The players in the agri-food supply chain should be predetermined and include suppliers, processors, distributors, retailers, and end consumers. Each member in the supply chain has to be fully aware of their responsibilities. The proposal envisioned a supply chain with production processes that take specific components and create goods from them at each point of the network. Figure A. *1* depicts an extensive schematic of the supply chain.

Process Management: The system should be able to manage the processes of each participant within the supply chain, including but not limited to, production, transportation, warehousing, quality control, and sales. To guarantee that each procedure is carried out successfully and efficiently, it should be tracked.

Item Tracking and Tracing: Each item should be able to be tracked and traced by the system all the way through the supply chain. The movement, location, state, and quality of the item are all tracked along the supply chain. A real-time status update on the item should also be possible through the system. The idea of traceable information about product with QR-code depicted in Figure 2. 5.

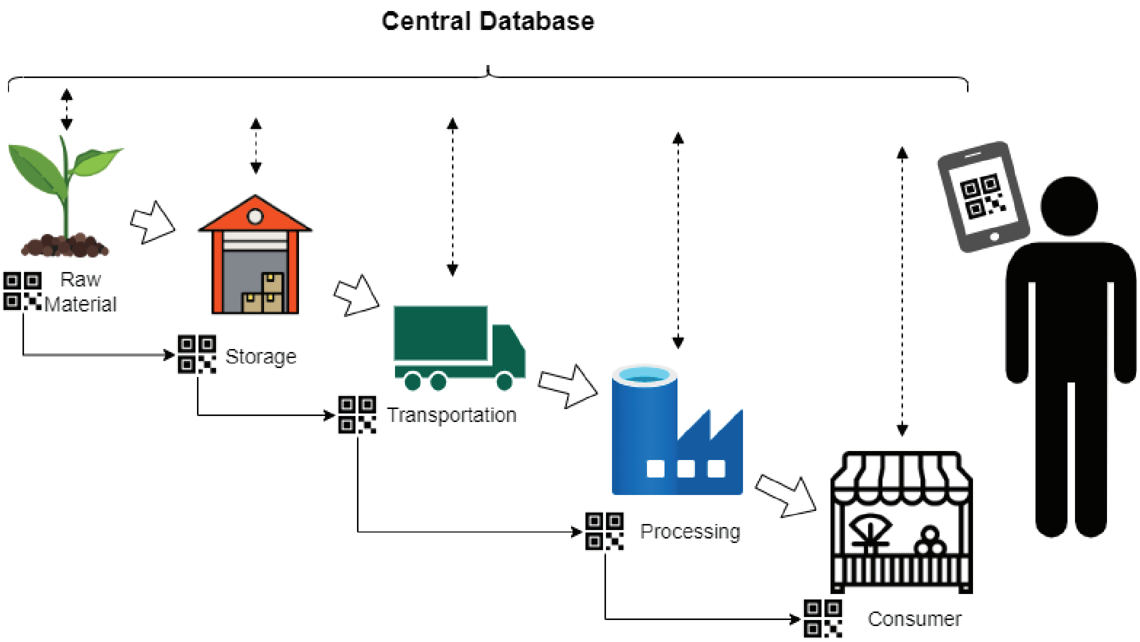

Figure 2. 5 Traceable Supply Chain

Data Security: The system must be safe and guarantee the security of all data. This involves having the capacity to control access to sensitive data, protect data privacy, and stop unauthorized data modifications.

Role Management: The establishment of a multi-level rights and role system is necessary for role management in the supply chain system in order to guarantee that only those with the proper authorization may access the data. The data submitter, additional supply chain partners, the general public, and regulatory bodies are just a few of the parties who have the right to examine the data. Each partner should be able to view the information that concerns them, and unauthorized parties should not be allowed access. For instance, partners may examine information on fungal type, batches, dates of production, and other crucial data for assessment, traceability, and production planning while the final consumer can simply see the source of protein, manufacturing circumstances, and components. Permission Management should be used in combination with the proper computer code to fulfil this need. It is crucial to take data privacy into account while putting these authorization levels into practice. Traceability is essential, but confidential information specific to each organization should also be considered. As a result, supply chain players may choose which of their product information is accessible to upstream and downstream supply chain participants as well as the final customer. This makes it easier to maintain data security while still ensuring the supply chain's traceability and transparency.

Database: For the project, a centralised database was selected for a number of factors. First off, a centralised database makes it possible to gather, store, and manage data from several sources in one place, which makes data administration simpler and decreases data redundancy. Second, real-time access to data provided by a centralised database makes it possible for rapid and efficient data retrieval and analysis. This is crucial in the Agri-Food supply chain, where it's essential to be able to monitor and track products in close to real-time. Lastly, a centralised database makes it simple to integrate with other systems that may be used by supply chain actors. A centralised database also makes it easier to install security measures like access limits and encryption, which are essential for guaranteeing the data's integrity and confidentiality.

In addition to the previously mentioned requirements, there are additional requirements related to the use of tokens idea retrieved from Blockchain technology and adapted to centralised system in the project. In order to guarantee the efficiency and dependability of the traceability system in the agri-food supply chain, it is crucial that these standards for token management, encryption and security, representation, and validation be met.

Token Management: Tokens ought to be created, controlled, and revoked by the system as needed. This involves allocating tokens to certain items, monitoring the tokens' validity, and revoking them as required. Moreover, the system needs to be able to offer details on each token's status, such as the date and time of creation, the product it is linked to, and its expiration date.

Encryption and Security: The tokens must be securely encrypted, and the system must make sure that the right authorizations are in place to limit access to the tokens. To prevent unwanted access to the tokens or tampering with them, this includes limiting access to authorized individuals and making sure that all data communications are encrypted. In order to safeguard the tokens from illegal access, alteration, or duplication, the system should also employ hashing algorithms. It gets harder to recognize and recall certain tokens (blocks in Blockchain) based only on their data as a number of such blocks increases over time. Hashing is used in this situation because it creates a secure, distinctive, and fixed hash value for each block. Overall, the use of hashing in such approach is an essential element that makes the system run securely and effectively, enabling the efficient administration and monitoring of data across several tokens (blocks).

Token Representation: Each token should be represented by a distinct QR code that the system may physically attach to the item. The unique identification for the product, the duration of the token's validity, and the database address connected to the token should all be included in this QR code.

Token Validation: When a token is scanned or read by a user, the system must be able to confirm the validity of each token's authenticity. This entails confirming the token's authenticity, that it has not expired, and that it is linked to the appropriate product. In the event that the token is incorrect, the system must issue the proper error messages and take the necessary remedial measures.

2.5.2 UN Supply Chain Reference Data Model Business Requirement Specification (Scrdm-Brs)

The four kinds of data in the supply chain are commercial, logistical, regulatory and financial, according to the UN Supply Chain Reference Data Model Business Requirement Specification (UN/CEFACT Bureau, 2017). Commercial data exchanges and procedures often include actions like producing a catalogue, quotation, confirmation of sales orders, materials management (including delivery planning, issue of dispatch advise and packing list), sales invoicing, and remittance advice. The parties participating in commercial data transfers may include manufacturers, processors, distributors, retailers, and end users.

Cargo space reservations, shipping instructions, the issuance of transport contract documents (like an air waybill), the transportation of goods, the requesting and issuance of transport status reports, and freight invoicing are a few examples of the data exchanges and processes related to logistics or transport. The participants in data exchanges related to logistics might be carriers, shipping and logistics firms, and customs officers.

Reporting to customs or other appropriate governmental agencies for activities like import/export declarations, certificates of origin, phytosanitary certificates, dangerous goods declarations (including OECD hazardous waste notifications), cargo and transit reports, and cross-border regulatory data pipeline are all examples of regulatory data exchanges and processes. Customs agents, governmental organizations, and regulatory authorities might be the players in data transfers for regulatory purposes.

Moreover, freight insurance and documentary credit processes may be used in financial data exchanges and operations. Banks, insurers, and other financial institutions may participate in financial data exchanges. To maintain effective and accurate supply chain operations, it is crucial to have appropriate data management and sharing systems in place for each type of data.

2.5.3 White Paper UN/CEFACT

White Paper UN/CEFACT describes the different points in the supply chain where information is exchanged. According to the paper not every waypoint must be utilized every time, but there should be a specified list so that pipelines may be established across all transport modes and have a shared understanding by all. We will concentrate on exploring the most relevant aspects from all other waypoints for creating our system in this study (Table 2.*1*). This paper within current scientific work is taken into account only as a recommendatory guide for designing supply chain, so we can consider more accurate data while creating a prototype for tracking system.

The sales contract acts as the main channel for the exchange of information among the parties engaged in the supply chain. It contains vital information about the commodities being sold, including their economic worth and Harmonized System Codes. Another crucial waypoint for information sharing is the point at which items are scheduled with a transport service provider and space is set up for their travel. Certain information from prior waypoints, such the quantity of packages, may need to be repeated for a particular movement since transport may take place over several shipments within a single transport-sales contract.

Before or after the shipment takes place, the transport service provider often gives the carrier instructions for shipment and requests that it provide the transport contract, such as a bill of lading or road consignment note CMR. The responsibility under the terms of the Transport Contract is transferred to the Transport Service Provider at the time the items are physically loaded into a mode of transportation. At the time of arrival at the port, responsibility for the cargo usually passes from the transport service provider to the port or carrier. As proof that transportation has occurred, the confirmation that the items have departed the port of loading acts as an important waypoint.

Some goods are sold while they are being transported, creating a new business transaction that adds information to the previous commercial contract. The final waypoint for information exchange in the supply chain is the delivery of the cargo to the consignee or dispatch party under the terms of the transport contract UN/CEFACT Bureau. (2018).

Table 2.1 UN/CEFACT Waypoints (from UN/CEFACT Bureau, 2018)

Input Waypoint	**Type of Data**	**Actor / Role / Source**
Sales contract	• Buyer • Seller • Despatch and delivery party	Buyer / seller

	• Country of origin • Harmonized System Codes • Commercial document reference (invoice number or other) • Commercial (invoice) value of goods • Quantity of goods ordered • Planned place of delivery	
Goods booked for transport	• Number of packages for shipment • Weights • Special handling instructions (perishables, dangerous goods information, temperature control) • Means of transport ID • Port of loading • Planned time of departure • Planned port of discharge • Planned transport route • Freight rate	Transport service buyer or transport service provider
Transport contract (shipping instruction)	• Actual point of departure/collection • Actual date of collection • Carrier • ETA - estimated time of arrival	Transport service buyer or transport service provider
Goods loaded for transport	• Actual arrival time at pickup place / the place of acceptance • Actual departure time from pickup place / the place of acceptance • Container number • Seal ID(s)	Transport service provider
Goods delivered	• Actual delivery point • Actual date/time of delivery • GPS position of delivery point • Acceptance of delivery (person) / goods receipt	Consignee or transport service provider

2.6 Summary

The food supply chain is a complex system of suppliers, producers, distributors, retailers, and consumers managed at various points of production or distribution. As well as any other system, supply chain (SC) has weaknesses and faces some concerns such as disruptions, transparency issues, safety and sustainability.

The success of ensuring food quality and safety relies heavily on having an efficient and effective supply chain network structure. However, the current systems face challenges due to the increasing global demand for healthier, and more nutritious and sustainable food, as well as technological advancement and legal regulation. According to Zhong and Wang (2017), currently, the design and development of the food supply chain network are centred on a single distribution centre or warehouse management system (WMS), ignoring the need for a comprehensive and global structure. Optimization efforts within the network mainly focus on planning, scheduling, profits, and costs, overlooking the need for sustainable practices and reducing environmental impacts. With the rise of product safety, ethical sourcing, and sustainability concerns, consumers are expecting more openness and responsibility in supply chains. Additionally, businesses can have better insight of the product's movement and sourcing by implementing traceable system within their SC. This can also be used to identify and fix problems such as fraud, unfair sourcing practices, and environmental issues. To meet all of the above needs, businesses have started to use new technologies like IoT, barcodes, RFID or blockchain to build traceable supply chains. Furthermore, with the development of advanced technologies such as IoT, the traditional network structure is no longer suitable, and an innovative and open structure for food supply chain management (FSCM) is needed.

The supply chain's existing traceability systems still have several flaws, notwithstanding these developments. Lack of system interoperability, which makes it difficult to trace products across several supply chains, is one of the major problems. Another key problem is the accuracy of the data being gathered and stored because there are frequently inaccuracies or discrepancies in the data that can cause misunderstandings and inefficiencies. Current traceability systems might be vulnerable to fraud and tampering, especially when it comes to paper-based data that are readily lost or altered. Finally, implementing traceability systems can be expensive and time-consuming, which can be a barrier for small and medium-sized enterprises who lack the funding to do so. Overall, even if current traceability systems have increased the efficiency and transparency of the supply chain, there is still potential for innovation to overcome these systems' flaws and restrictions.

Considering the theoretical data discussed in this section, as well as the fact that each supply chain should be considered individually, in accordance with the tasks and goals of a particular chain, a number of requirements for various elements of the supply chain were formed within the framework of this study and conducted by requirements of "MaltFungiProtein" project and international advisory papers.

3 A Comprehensive Analysis of Databases, Access Control and Unique Value Generation Approaches for Securing the System

To build a software system, it is important to define a structure of future system and a way how its components should interact with each other. The fundamental ideas and guidelines of software architecture theory is conducted by SOLID principle (Martin, 2020):

1) Single Responsibility: Software should be divided into separate parts so each of which is responsible for specific concern of duty.

2) Open-Closed Principle: Breaking down software into modules, which are self-contained and can be developed and tested independently makes it easier to maintain and update the software.

3) Liskov Substitution Principle: Independent objects should have the ability to communicate and replace one another.

4) Interface Segregation Principle: Complex systems and processes should be simplified so that the software is much easier for the user to understand and there are no redundancies.

5) Dependency Inversion Principle: This principle ensures that software can easily be scaled up and handle increased loads and usage over the time. In case when one component is modified it should not have any consequences on other parts of the system.

The software architecture provides a blueprint for the components of the system and how they interact. It is designed to ensure that the system is structured in such a way that, among other things, performance and security requirements are met. A well-designed software architecture can have a significant impact on the quality, maintainability and overall performance of the system. It involves decisions about how the system is partitioned, what components it contains, and how these components interact with each other and with external systems (Kirsten, 2019).

The software architecture selected for this project adheres to the client-server architecture, a popular paradigm for web-based application design. In this design, the server processes requests, and provides data and resources to the client, while the client is in charge of handling user interactions and displaying information. A high-level overview of the different components in this architecture is as following (Figure 3.1):

1) Client: The client, which is commonly a web browser, renders HTML, CSS, and JavaScript to produce the application's user interface. The client communicates with the server

by sending requests, and the server responds with information that the client uses to modify the user interface (UI).

2) Web server: The web server is in charge of taking client requests and responding to them. Additionally, it provides access to static files like JavaScript, HTML, and CSS and may help manage user authentication.

3) Application Logic: This component manages the application's business logic, responding to client requests, and communicating with the database to retrieve or modify data as necessary. It might also make APIs available for use by other clients.

4) Database: The database provides a mechanism for the application logic to retrieve and modify the data that is stored by the application. Depending on the requirements of the application, it might be a relational database, a document-based database, or another kind of data store.

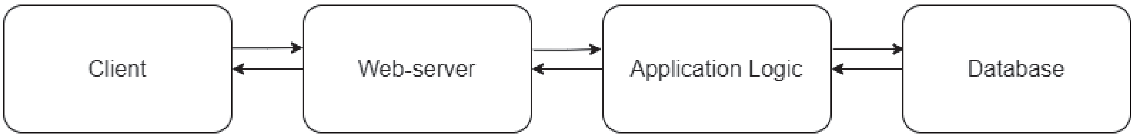

Figure 3.1 High-level scheme of Web-based software architecture

Before starting the actual development of the system, it is necessary to analyse the theoretical basis according to the requirements on which the solution will be built. Therefore, this chapter provides a theoretical background for further practical application. Despite the fact that, according to the description of the “MaltFungiProtein” project, the project participants chose a centralised database for the system, this research work should investigate the advantages and disadvantages of different options to ensure that a centralised database is sufficient and can meet all the requirements of the system, even though most existing solutions are based on a decentralised database.

3.1 Database Analysis

A database is a structured collection of data that is stored and organized in a way that allows efficient storing, retrieving and manipulation of different amount of data. A database typically consists of one or more tables or files that are organized in a logical and hierarchical manner. A conceptual representation of the data in the database is a data model, which defines the database structure. A data model typically includes entities, relationships between those entities, attributes, and constraints. Entities represent objects or concepts such as supplier, manufacturing process, product etc. To add the characteristics to an entity, such as process start time, supplier name, or product’s colour, attributes are used.

The relationships describe how one entity related to other, for instance, supplier sends the product to a customer. There are three relationships: one-to-one, one-to-many and many-to-many. A one-to-one relationship is when one record in a table is related to only one record in another table. For example, a person can have only one passport and a passport can only belong to one person. A one-to-many relationship is when one record in a table is related to one or many records in another table, but a record in the second table can only be related to one record in the first table. For example, a customer can place many orders, but each order can only be associated with one customer. A many-to-many relationship is when many records in a table are related to many records in another table. For example, a student can take many courses, and each course can have many students. This relationship requires a third table, called a junction or associative table, to track the associations between the two tables. To ensure data integrity, some rules or constraints are used, for instance, one supplier can have a lot of products, but each product could be produced only in one exact place (Coronel & Morris, 2016). Additionally, there are several extra relationships such as one-to-zero. For example, consider a table of employees and a table of employee equipment. Each employee can have zero or one equipment assigned to them, but each equipment can only be assigned to one employee. In this case, the relationship between the two tables is a one-to-zero relationship. If an employee does not have any equipment assigned to them, there will be no record in the employee equipment table related to that employee.

There are several types of data models such as hierarchical model, network model, relational model, and object-oriented model (Powell, 2006). In the hierarchical model, data are organized in a tree-like structure with a single root, where each record has a single parent and can have many children. This model is useful for data representation when the natural hierarchical structure is needed, but it is inflexible and become difficult to maintain when some changes are made. Network model is more complex graph-like structure, which allows multiple parent-child relationships between records and is useful to represent many-to-many relationships but is difficult to maintain and navigate. Today, the most common data model is relational, which organizes data into tables with rows as records and columns as attributes. This model is flexible, vertically scalable, and easy to maintain, but it is neither sufficient for modern big data approaches nor horizontally scalable. Another data model is object-oriented, which stores data in objects that are created from classes and contain both attributes (data) and methods (behaviour). This model is useful for complex real-world systems, structures, and inheritances, but could be difficult to implement and maintain (Powell, 2006, Coronel & Morris, 2016).

Experts divide databases into centralised and distributed ones, depending on the approach to data storage and access. With centralised database, there is an opportunity to keep data in one place, usually on a single server or mainframe. This indicates that there is a single point of control and that a single team or entity handles all data operations. Small to medium-sized businesses or applications that do not need a lot of performance or scalability frequently employ centralised databases (Iacob & Moise, 2015).

On the other hand, distributed databases disperse data across various locations, such as multiple servers, data centres, or even geographic regions, which enables them to handle large amounts of data and high traffic, resulting in better horizontal scalability and performance. Moreover, distributed databases offer enhanced fault tolerance and redundancy, as data is replicated across several servers, ensuring that it is always available, even if one of the servers fails. However, it may be more complicated to manage a distributed database than a centralised database. To ensure that data is distributed uniformly and consistently across all nodes, distributed databases frequently require more complex data partitioning and replication procedures. Also, to guarantee that data is secure across numerous locations, distributed databases frequently need more strong security and access control techniques. Overall, the choice between a centralised and distributed database depends on the specific needs of an organization, including factors such as scalability, performance, fault tolerance, and manageability (Valduriez et al., 2021, GeeksforGeeks, 2022).

An important element of working with databases is database design, which involves creating a database structure that will be used in the future. The phases of database design typically involve the following steps (Batini et al., 1986, Dey et al., 1999, Hegazi, 2014):

1) Requirements gathering: To create effective and efficient database it is important to understand the needs and requirements of the project as well the purpose of the database. At this step, specialist should define data needs to be stored, the relationships between different data types, and how the data will be used.

2) Conceptual design: Based on the requirements gathered, the specialist creates a high-level conceptual model of the database. This model describes the main entities and their relationships.

3) Logical design: This phase involves translating the conceptual model into a logical model that can be implemented in a database management system. The logical design involves creating tables, columns, keys, and constraints.

4) Physical design: In this phase, the logical model is transformed into a physical design that can be implemented in a specific database management system. The designer specifies data types, file organizations, indexes, and other implementation details.

5) Implementation: The physical design is implemented in a database management system, and the data is loaded into the database.

6) Testing and maintenance: The database is tested to ensure that it meets the requirements of the users and stakeholders. Maintenance involves updating the database as needed to reflect changes in the organization or data requirements.

As part of the present research endeavour, a comprehensive analysis will be undertaken in the next subsections to explore the merits and limitations of two distinct types of databases: centralised and distributed. This is due to the need for a deeper understanding of the unique features and functional characteristics of these databases in order to assess their potential applicability in the context of the research problem at hand. Through a thorough examination of the advantages and disadvantages of each type of database, the information provided in the following subsections aims to shed light on the most appropriate database architecture for the specific requirements and constraints of the current research project.

3.1.1 Advantages and Limitations of Centralised Databases

As was mentioned above, centralised database is a database which stores all data in a single location (Figure 3.2). Therefore, database management system (DBMS) used for this type is designed to store, manage, manipulate and retrieve data on a single server and provides a variety of tools and interfaces for managing database. It makes easier to maintain, manage, secure and control data access.

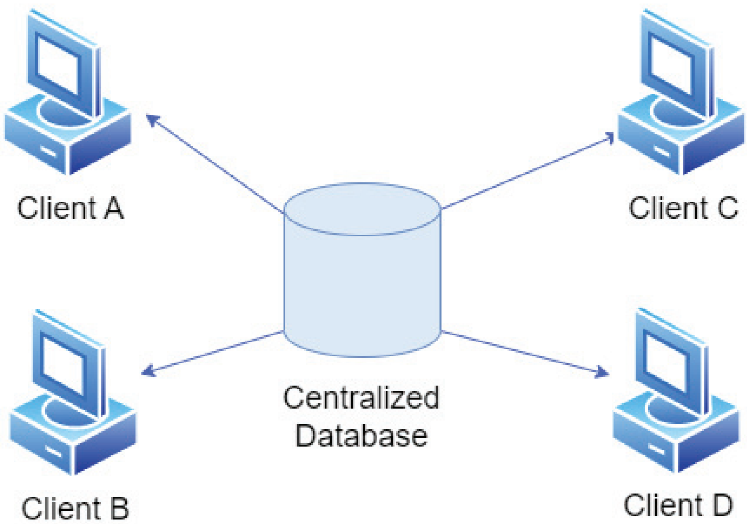

Figure 3. 2 Centralised Database

Nowadays, widely used centralised database are relational (SQL) and non-relational (NoSQL). Nevertheless, these both SQL and NoSQL can be used also in distributed databases. The name SQL comes from Structured Query Language which is used in relational databases to work with the data. As was already mentioned, in relational database data is organized in the tables which consist of column and rows. As each row in relational database should be uniquely identified, there is necessarily a column which should contain a unique value for each row (Stepantsov, 2018).

The relational model is characterised by four widely recognised properties known as the ACID properties. These properties include atomicity (A), which ensures that a data operation entirely either succeeds or fails; consistency (C), which requires that the value of the data is preserved before and after an operation; isolation (I), which mandates that concurrent users accessing data from the database at the same time remain isolated from each other; and durability (D), which guarantees that once an operation is complete and the data is committed, the changes made to the data remain permanent (DBMS | Types of Databases - Javatpoint, n.d., Khan et al., 2022).

SQL comprises several subsets, including Data Manipulation Language (DML), which facilitates retrieving and modifying data in a table using statements such as SELECT, INSERT, UPDATE, DELETE, and more. Data Definition Language (DDL) is another subset and it enables defining and altering data structures using statements such as CREATE, ALTER, and DROP. Third SQL subset is Data Control Language (DCL), which enables setting access rights in a database using statements such as GRANT and REVOKE (Chapple, 2020, Mohammed & Saleh, 2017).

Some examples of DBMSs used for centralised relational databases include MySQL, PostgreSQL, Oracle Database, Microsoft SQL Server. These DBMSs are designed specifically for managing data on a single server or mainframe, and offer a variety of features and tools for managing data, such as transaction management, data backup and recovery, and security controls.

SQL databases have both advantages and disadvantages. The advantages include wide support and large community of developers, which means that there are many resources and tools available to help with development and maintenance. Among other is that SQL databases are based on the ACID model, which ensures data consistency and integrity, that means that the data is reliable and can be trusted. They are highly vertically scalable and can handle large amounts of data, which makes them suitable for enterprise-level applications. SQL databases contain built-in security features such as authentication, authorization, and encryption to protect the data from unauthorized access and breaches. In contrast to the advantages, the disadvantages include limited flexibility, because of highly structured design of SQL databases, and changes to the structure require altering the database schema. This can make it difficult to adapt to changing requirements and may require significant development effort. Another flaw is that setting up and maintaining SQL databases can be complex and require skilled database administrators as well as processing of large datasets, complex queries require careful optimization and indexing to ensure good performance (Oracle Cloud Infrastructure (OCI), 2021).

On the other hand, NoSQL (Not Only SQL) is a type of database that stores data in various formats, not just in the form of table like relational databases, but using a flexible data model. NoSQL was developed to meet the demand for modern applications which need to process large amount of data and in different formats. Therefore, NoSQL databases are used for processing massive data and unlike the SQL, it is horizontally scalable (Khan et al., 2022).

There are four types of NoSQL databases (DBMS | Types of Databases - Javatpoint, n.d.):

1) Key-value storage: stores each item as a key-value pair.

2) Document-oriented database: stores data in a JSON-like format, making it easier for developers to work with.

3) Graph database: stores data in a graph-like structure and is often used by social networking sites.

4) Wide-column stores: stores data in large columns instead of rows, similar to relational databases.

NoSQL DBMS (Database Management System) refers to the software that manages and operates NoSQL databases. There are several popular NoSQL DBMS, such as MongoDB, Cassandra, and Couchbase. These systems are designed to handle the unique characteristics of NoSQL databases, such as horizontal scalability, flexible data models, and distributed data management.

Among advantages of the NoSQL databases are their scalability across many servers (which makes possible to also create and manage distributed database) and ability to handle large amount of data and high levels of traffic; as they are schema-free databases, they become more flexible than relational databases, because they can store wide range of data types and structures; require less administration and maintenance and can be less expensive than traditional databases. However, there are also disadvantages such as lack of ACID compliance: Unlike traditional relational databases, NoSQL databases do not always guarantee the ACID (Atomicity, Consistency, Isolation, Durability) properties, making them less suitable for applications that require strong consistency and transaction support. Another weak point is limited query capabilities which makes it difficult or completely impossible to support complex relational queries that are common in traditional databases. NoSQL databases are still a relatively new technology, and as such, they may have a smaller community and fewer tools available than traditional databases (Akhtar, 2023).

According to analysis of the literature regarding the centralised databases which currently used worldwide, including the investigation of relational and non-relational databases, pros and cons of centralised databases in general were summarized. One of the main benefits of a centralised database is its simplicity and ease of management. Because all the data is stored in a single location, it is easier to ensure that the data is secure and up to date, and there is no need to synchronise data across multiple servers. In addition, a centralised database is often easier to scale up or down, as the DBMS can be upgraded or downgraded as needed to accommodate changes in data volume or traffic. Among other advantages, specialists also emphasise: data integrity, data security, data portability and cheaper costs in installation and maintenance. Data integrity refers to unification of data as it stored in single computer system, so it makes it easier not only to communicate and manage data but also get more meaningful and reliable one (Akhtar, 2022).

However, a centralised database has some disadvantages such as vulnerability to data loss or corruption if the single server fails or is compromised. In addition, a centralised database may not be able to handle large volumes of data or high traffic levels as efficiently as a distributed database, which can distribute data across multiple servers for better scalability and performance. A high number of connected users trying to access data from a centralised database may slow down the speed of response and reduce the efficiency (Akhtar, 2022).

3.1.2 Advantages and Limitations of Decentralised Databases

A distributed database is defined as collection of multiple, logically interconnected databases distributed over a computer network (Figure 3.3). From this definition comes that distributed DBMS should allow the management of the distributed database and make this distribution transparent to the users (Özsu & Valduriez, 2011).

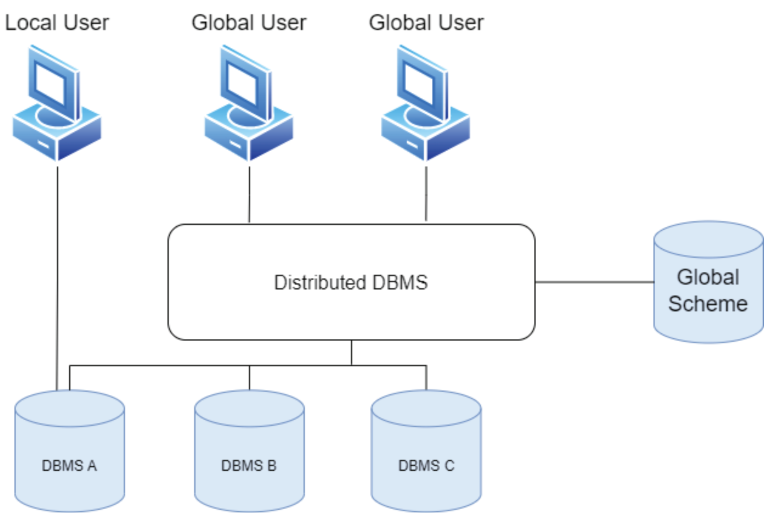

Figure 3. 3 Decentralised Database

According to Valduriez et al. 2021 there are two types of distributed database systems: geo-distributed and single location. Geo-distributed systems consist of sites interconnected by wide area networks, while single location systems consist of nodes located in close proximity, allowing for faster exchanges. Single location systems are commonly known as parallel database systems and are characterized by computer clusters in one data centre. Distributed database systems made up of multiple single site clusters connected by wide area networks are referred to as hybrid, multisite systems.

Distributed database systems are attractive for accommodating increasing database sizes and bigger workloads. Expansion can be handled by adding processing and storage power to the network. This can result in significant improvements in performance and availability. Distributed database systems have gained much interest in scale-out architectures in the context of cluster and cloud computing. Scale-out involves adding more servers in a loosely coupled fashion to scale almost infinitely, while scale-up involves adding more power to a server and is limited by the maximum size of the server.

In the context of the cloud, distributed database systems need to support elasticity, which requires dynamically provisioning or deprovisioning servers to adapt to workload changes and process higher or lower transaction rates. Live data migration, such as moving or replicating a data partition from an overloaded server to another while the system is running transactions, is also required to support elasticity (Valduriez et al., 2021).

Since ACID (Atomicity, Consistency, Isolation, Durability) qualities are often connected to relational databases, they can become a barrier for distributed systems that need great scalability and availability. On the other hand, BASE (Basically Available, Soft state, Eventually consistent) consistent is a set of principles for designing distributed systems that prioritize availability and partition tolerance over strong consistency. "Basically Available" concept states that the system should always be usable, even if it does not always provide strong consistency guarantees. This means that the system must be built to gracefully accept network partitions and outages, and to offer a reduced level of service as needed. "Soft state" concept claims that a system's state can vary over time even in the absence of input. This contrasts with conventional ACID systems, where the system state is constant and predictable. A distributed system may have delays in propagating modifications to all nodes, which can cause data to become temporarily inconsistent. But eventually, the system should converge to consistency over time. Finally, "Eventually consistent" – is a BASE's concept which states that even if there are brief inconsistencies along the way, the system should ultimately achieve a consistent state. It follows that the system must be built to manage conflicting updates and offer tools for resolving them over time. (Tai et al., 2017).

NoSQL databases, which are made for distributed systems that need high scalability and availability, frequently adopt the BASE model. To spread data over numerous nodes and provide high availability and performance, NoSQL databases frequently employ techniques like fragmentation, replication, and partitioning. The BASE paradigm offers a flexible and scalable method for developing distributed systems by emphasizing availability and partition tolerance above strict consistency.

Nevertheless, a distributed database development has its limitations, namely CAP theorem. The CAP theorem, commonly referred to as Brewer's theorem, is a key idea in distributed computing that has a big impact on how distributed databases are created and run. Consistency, availability, and partition tolerance are three qualities that cannot be offered by a distributed system at the same time, according to the theorem.

Consistency is the condition that each node in the system always has access to the same set of data. In order for a system to be available, it must always be reachable and able to respond to client requests—regardless of node failures or network breaks. When a network splits, the system must still function and updates to the data must ultimately reach all nodes. This is referred to as partition tolerance (Gilbert & Lynch, 2012, Muñoz-Escoí et al., 2019).

Exactly because it emphasizes the trade-offs that must be made while creating and managing distributed systems, the CAP theorem is a restriction of distributed databases. For instance, the system might neglect partition tolerance if consistency and availability are given top priority. On the other hand, if availability and partition tolerance are given top priority, robust consistency guarantees may be chosen to avoid. Because the trade-offs must be carefully balanced based on the unique requirements of every application, this trade-off is an important challenge for distributed database designers and operators. To guarantee that users can always access their feeds and publish changes, even in the event of brief inconsistencies in the system, a social media platform, for instance, may emphasize availability above consistency. On the contrary, a financial application can put consistency over availability to guarantee that all nodes have a correct understanding of financial transactions, even in the event of node failures or network breaks (Gilbert & Lynch, 2012).

There are several types of distributed databases, including (Tutorialspoint, n.d.):

a) Replicated databases: This type allows each node to read from and write to its local copy of the data, which is replicated across a number of the system's nodes. Replication is frequently used to increase fault tolerance and data availability.

b) Partitioned databases: A number of nodes are used to deliver the partitioned data. A certain subset of the data is stored and processed by each node. Scalability and performance are frequently improved through partitioning.

c) Federated databases: This kind connects various separate databases and treats them as a single logical database. Although they can be viewed and queried as if they were one database, each database has its own data and schema.

d) Shared-nothing databases: With this type, there is no shared memory or disk between nodes; instead, each node has separate hardware and storage. The shared-nothing architecture is a distributed architecture used in SQL database systems. In this architecture, server nodes do not share either memory or disk and have their own copy of the operating system. This architecture is cost-effective as servers can be off-the-shelf components connected by a low-latency network such as Infiniband or Myrinet. Shared-nothing provides excellent scalability through scale-out, unlike shared-memory and shared-disk architectures (Valduriez et al. 2021).

e) Distributed file systems: In this type, files are stored across multiple nodes in a distributed fashion. Large files and information are frequently stored in this way in big data applications because it improves scalability and fault tolerance.

In general, distributed databases as well as centralised can be classified into two categories: NoSQL and distributed SQL (Custer, 2022). SQL (relational) database systems as was described above use data independence to enable high-level manipulation of data through queries expressed in SQL. SQL databases come in two main variants: operational and analytical, which have different architectures and workloads. Operational databases use a shared-disk architecture and are designed for OLTP workloads, while analytical databases use a shared-nothing architecture and are designed for data warehouses and OLAP workloads. Shared-nothing architecture provides excellent scalability through scale-out, but requires careful partitioning and fault-tolerance management. NoSQL database systems typically use a scale-out approach in a shared-nothing cluster to provide scalability and rely on replication and failover for high availability. The architecture of key-value database systems is client-server and supports the master-worker model for executing parallel tasks (Valduriez et al. 2021).

Distributed SQL databases are relational databases designed to scale horizontally by distributing data across multiple nodes. These databases use SQL as their query language and offer strong consistency and ACID transactions. Distributed SQL databases are best suited for applications that require complex queries, strong consistency and transaction guarantees. NoSQL databases, on the other hand, are non-relational databases designed to scale horizontally by sharing data across multiple nodes. These databases mostly do not use SQL as their query language and offer weaker consistency guarantees than distributed SQL databases. NoSQL databases are best suited for applications that require high scalability, high availability and eventual consistency (M. Özsu, n.d.).

In addition, we can include a Blockchain in the category of distributed databases. Actually, Blockchain is not decentralised database, but according to the investigation in Chapter 2, we can conclude that in principal both distributed database and Blockchain work in the same way. Unlike distributed SQL and NoSQL databases, blockchain does not support traditional query and transaction operations. Instead, it is designed to promote trust and transparency in a decentralised system where multiple parties can participate in a transaction without the need for a trusted intermediary (Crosby et al., 2016). In summary, while distributed SQL and NoSQL databases are designed to provide high scalability and strong consistency, blockchain is designed to provide trust and transparency in a decentralised system.

The choice between centralised and distributed databases for the project is not a trivial one, given all the advantages and disadvantages of both approaches. For current project a centralised database approach was chosen with using MySQL database management system.

3.2 A Comprehensive Examination of Access Control Approaches

Access control is a security mechanism used to regulate access to resources such as systems, applications, files or data based on predefined policies or rules. According to the objective and tasks of this work, it is important to consider the need for access control based on some characteristics, such as the role of the actor in the supply chain, the devices used to retrieve data from the database, etc.

There are several existing approaches for access control, which can be broadly categorized into three main types: Discretionary Access Control (DAC), Mandatory Access Control (MAC), Role-Based Access Control (RBAC). Additionally, specialists distinguish a new more flexible approach called Attribute-Based Access Control (ABAC).

Discretionary Access Control (DAC):

In DAC, each system resource has its own owner and an access to resources is controlled by this owner. The owner of the resource is responsible for defining the access policies and granting or revoking access to other users (Figure 3.4). Advantages of this type are that it is easy to operate the permissions because the user interface is mostly simple (SecurePass, n.d.). This system allows users with certain level of access to grant such access to others as well. However, DAC system provides less security for data as access can be given from one person to another. Therefore, DAC is not suitable for enforcing security policies in a large organization because it lacks centralised control, but it can be used in small businesses and organizations where is no need in high-level security system (Techopedia, 2022).

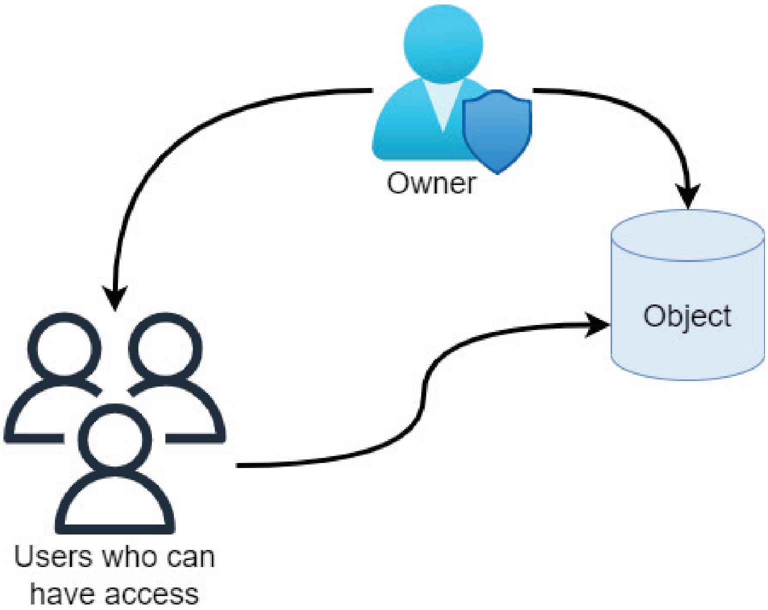

Figure 3. 4 Discretionary Access Control (DAC)

Mandatory Access Control (MAC):

In MAC, access to resources is controlled by a central authority based on a set of predefined security policies such as level of sensitivity, for example (Figure 3.5). These policies are typically defined by system administrators or security officers and are enforced centralised by the operating system or security software. In fact, users categorized here into various security levels, and each object in the system is labelled with relevant security label. Users are allowed to access resources with security labels at or below their own security level. This type is more flexible and secure than DAC and suitable for enforcing security policies in a large organization, but it can be complex to configure and manage (*IBM Documentation*, n.d.).

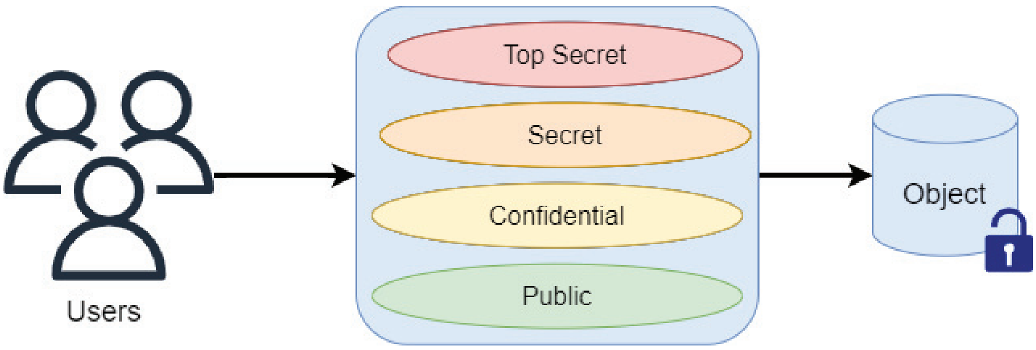

Figure 3. 5 Mandatory Access Control (MAC)

Role-Based Access Control (RBAC):

This model grant and restrict access to system resources based on the role of the user assigned to it within an organization. RBAC based on five different entities: objects, actions, permissions, roles, and users (Figure 3.6). Objects represent system resources, such as files, directories, or devices. Actions are the operations that can be performed on objects, such as read, write, execute, or delete. Permissions, which stand for the access permissions given to users, are a combination of an object and an action. A permission might read "edit document X" or "view directory Y," for instance. Roles are containers that make the cluster of related permissions assigned to user. Each role is defined based on the user's job function, and access policies are associated with each role. By allowing administrators to grant permissions to a role rather than to each individual user, roles make access control management simpler. One possibility is to give all users with managerial positions access to a role named "managers," which would grant rights for all managerial responsibilities (Aftab et al., 2019). This approach simplifies access control management by assigning roles to users instead of managing access policies for individual users. RBAC is widely used in large organizations and is considered an effective approach for enforcing security policies (Aftab et al., 2022).

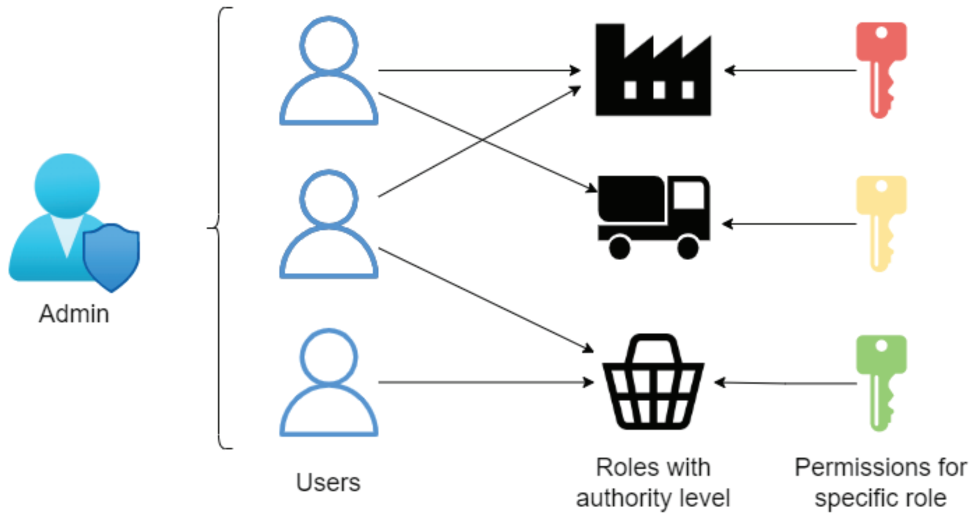

Figure 3. 6 Role-Based Access Control (RBAC)

Attribute-Based Access Control (ABAC):

ABAC focuses on defining access control policies based on a combination of attributes of user, resource or environment. For example, it is possible to grant with permission only employees who are in a certain department and have a certain security clearance to access a particular resource (Figure 3.7). Examples of attributes could be This approach allows access control policies to be more flexible and dynamic, which can be useful in complex environments where access control requirements may change frequently. ABAC is suitable for complex environments and dynamic access control requirements. Nowadays there is common approach to combine RBAC and ABAC systems to develop more efficient software (Kuhn et al., 2010, Aftab et al., 2022).

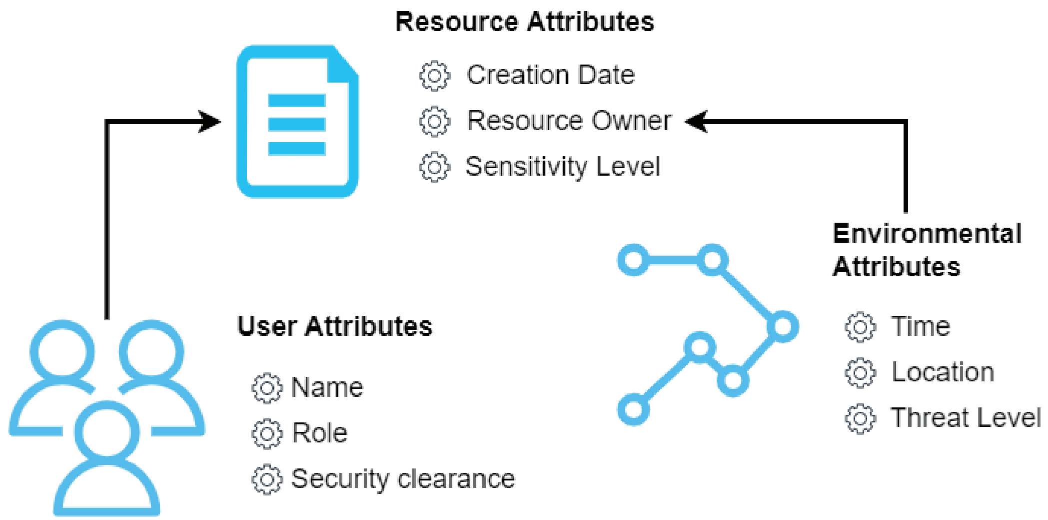

Figure 3. 7 Attribute-Based Access Control (ABAC)

In the context of the current project, which involves the development of a prototype system, a sophisticated approach has been adopted for access control. Specifically, it has been determined that users will be granted permission to access specific subsets of data based on their position in the supply chain and their relationship to the particular data in question. This approach ensures that access to confidential information is limited to only those users who have a legitimate need for it, thereby enhancing the overall security and integrity of the system.

3.3 Levels of the information access

As previously clarified, the supply chain is comprised of a variety of actors operating on distinct levels of upstream and downstream relationships. Each level necessitates the exchange of specific information throughout the supply chain. The Supply Chain Reference Data Model Business Requirement Specification (SCRDM-BRS) paper (UN/CEFACT Bureau, 2017) identifies four presently applicable categories of information, namely commercial, logistical, regulatory, and financial. Moreover, within the same document, four actors are identified in the supply chain: Supplier, Customer, Intermediary (which may act as the Transportation Company or Bank), and Authority. Commercial information exists in the "Supplier-Client" plane of interaction and encompasses data regarding product characteristics and parameters, sales order confirmation, delivery scheduling, and sales invoicing. On the other hand, logistical information is shared between Intermediary, Supplier, and Customer (in this case Carrier, Consignor, and Consignee, respectively), which may include issuing shipping instructions, transport contract documentation, transportation of goods, and freight invoices. Regulatory data is necessary for the Authority and the remaining members of the supply chain, who, in a regulatory context, could be deemed as the Carrier, Exporter, and Importer. Regulatory information could include reporting to the appropriate regulatory body, such as import/export declaration, certificates of origin, and cargo and transit reports, among others. Finally, financial information, such as documentary credit procedures or cargo insurance is transmitted by the Intermediary (Bank) to the Customer (Payer) and the Supplier (Payee).

For the prototype within current work, using Commercial, Logistical data was considered to be the most appropriate. The concept of a transparent supply chain does not imply unlimited visibility of all data by every member of the chain, as this would raise concerns over privacy and personal data security (Sarfaraz et al., 2022). Thus, the present work advocates for the implementation of various levels of control to address these concerns. First and foremost, the proposal recommends the regulation of the ability to write, edit, and amend information based on the role of the interacting subject. This implies that each actor (i.e., company) would have its own sales contracts, storage or transportation information, and other data within its competence. The access to such information could be restricted either by the company itself or rendered inaccessible to external parties.

Another aspect related to access control is connected with a product information, which is tokenized to maintain confidentiality. It is crucial to note that specific product parameters may contain sensitive information, and therefore, access to such data could be governed by the actor who created the token. In this case, the relevant actor would regulate the "reading" of information and make it impossible to "edit" information about the tokenized product.

3.4 Methods for Unique Token Values development

In context of current implementation of so-called “token” approach taken from Blockchain technology, author states that creating a unique value for this “token” is one of essential and initial tasks in this research work. Unique values are used to distinguish between individual entities or objects and are crucial for accurate data representation and manipulation.

In the pursuit of generating unique values for various software solutions, normally GUIDs (Globally Unique Identifiers) is used, the unique 128-bit numbers that can be generated by software applications. While they provide globally unique identifiers, their size renders them impractical for use as booking or reference numbers. Therefore, the use of GUIDs depends on the specific requirements of the application and the trade-offs between uniqueness, size, and simplicity (guid.one, n.d.). Therefore, author decided to investigate other possible ways to generate unique values for ‘tokens’ and implement the most suitable and simpler solution that would provide both uniqueness and practicality.

One such solution is to create sequential IDs of appropriate size, but this presents a significant security threat to websites. With sequential reference numbers, it is possible to employ brute force methods to retrieve records and sensitive information (Al-Amin, 2006). Therefore, it is crucial to consider alternative approaches for generating unique IDs that do not compromise security. Another possible way to generate unique IDs is to use a combination of timestamp, counter (if available), system value (such as IP address or machine ID), and a random integer. This approach is often used by large companies in distributed systems as it ensures that the generated IDs are independent and the chances of collisions are very low. While there may be some degree of collisions in this method, it can still be effective if some degree of collisions can be tolerated (Brzóska, n.d.). The most common ways to generate unique values are as following: sequential numbering, random generation and hashing.

Sequential numbering. Looking at it in the context of databases, this is the easiest way to create a unique key. This involves assigning unique numbers or identifiers to each entity in a sequence. As was mentioned above, this method is simple to implement, but is not secure and, additionally, it may not be appropriate for scenarios where multiple users or systems are creating entities simultaneously.

Random generation. Random generation involves generating unique values using a random number generator. This method is highly unpredictable and can generate a vast number of unique values, but it may not be suitable for scenarios where sequential numbering is required. There are several methods of generating random numbers, including:

Pseudo-Random Number Generators (PRNGs). PRNGs are algorithms that generate a sequence of numbers that appear to be random, but are actually determined by a starting value called a seed. The sequence produced by a PRNG is not truly random, but is often sufficient for many applications. There several methods used within this type of generators such as Middle-Square Method which involves squaring a starting number of n digits, taking the middle n digits of the result as the next "random" number, and repeating the process. The method can quickly generate a sequence of pseudo-random numbers, but the quality of the randomness depends heavily on the choice of the starting number. In practice, the method is not used extensively due to its simplicity and limitations in terms of randomness and statistical properties (Łukasiewicz, 2021). Another method is Linear Congruential Generator (LCG), which is a widely used and it involves using a recursive formula to generate each number in a sequence, where each number depends on the previous number in the sequence. The formula takes the form (3.1):

$$\mathrm{Xn} + 1 = (\mathrm{a} \cdot \mathrm{Xn} + \mathrm{c}) \bmod \mathrm{m} \qquad (3.1)$$

where “Xn” is the previous number in the sequence, “a”, “c”, and “m” are constants, and “mod” denotes the modulo operation. The quality of the created sequence's randomness and statistical qualities depends on the values chosen for the constants a, c, and m. A bad selection of constants may lead to statistical anomalies or patterns in the sequence. Nonetheless, a well-built LCG can generate pseudo-random numbers that are statistically equivalent to actually random numbers. Because of their determinism and the ease of predicting the next numbers in a sequence from a few initial numbers, PRNGs, despite their ubiquity and simplicity, are not considered secure enough for cryptographic applications. On the contrary, they are often used in computer games, simulations, and other non-cryptographic applications where high-quality randomness is not required (Janke, 2002, Łukasiewicz, 2021).

Lagged Fibonacci generators (LFGs) are another subset of RRNGs that create a series of numbers by adding up earlier values in the series using modular arithmetic. By taking the modulo of the sum of the two lagged values, it creates the subsequent number in the series using a set of two or more seed values, known as lags. A series of random numbers is produced by shifting the delays each time a new number is generated and then repeating the process. The generalized formula is depicted as (3.2), where ◇ is some mathematical operator (for instance, addition, subtraction, XOR etc.), "Xn" is the random number generated, "r" and "s" are the lag parameters, and "m" is the modulus

$$\mathrm{Xn} = \left(X_{n-p} \diamond X_{n-q}\right) \bmod \mathrm{m} \leftrightarrow \mathrm{n} \geqslant \mathrm{p} > \mathrm{q} \geqslant 1 \qquad (3.2)$$

LFGs are comparatively easy to implement and have acceptable statistical characteristics, although they could show periodicity if the lags for formula are not carefully set. Compared to other linear generators, the Fibonacci Generator exhibits good quality, but at the cost of requiring significantly more computation. However, it suffers from high correlations between sequence elements, which reduces its performance. Sequences generated by this method satisfy the decomposition condition, but do not satisfy the independence condition.

True Random Number Generators (TRNGs). TRNGs generate numbers that are truly random, meaning that they are not determined by any algorithm or mathematical formula. TRNGs typically rely on physical phenomena such as atmospheric noise or radioactive decay to generate random numbers. It provides a high level of randomness and absence of predictability, but can be expensive and slower compared to other methods (Stipčević & Koç, 2014).

Cryptographically Secure Pseudo-Random Number Generators (CSPRNGs). CSPRNGs are a subclass of PRNGs that are designed to be more secure and less predictable than standard PRNGs. These algorithms use approach of PRNG but instead of simple seed this method use cryptographical representation of random number which is difficult to predict. They are often used in cryptography and other security-sensitive applications. Although this method is secure, high quality random and relatively fast, it may be vulnerable if the seeds are compromised. In addition, the randomness of the results depends on the quality of the seeds (Baldanzi et al., 2020, University of Babylon, n.d.).

Hardware Random Number Generators (HRNGs). HRNGs are physical devices that generate random numbers based on some form of physical noise, such as thermal noise, atmospheric noise or photon emissions. One of the most common types of HRNGs is based on thermal noise. In this type of HRNG, a voltage is applied to a resistor, which causes a current to flow through the resistor. The random current fluctuations caused by the thermal noise are amplified and digitized to produce random numbers (Shaw, 2020, Tkacik, 2002). HRNGs are often used in situations where true randomness is critical, such as in cryptography, scientific simulations. The disadvantages of this approach are its expensive price, slower processing and the fact that they may require additional hardware to be integrated into a system (Tkacik, 2002, Onomi & Mizugaki, 2020).

In general, the choice of which method to use depends on the specific requirements of the application, such as the level of randomness needed, the speed and efficiency of the algorithm, and the level of security required.

Hashing. Hashing functions, similar to cryptographic algorithms, are used to secure data and protect it from unauthorized access. They both involve complex mathematical operations and are designed to be difficult to reverse or decrypt without the correct keys or passwords, but their purposes differ. The difference between them is that cryptographic algorithms are designed to provide confidentiality, integrity, and authenticity of data by transforming plain text into unreadable ciphertext. Cryptographic algorithms use keys to encrypt and decrypt data, and the security of the encryption depends on the strength of the key, and the algorithm used, and the length of the key. Hashing algorithms, on the other hand, are used to verify the integrity of data by generating a fixed-size message digest, or hash value, from input data. Hashing algorithms are one-way functions, meaning that it is virtually impossible to reverse the process to recover the original data from the hash value (Farhan & Al-jabber Ali, 2017). The output value of the hashing is unique to the input value, and even minor changes to the input value will result in a completely different output value. However, sometimes different pieces of data may produce the same hash, which can result in a collision, especially when it comes to the random numbers. Using stronger hashing algorithms can reduce the probability of such collisions (Stepantsov, 2018a).

Widely used hash functions include the following: MD5, SHA-1, SHA-2 and its family, as well as SHA-3.

MD5 (Message Digest 5) is a widely-used cryptographic hash function that produces a 128-bit hash value, which is typically expressed as a 32-digit hexadecimal string. However, due to security vulnerabilities that have been discovered in recent years, it is no longer considered a secure cryptographic hash function for sensitive applications (Sagar, 2016).

Among the various SHA functions, the most secure, popular and without collisions is the SHA-2 standard, which includes three algorithms: SHA-2(256), SHA-2(384), and SHA-2(512). Respectively they produce 256-bit (32-byte), 384-bit (48-byte) and 512-bit (64-byte) message digest. These hash functions allow to determine the integrity of the message, since any change in the message is likely to result in a different message digest. The three new hash functions specified in the standard are considered secure, as it is impossible for an attacker to find a message that corresponds to a given message digest or to find two different messages that produce the same message digest. SHA-2 family hash functions differ in the length of the message digest they produce, ranging from 256 to 512 bits, depending on the algorithm used (Sklavos & Koufopavlou, 2003). This method is highly secure and is commonly used for password storage, but it can be computationally expensive, especially for large amounts of data.

3.5 Proposed Methods for The Generating of a Unique Token

Within current solution is proposed to implement combination of random number generating using several parameters for combination and using of hashing function to generate unique value for our so-called "token". There are two proposed solutions to generate unique tokens: 1. Creating a predefined list of values; 2. Combination of different parameters.

1. Predefined list.

The function of generating a unique token value involves creating a predefined list of tokens that are generated using a certain order of numbers, for example, a random number plus a specific number. To ensure uniqueness, the random number generated must be unique every time. The tokens are stored in a pre-created list and are pulled from there as needed. It can be imagined as person presses a button that generates a token using a pre-created randomiser function. The main challenge is to ensure that the generated random number is unique each time, so that each token in the list is also unique. In generalized form this method can be represented as function f(x) (3.3):

$$f(x) = (k + R(min, max)) \bmod n \quad (3.3)$$

Where *n* is the total number of tokens in the pre-created list; *R* is a function that generates a random integer between a minimum value min and a maximum value max (inclusive); *k* is a fixed integer representing a unique number for a certain supply chain; *x* is the index of the token in the list, and *mod* is the modulo operator that returns the remainder of the division. This function generates a unique token value by adding a random integer to a fixed number (k) and taking the remainder when divided by the total number of tokens (n). The randomness of the function is introduced by the *R* function that generates a random integer between *min* and *max*.

2. Combination of different parameters.

To create a unique token value, we can include various parameters such as date of token creation, vendor ID, process ID, process type, and input data, we can create a function that combines these values using mathematical operations such as multiplication, addition, or concatenation. The resulting value can then be converted to a hash value using a hashing algorithm, such as SHA-256, which creates a unique fixed-length string representing the input data.

We must consider the possibility of collisions when two different inputs produce the same hash value in order to guarantee that the generated token remains unique. Before using the hash function, we can add a timestamp or a random number to the input parameters to avoid collisions. Because of this, it will be extremely unlikely that two tokens will be generated simultaneously. This will introduce enough variation in the input values.

We can also implement a token repository that keeps track of all previously created tokens and verifies each new token against the repository to make sure it hasn't been used before. The function can generate a new token if a collision is found by changing or adding one of the input parameters, and it can keep doing this until a unique token is created. In general, by including multiple input parameters and using a hashing algorithm to convert them into a unique token value, we can create a reliable and secure method for generating unique tokens that can be used to track goods in a supply chain or other systems. Generalized mathematical formula can be expressed as (3.4):

$$\text{Token} = \text{hash}\ (f\ (\text{Supplier ID, Process ID, Process Type, Inputs, Date of Creation})) \qquad (3.4)$$

Where *Supplier ID*: unique identifier for the supplier involved in the process;

Process ID: unique identifier for the process;

Process Type: type of process;

Inputs: any relevant inputs for the process;

Date Of Creation: date the token is generated;

f is a mathematical function that can be any combination of mathematical operations, such as multiplication, addition, subtraction, etc., to create a unique number based on the input parameters.

The obtained number is then subjected to the *hash* function in order to produce a distinct token value, which is represented as a string of characters. To prevent collisions and ensure that it produces a unique value for each unique input, the hash function should be carefully chosen.

To simplify the demonstration of system testing, this paper uses a simple sequence of unique values for the token, but the approaches to generating reliable unique values discussed here may be useful for use in real-world applications.

3.6 Summary

In this section, a thorough investigation and analysis were conducted on the software component, specifically the database models, to identify the advantages and disadvantages of each type and determine the most suitable option based on the requirements outlined in the previous section. Furthermore, issues surrounding access control and unique value generation were examined to establish additional requirements for the software system's development.

In centralised databases, all data is stored and managed on a single server, but in distributed databases, data is stored and managed on a number of servers that collaborate across several locations. Centralised databases execute transactions more quickly, are safer, and are easier to build and operate. They are, however, vulnerable to single points of failure and can end up becoming a bottleneck for large-scale systems. On the other hand, distributed databases are more scalable, fault-tolerant, and cost-effective, but are more complex to design and manage, less secure, and can be slower at processing transactions. Scalability, availability, security, and cost-effectiveness are only a few of the unique needs and limitations that determine whether to use centralised or distributed databases.

Even though SC is required to be transparent and traceable, access control is important in such supply chains because it ensures that only authorized personnel have access to sensitive information, such as trade secrets or customer data. It also helps prevent unauthorized modifications to the data, ensuring the integrity of the supply chain. With access control in place, organizations can better manage their resources and reduce the risk of data breaches or other security incidents. Furthermore, access control can help demonstrate compliance with various regulations, such as data protection laws and industry standards. Since there are several types of access control, choosing which one to implement in a particular case is important to ensure effective system functionality. The factors that influence the choice depend on who owns the data, whether access should be different for different users, whether one user can perform different roles depending on the situation, etc.

Generating unique values is critical for accurate data representation and manipulation, and there are several methods to achieve this, including sequential numbering, hashing, and random generation. In addition, the author proposed two approaches to generate unique values that combine randomness, the use of a combination of certain characteristics, such as date, supplier id, product id, etc., and hashing. The choice of method will depend on the specific requirements and constraints of the context in which the unique values are needed.

4 Developing a Traceable Supply Chain System Prototype

After an extensive analysis of centralised and distributed databases in Chapter 3, their impact on the software's efficiency and functionality, and their respective pros and cons, a centralised database using MySQL DBMS was selected for further work. To meet the demands of modern supply chain technology, a "tokenized" approach inspired by Blockchain technology has been found sufficient to strike a balance between centralised and decentralised approaches, cost and efficiency, and data traceability and privacy.

The general scheme of the system architecture is shown in Figure 3.1 in the previous chapter, which is the basis for the development of the solution in this paper. The system consists of four main components: client-side which is a user interface, web server, application logic and database (Figure 4. 1).

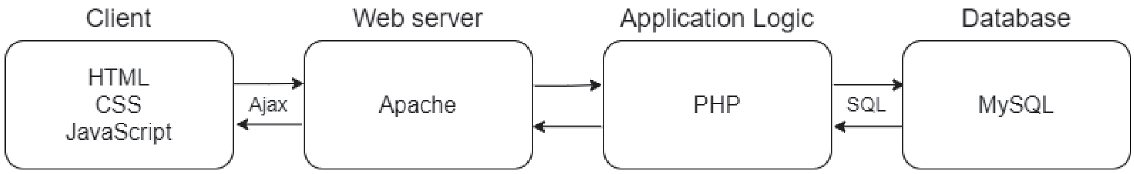

Figure 4. 1 Software architecture components of the developing system

The architecture of current system is structured into two main components: backend and frontend, and follows a client-server architecture, where the frontend is the client and the backend is the server (Figure 4. 2). The backend architecture of the software system that will be developed in this section consists of the following key components:

1) Local MySQL database server: With this component, storing and managing the data for the system is provided in local database storage. To reflect the requirements of the system, including the data entities and relationships, the database schema is designed within the main steps of database designing.

2) PHP interpreter: Responsible for handling the logic for retrieving and storing data in the database and communicating with the frontend. It provides the connection between the MySQL database and the frontend user interface, and it communicates with the database server using SQL queries.

3) Apache: Apache is an open-source web server software that is used as a component of the backend in a web application architecture. By delivering content and running application code, Apache is in charge of receiving and responding to client requests.

The key components of frontend architecture in this work are:

1) User interface (UI): This component is responsible for providing the visual interface for the system. It is written in HTML, CSS, and JavaScript and is designed to be visually appealing

and intuitive. Given the prototype form of the system being developed, the graphical interface serves as a simple and understandable visual element, but without the advanced features that are inherent in a real project like linkage between pages with main menu or real scanning of the QR-code.

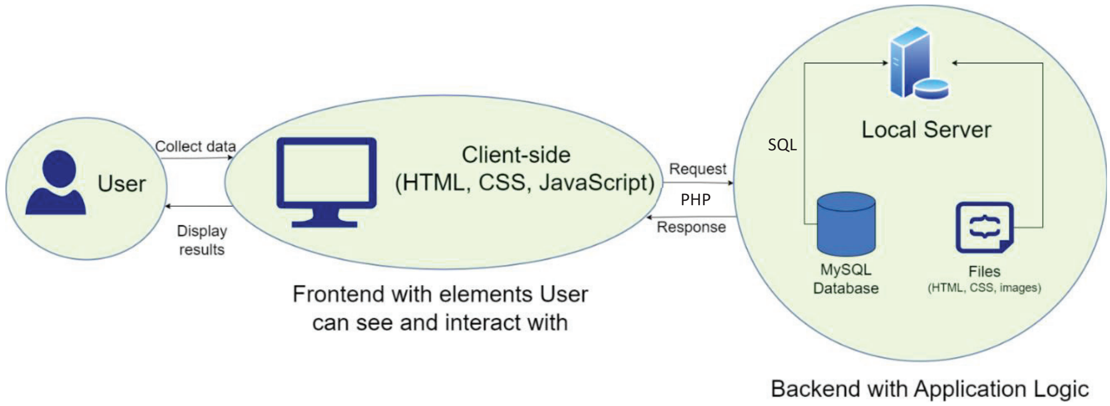

Figure 4. 2 Frontend and backend of the system

Given the analysis of the requirements for the system to be developed, as well as the architecture of this system, the main stages of work are the development of the database, creation of the user interface, connection of the interface and the database, and, if necessary, creation of advanced elements to improve user interaction with the system.

4.2 Database designing

Referring back to the requirements outlined in Chapter 2, it is important to develop a database that is capable of storing information about the supply chain actors, including their roles, the processes that take place along the chain, such as manufacturing processes, transport, storage, etc. In addition, the database should be able to store so-called unique "tokens" that provide a history of a particular product along the supply chain, as this is the intended purpose of the system being developed in this paper. As noted in Chapter 3, in the practical part of this paper, a simple sequence of numbers will be used for unique token values, which can then be easily replaced in future research or in a real-world implementation with one or a combination of the algorithms proposed in Chapter 3.

According to fundamental principles of relational database design, it is important to complete several main stages. Among such stages there are developing and refining database structure based on the requirements, including designing of conceptual, logical and physical models. A Conceptual Data Model is a structured representation of database concepts and their connections. To build entities, their qualities, and relationships, a conceptual data model must be created. There isn't much information accessible at this level of data modelling about the actual database structure.

The Logical Data Model is a representation of the structure of data elements and their relationships. It provides a more detailed view of the conceptual data model by adding specific information about the attributes, entities, and relationships. The primary goal of the Logical Data Model is to create a clear and comprehensive understanding of the data requirements of an organization or system.

This type of Data Model specifies the data types, constraints, and relationships between the entities in the system. It also ensures that the data is normalized, which means that the data is structured to eliminate redundancy and inconsistencies. For instance, if the same data is stored in multiple tables, then any changes made to the data must be updated in all the tables, which can lead to inconsistencies and errors. Overall, normalization is an important process in database design that helps to ensure data consistency, reduce data redundancy, and improve data integrity, which are essential for the efficient management of data in a database. In general, the Logical Data Model is an intermediate step between the Conceptual Data Model and the Physical Data Model and helps to bridge the gap between the requirements and the actual database design (Powell, 2006, Actian Documentation, n.d.).

The physical data model offers an in-depth look at the database structure, including details on the database design, tables, columns, keys, indexes, and constraints. The physical data model (PDM), which is unique to a single DBMS, serves as a guide for building the database itself. A comprehensive collection of metadata is also made available by the physical data model, which is helpful for designing databases. Overall, the physical data model is a critical component of the database design process. It provides a detailed view of the database structure and a blueprint for creating the database schema. It also helps to ensure that the database is optimised for a particular DBMS platform, enhancing performance and scalability (Taylor, 2023).

4.2.1 Conceptual Data Model Design

Before creating the Conceptual Data Model itself, a general scheme (Figure 4. 3) of future model was formed, which identified the main elements (entities) around which the future solution should be built.

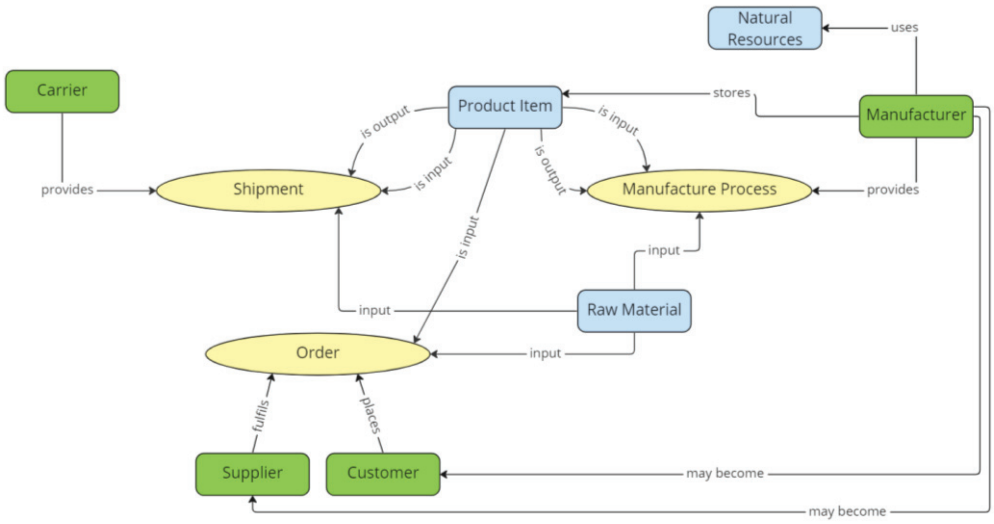

Figure 4. 3 General scheme of the future Conceptual Model

To develop a robust and efficient traceable supply chain system, it is essential to establish a well-defined work backbone that can be extended and complemented with further necessary entities. Although the current system is a prototype, it is crucial to take into account as many supply chain activities as possible to make sure the prototype's correctness is as close to reality as feasible. As a result, a more effective and traceable supply chain system will be developed by expanding upon and improving the prototype in subsequent work and real projects. The main entities for the future database can be categorized into three main groups. Firstly, the processes within the supply chain such as transportation (shipment), manufacturing, ordering, or storing. These processes should be well-defined and clearly outlined to ensure that they can be accurately captured and traced within the system. Secondly, the actors involved in these processes such as suppliers, customers, manufacturers, or carriers, should also be identified and included in the database. These actors provide the necessary resources, information, and services to enable the processes to be completed. Finally, the items involved in the supply chain, such as raw materials, product items, or natural resources, should be included in the database. These items are used or produced by the actors involved in the processes and are critical to the success of the supply chain system. Therefore, model depicted on the Figure 4.1 can be reduced and simplified as it shown in Figure 4. 4.

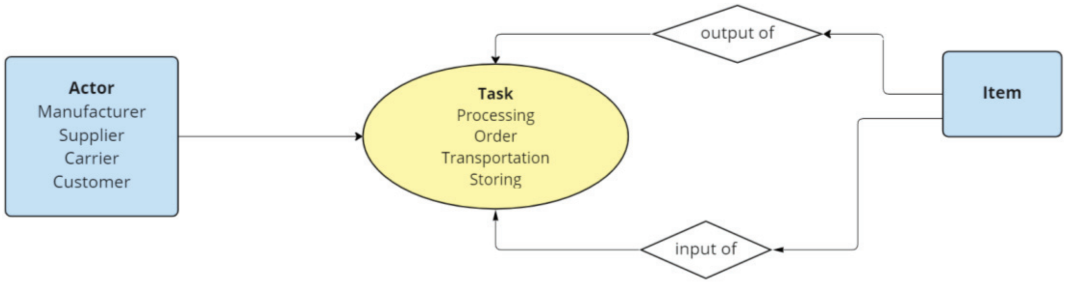

Figure 4. 4 Simplified general scheme

A generalized model indicates that we can optimize the future database by merging entities that share similar attributes. This would allow us to normalize the database already at the stage of the Conceptual Data Model design by reducing the number of the entities. To ensure the effectiveness of this approach, we need to add attributes to each proposed entity and test the hypothesis. Therefore, we first design a Conceptual Data Model for each separate process to validate its accuracy.

Manufacturing Process

Creating a database for a manufacturing process involves capturing essential information about the process itself, the manufacturer providing the process, and the inputs and outputs related to the process. The manufacturing process should have a unique identifier and its name, to distinguish it from other processes. Other essential details include the start and finish dates of the process, the manufacturer involved in the process, and the location where the process occurs. Inputs and outputs are crucial components since they are the main core of the database which need to be tracked and traced, forming the basis for monitoring all processes and information within the supply chain. Data model, designed specifically for manufacturing process is shown in Figure 4. 5.

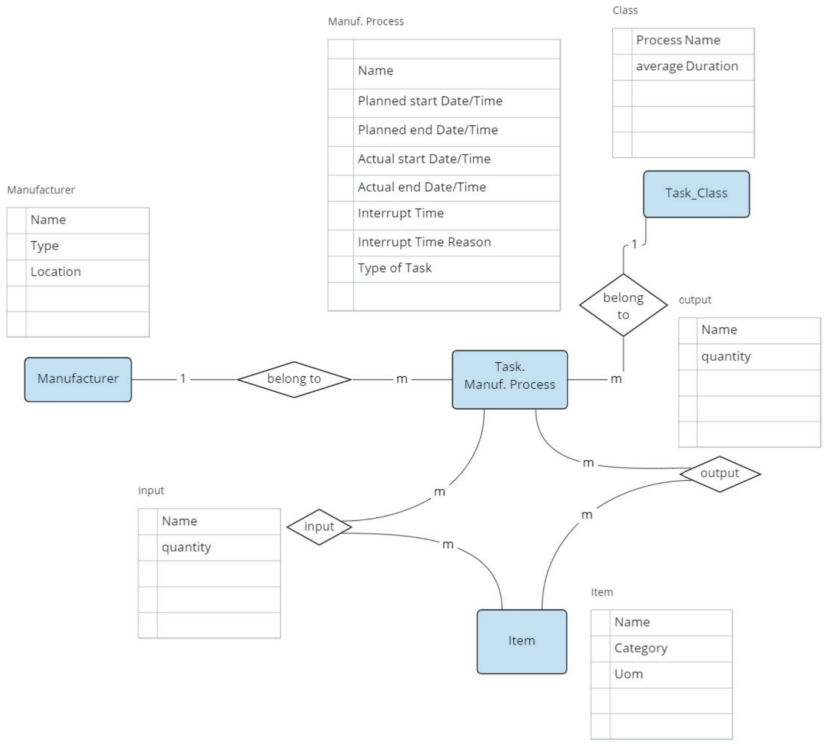

Figure 4. 5 Conceptual Model of Manufacturing process

Transportation Process

For an efficient transportation process, it's essential to gather accurate information regarding the dispatch and delivery locations, including the exact addresses and any specific requirements or instructions for each location. In addition, it's important to have complete information on the companies involved in the transportation process, including the sender, carrier, and receiver of the products. Given the complex nature of transportation processes, which can include multiple destinations, each containing a variety of products, it's necessary to design a comprehensive database for managing the supply chain. This database should include information on the products being transported, such as their type, quantity, and dimensions, as well as any special handling instructions or temperature requirements.

Furthermore, the database should be able to track the movement of products throughout the transportation process, including the date and time of departure and arrival at each location, any delays or issues encountered along the way, and the current status of each shipment. As a preliminary step, the transportation-specific conceptual data model can take the form illustrated in Figure 4. 6.

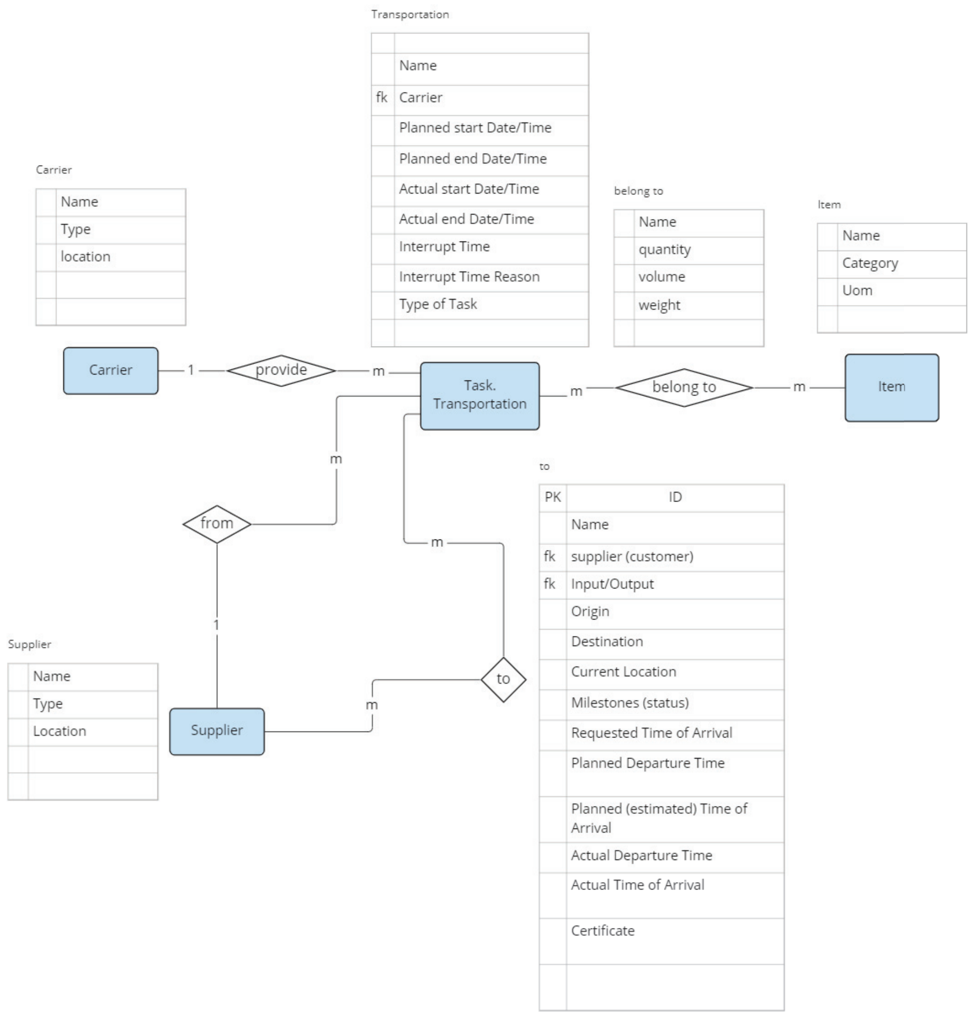

Figure 4. 6 Conceptual Model of the Transportation process

Storage Process

Just as with the previous processes reviewed, the storage process is an essential aspect of supply chain management. A comprehensive storage database should contain detailed information on the process itself, as well as the location and the company responsible for providing storage services, such as a warehouse or other storage facility. To ensure complete information about the storage process, it's essential to track the inputs and outputs of the storage location, including the products coming in and out of the facility, their quantity, condition, and any relevant details. This data can help optimize the storage process and improve overall supply chain efficiency. The resulting database should be capable of tracking and managing the movement of goods in and out of storage locations, including the date and time of arrival and departure, the status of each shipment, and any relevant information about the storage facility itself. An example of a comprehensive conceptual model for a storage database is depicted in Figure 4. 7.

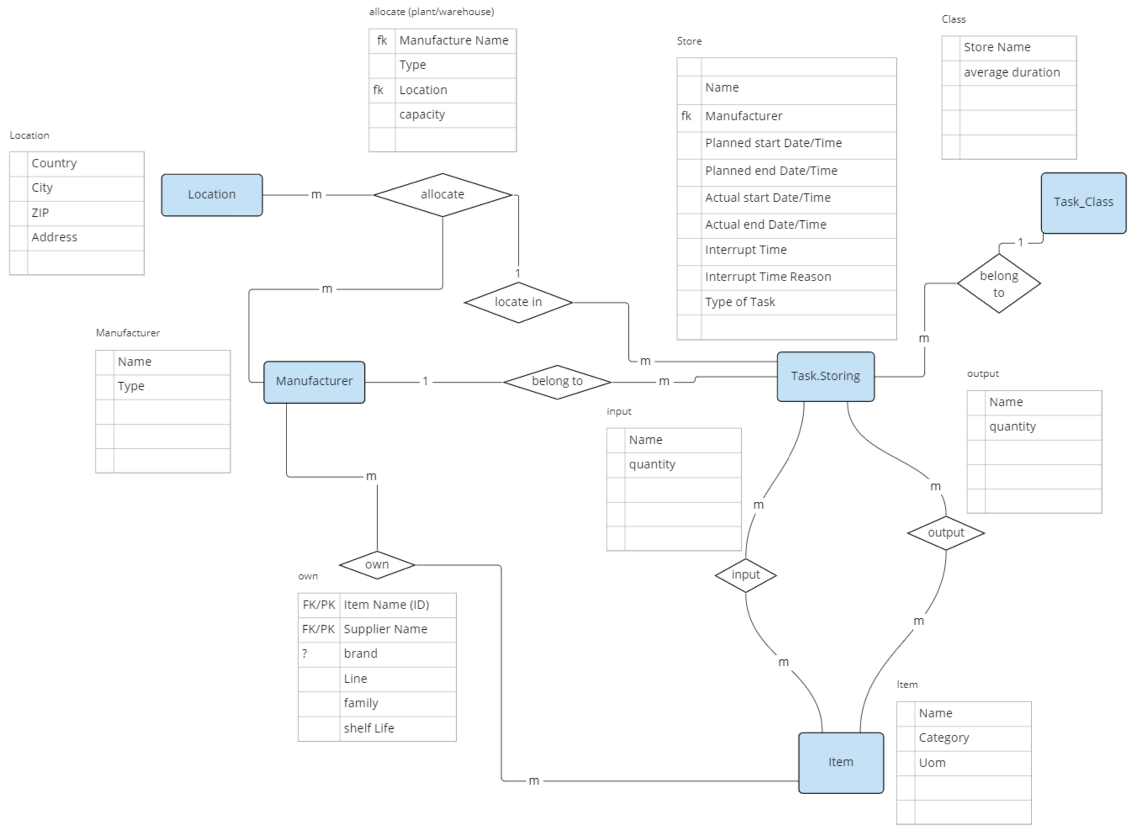

Figure 4. 7 Conceptual Model of the Storage process

Ordering process

Although the Ordering process is not a primary focus of this paper, it's of significant interest to researchers (e.g., Dani, 2015, Schmitt et al., 2017, Ivanov & Rozhkov, 2020, Framinan, 2022) and its importance cannot be overstated in a real-world supply chain traceability system. Therefore, we briefly examine and include the Ordering process in the current database system. To achieve an efficient and accurate ordering process, it's necessary to capture information on the initiator of the order (customer) as well as the supplier fulfilling the order, including their respective locations. Additionally, information on the required delivery date and other relevant details should be included. Given that orders may be split during transportation and that one transportation may include several orders, it's essential to consider this complexity in the database design.

However, as the ordering process is a complex structure and is beyond the scope of this paper, the ordering model can be reviewed and modified in subsequent stages and in particular in further real-world projects. The draft of the Order process is depicted in Figure 4. 8. This model is a starting point that can be expanded upon and customized to meet the specific needs of a particular supply chain traceability system.

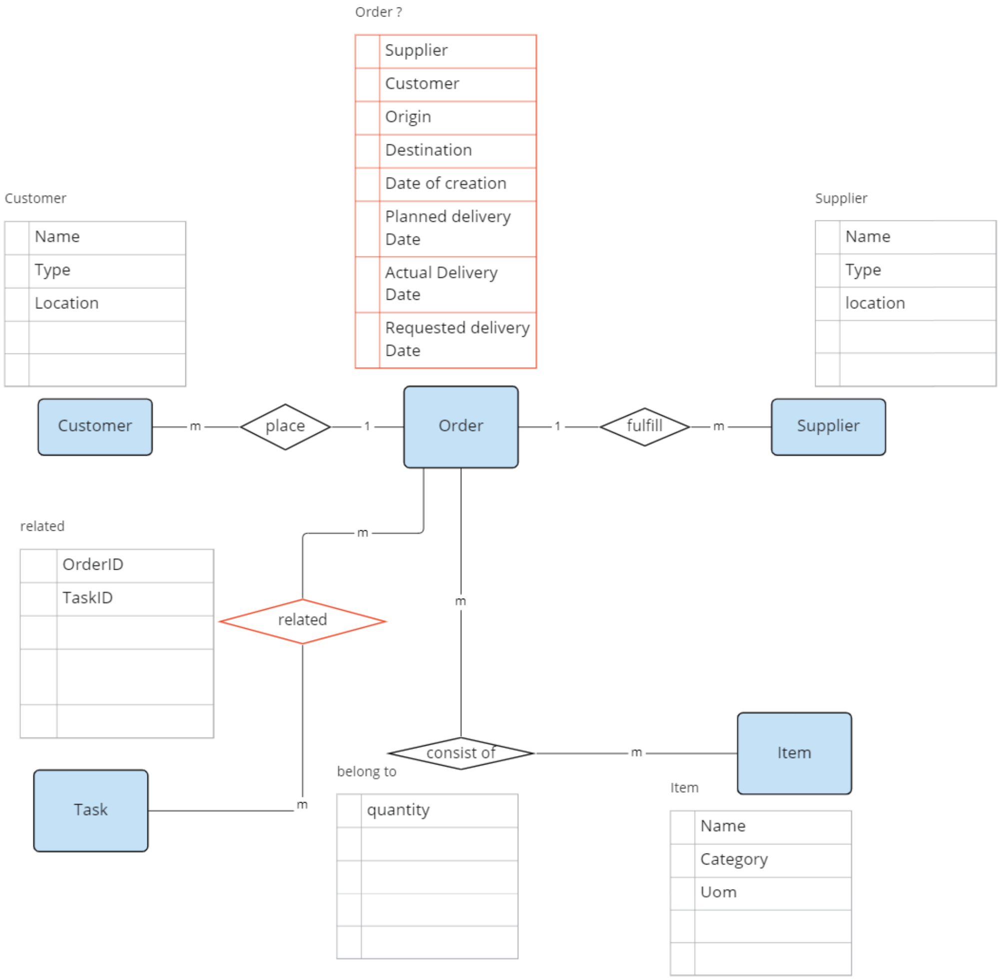

Figure 4. 8 Conceptual Model of the Ordering process

We examined each process separately and created a comprehensive conceptual model instead of multiple ones. We noticed some similarities among different models, which allowed us to combine some elements to make our future database more standardized. However, we kept Ordering separate because it's unique and can't be merged with other important processes. We grouped all the main processes together as "Task," companies as "Actor," and products as "Item." At this step we assigned for "Item" a unique hashed token, and since "Item" is a general type of product with its own parameters and specifications, different hashed tokens can be used for the same product. This will be explained in more detail in the next sections. You can see the overall General Conceptual Data Model in Figure 4. 9.

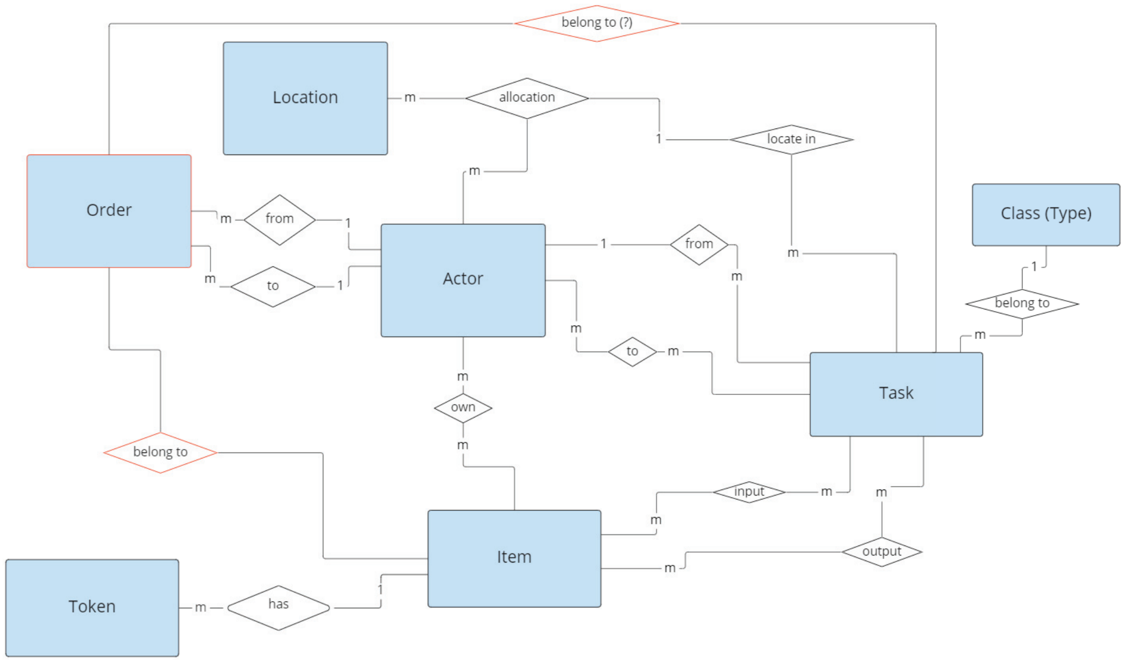

Figure 4. 9 Conceptual Data Model

A conceptual data model is an abstract representation of the data that will be kept in a database at a high level. It is a crucial component of database design since it aids in comprehending the general organization of the data and serves as a platform for creating the actual database schema. A conceptual data model is created by defining the entities (objects or concepts) that are relevant to the subject area being modelled and the relationships between these entities. The model is represented using Entity-Relationship Diagrams (ERDs), where entities are represented as cells and the relationships between them are represented as lines.

A conceptual data model is significant because it can convey the data's structure in a way that is clear to both technical and non-technical stakeholders. It serves as a guide for creating the logical and physical database models and offers a common language for discussing the data. The conceptual data model, however, is just the first step in the database design process. Although it gives a high-level overview of the data, it omits some of the specifics required to actually create the database.

4.2.2 Logical Data Model Design

Unlike the Conceptual ERD, a Logical ERD is a more detailed representation of the database design that describes the attributes of each entity, their relationships, and the constraints that govern them. It defines the tables, columns, relationships, primary and foreign keys, and other details required to implement the database design. It is more concrete in nature and provides a clear understanding of how the data will be organized and stored. But it is independent of the database management system (DBMS) and does not include implementation details such as storage considerations, indexing strategies, or hardware configurations.

In the current phase, the normalization process was re-executed to establish a comprehensive database that conforms to the necessary criteria for both the supply chain system and the relational database. It is worth mentioning that the ordering procedure is still subject to possible alterations, hence the identification of areas of uncertainty denoted by red font, which may be modified in accordance with real-world project requirements.

In Figure A. *2* the Logical Model is depicted with required entities, constraints and relationships. Within the scope of this work, several layers of entities can be distinguished in the model, due to the sequence of model designing. That is, first, the main entities were created, then the relationships between the entities were developed, some of which have many-to-many relationships, thereby making it possible to create additional necessary entities in addition to the requirements. There are following entities within "first layer":

- Task Class. A task class is a grouping of similar tasks that have common characteristics or requirements. For example, all transportation tasks might be grouped together in a "transportation" task class or some manufacturing tasks such as "isolation" or "brewing" can be stored in this table as well. It can contain name and average duration of the process. This entity has relationship "one-to-many" with entity "Task", because one Task Class can be associated with multiple specific Tasks and not vice versa.
- Task. A task is a specific activity that needs to be performed as part of the supply chain process. Examples of tasks might include manufacturing a product, packaging it for shipment, storage of the product or delivering it to a customer. This entity consists of several attributes such as start and end dates and times of process, time and reason of interruption when such occurs. Due to the relationships formed between this and other entities, its attributes also include foreign keys of such tables as Task Class, Actor and Place Location. An Actor foreign key is representation of the company which provide processes, therefore, when it comes to "transportation" task, Actor here is a "carrier". Currently on the temporal base, foreign key of Order also belongs to Task.
- Item Class. An item class is a grouping of similar items that have common characteristics or properties. For example, all types of malt might be grouped together in a "malt" item class. Among attributes could be name, category, units of measure and CPA (Classification of Products by Activity).

- Item. An item is a physical object that is part of the supply chain. At the same time this entity is responsible for general bunch of one item with specific parameters and not actual unique item in the supply chain. This could include raw materials, components, finished products, or natural resources used for process. For example, malt could be with different parameters like type or size of grain, origin of growing, etc. Attributes in this case could be following: specific parameters (for current work was decided to use determined parameters, but in future perspective this attribute can be distinguished as separate entity in order to give opportunity for the user to determine such parameters) such as brand, family and line; best before day (BBD) and comment. Additionally, here stores foreign keys of Item Class and Actor. An actor is associated with an item due to the specific design of this database, within which it is decided that each specific product item can belong to a specific actor. At the same time, one actor can be associated with many items.
- Actor. An actor is a person or organization that is involved in the supply chain process. This could include manufacturers, distributors, or customers. It has attributes such as name of the actor and its role (“Supplier”, “Manufacturer”, “Carrier” etc.)
- Location. A location is an address of facility, which contain information about country, region, city, ZIP-code, street and street number. Since different facilities theoretically could be located in one address there is a relationship “many-to-many” between Location and Actor entities, which generates new “joint” table called “Place Location” with more detailed information about the type of place.
- Order. An order is a request to purchase or produce one or more items as part of the supply chain process. It can contain such attributes as date of order creation, requested date of delivery, status of order and date of status modification. It also can contain foreign keys of Actor table, which assigned as sender (consignor) and receiver (consignee).
- Token. A token is a unique identifier that can be used to track an item or task through the supply chain process with such attributes as creation date and time, amount (according to item’s unit of measure) and shelf life called “MHD” from German word “Mindesthaltbarkeitsdatum”, since every token can have its validity time which can expire.

The interrelationships between various entities can potentially exhibit a "many-to-many" configuration. For instance, the connection between Location and Actor entities results in the creation of a third linking table termed "Place Location" (Figure 4. 10) which represents a physical space where items or tasks are situated, such as warehouses, manufacturing plants, or retail stores. This table may contain details about the type of space and other pertinent information such as room area.

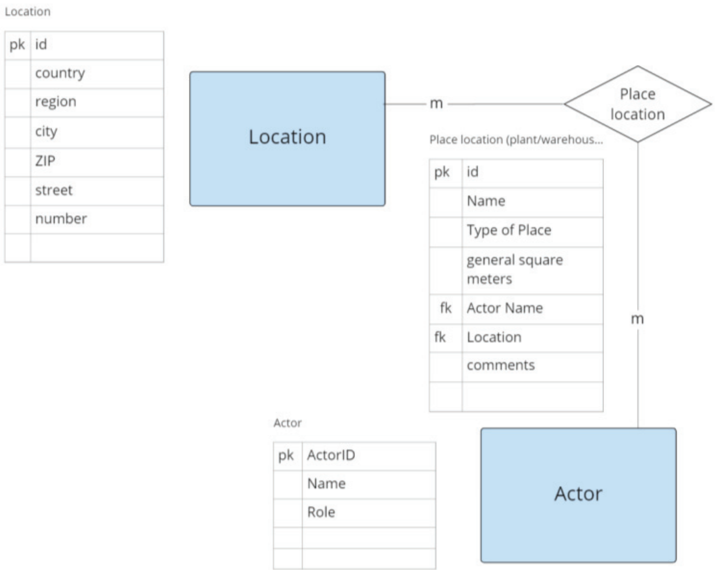

Figure 4. 10 Many-to-many relationship between "Location" and "Actor" tables

Furthermore, an order can cover encompass ordered items, and an item can be associated with several orders, forming a third table called "Ordered Items" (Figure 4. 11). This table contains information about the quantity or amount of a particular item in addition to the corresponding foreign keys. Ordered items refer to specific items requested as part of an order.

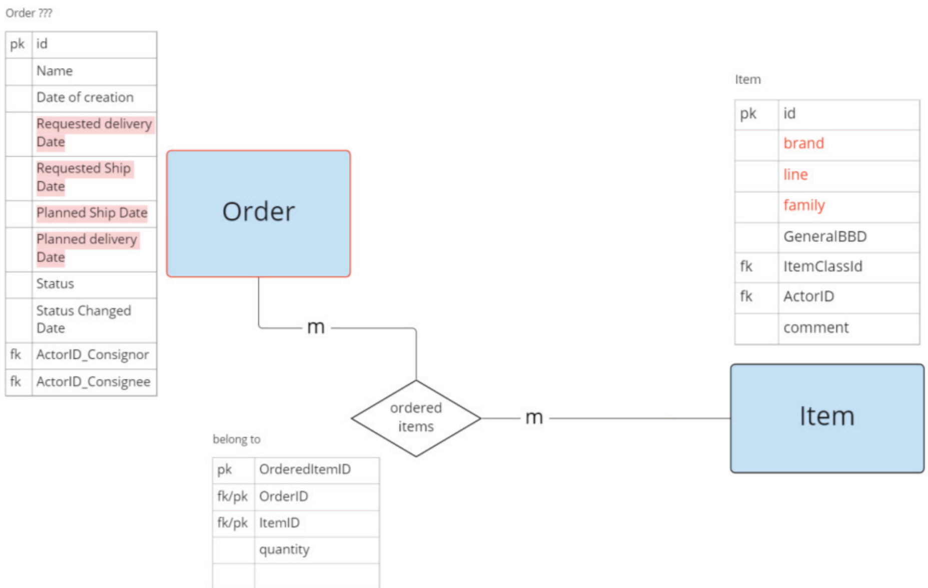

Figure 4. 11 Many-to-many relationship between "Order" and "Item" tables

Could be also connection between Order and Task which is can be called “Order Task” and also contain Ordered Items (Figure 4. 12).

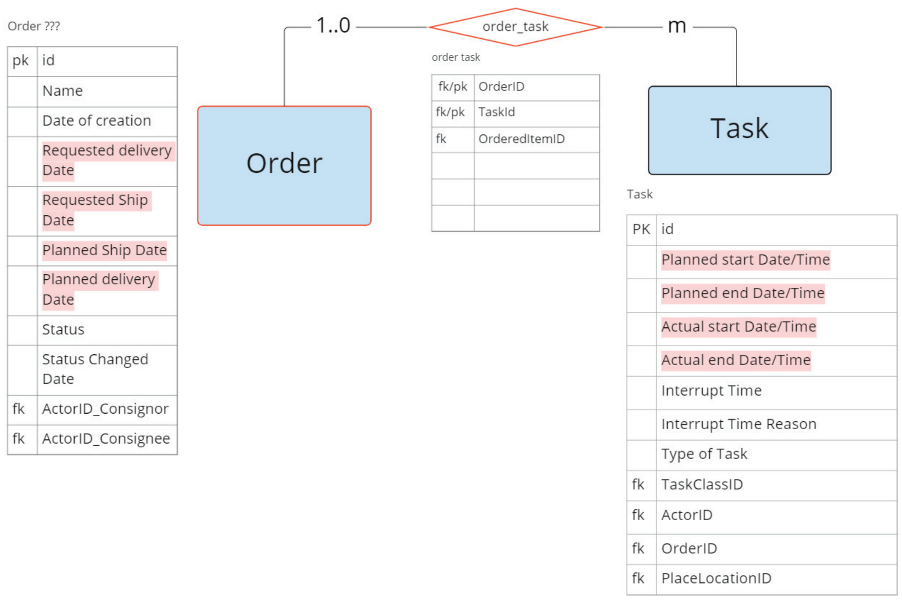

Figure 4. 12 Many-to-many relationship between "Order" and "Task" tables

The Item Class and Task Class can be linked to create a bill of materials that describes the overall inputs and outputs of a specific process (Figure 4. 13). A bill of materials is typically necessary for the manufacturing process to identify the materials and products associated with a particular process. For example, "Brewing" can contain "Malt", "Barley" and "Hops" as inputs and "Beer" as output. Therefore, this table should contain information about quantity of each item for specific task.

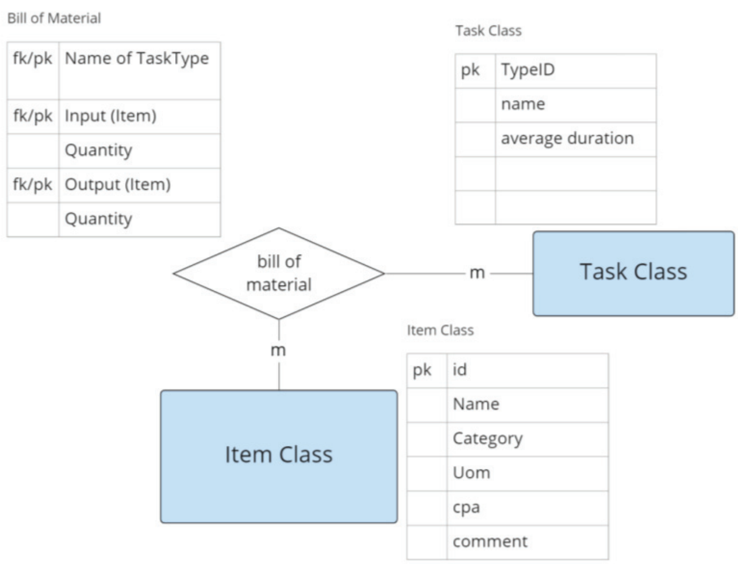

Figure 4. 13 Many-to-many relationship between "Item Class" and "Task Class" tables

In addition, the connection between Item and Task involves two distinct links that result in the creation of two tables, Input and Output (Figure 4. 14). An Input is a resource or material that is consumed or used as part of a process. Examples of Inputs could include raw materials, components, energy, or information. Inputs may be transformed or combined with other Inputs to produce an Output. An Output is a product or result that is generated by a process. Examples of Outputs could include finished products, waste, or information. Outputs may be produced through a combination of Inputs and the actions performed by the process. Therefore, these entities have information about quantity of the products, foreign key of the Token and could also contain information about the sizes, area or weight.

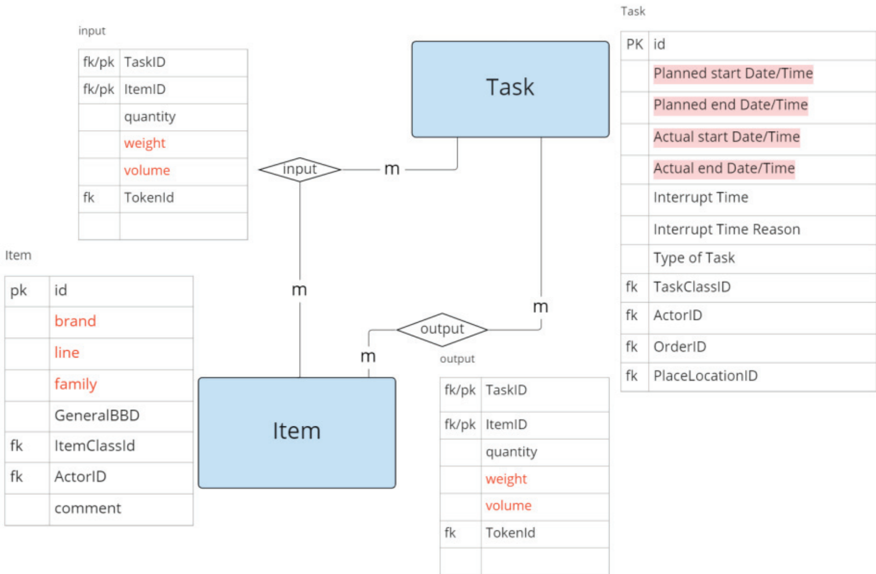

Figure 4. 14 Many-to-many relationship between "Item" and "Task" tables

Task and Actor can also be connected to generate a third table assigned to represent information related to the "transportation" task (Figure 4. 15). This table may contain details such as shipping methods, status of transportation, certificates required for transportation and also it can be connected with Input, since one input theoretically can be divided for different shipments.

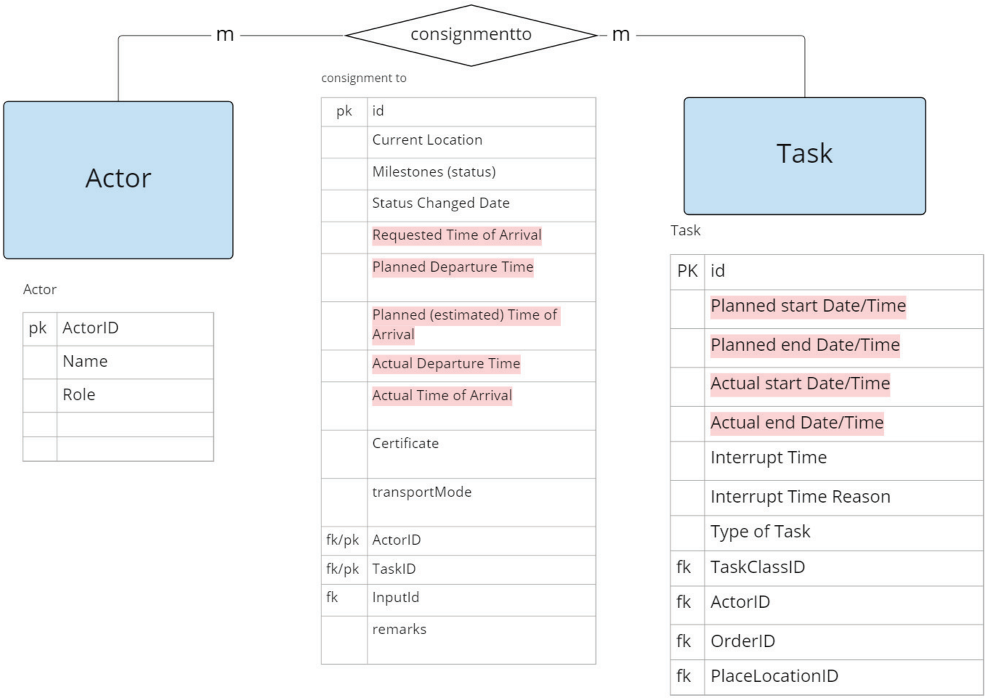

Figure 4. 15 Many-to-many relationship between "Actor" and "Task" tables

To track the transformation of inputs into outputs, a third table with a connection to the Token entity can be created (Figure 4. 16). This table is known as "Token inheritance," which refers to the process by which a token is passed from one entity to another as an item moves through the supply chain process.

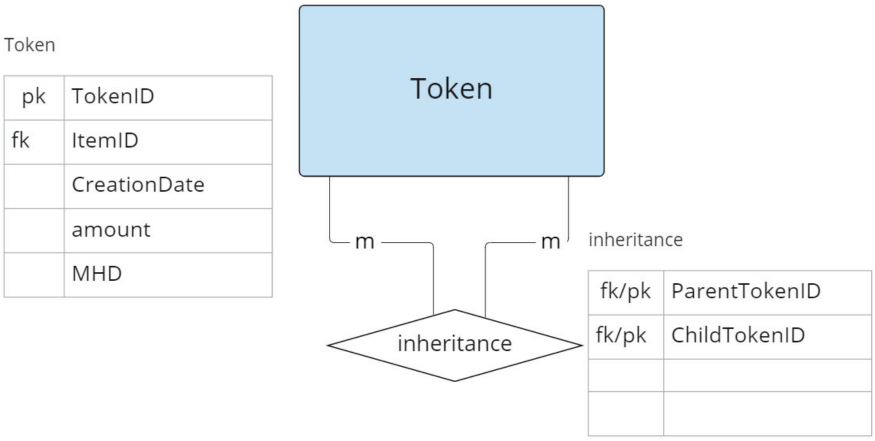

Figure 4. 16 Many-to-many relationship "Token" table to itself

Finally, to facilitate warehouse management in the future, a relationship between Item and Place Location tables can be established (Figure 4. 17). This enables tracking of the location where a particular item is stored in a warehouse.

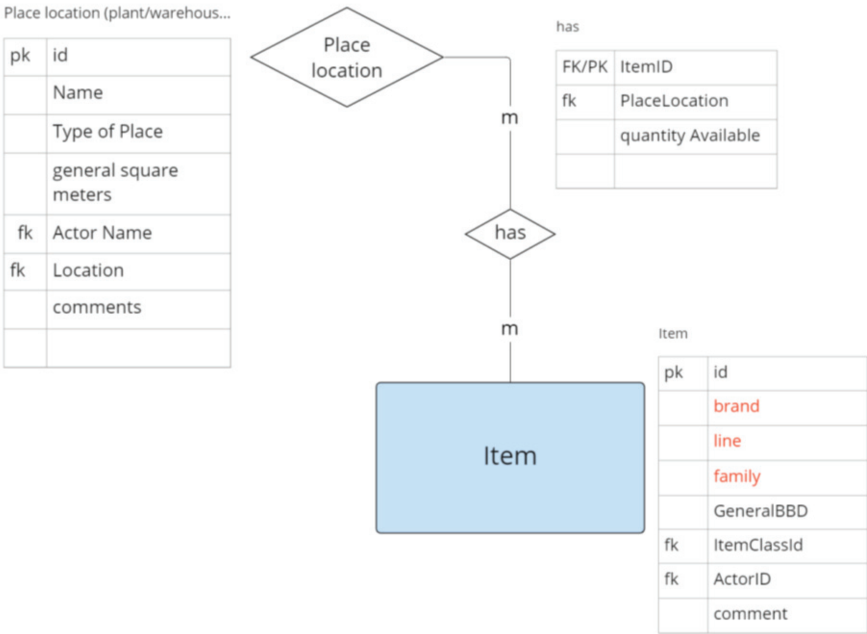

Figure 4. 17 Many-to-many relationship between "Item" and "Place location" tables

Relationships that demonstrate a one-to-many configuration are observed in the following entities:

- The Task entity is linked to a Task Class, where one Task Class record can be linked to multiple Tasks. In addition, the Task entity contains a foreign key, Location, which indicates the location where the task is performed.
- The Item entity is associated with an Item Class, where one Item Class can be associated with several Items, indicating a one-to-many relationship.
- Actor is linked with Task, Order, Place Location, and Item entities, with the potential for one actor to be associated with multiple tasks, orders, locations, and items.
- Token includes the foreign key of Item, indicating that a single product element can be linked to several unique tokens. This relationship represents a one-to-many configuration.

The "one-to-zero" relationship can be observed in the following scenario:

- The Input and Output tables, in addition to Item and Task IDs, include a foreign key of Token. However, it should be noted that not all items are associated with a hashed token, such as electricity or water, indicating the potential for a "one-to-zero" configuration.

4.2.3 Physical Data Model Design

After the logical model was transformed into a physical model, the latter was created in MySQL Workbench software with additional database normalisation steps. As a result, some relationships between entities were changed and entities responsible for access control were added. Namely, the many-to-many relationship between Order and Task was changed to a many-to-many relationship between Order and Transportation, which resulted in the creation of the third table. Access control will be regulated by the following tables: Parameter, which contains information about the relevant access parameters (products parameters of specific token, its quantity, predecessors of this token, its owner and so on), and a connecting table in the relationship between the Actor and the Parameter responsible for the access level. There are four access level: 1. Only owner of product with token can see the information. 2. Other actors with role "Manufacturer" can have access to the information. 3. All supply chain's members can see the information. 4. Everyone can see, including final consumer. Physical model is depicted in Figure A. *3*.

The next step is to create a database based on the physical model created in this section. The script to create the database was created in MySQL Workbench and then imported into PHPMyAdmin, the local host where the database is stored and connected to using XAMPP.

4.2.4 Implementing and Integrating Database with Client-side interface

After database is set on the local server, we should provide a connection between developed database and user interface in order to make it possible to easy and comfortable enter and retrieve data from database. This creates the application logic (Figure 4. *1*) and establishes a connection between the database and the server, and thus with the user interface. PHP (Hypertext Preprocessor) is a popular server-side programming language used to create dynamic web pages and connect them to databases. PHP provides built-in functions to connect to a database using a database management system, such as MySQL or PostgreSQL. These functions include mysqli_connect() and PDO (PHP Data Objects) for connecting to MySQL databases, first one is used in this work. Once connected, PHP can be used to execute SQL queries to retrieve, insert, update or delete data from the database. For example, a query can be executed to retrieve all the information of a specific record in a table. The retrieved data can then be formatted into an appropriate format, such as JSON, to be sent to the client-side HTML page.

On the client-side, the HTML page then uses JavaScript to make a request to the PHP script on the server-side to retrieve data from the database. Once the data is received, JavaScript can then dynamically update the HTML page to display the retrieved data. Additionally, PHP can also be used to handle form submissions from client-side HTML pages. When a user submits a form, the data is sent to the server-side PHP script through a POST request. The PHP script can then retrieve the form data and process it by inserting or updating data in the database (PHP Manual, n.d.).

4.3 User Interface Development

After completing the backend part, it is necessary to develop an interface for testing the system (Figure 4. *1*). As the frontend component of the project, a user interface structure was developed in the form of simple web pages using HTML and CSS. The design was then enhanced with the use of JavaScript programming language to incorporate additional functionality, enabling the application to fetch data from the server side and provide a more interactive and user-friendly experience for the end-users. The JavaScript code was utilized to implement dynamic features such as real-time updates, asynchronous data fetching, and user input validation, making the prototype more responsive and intuitive. Overall, the combination of HTML, CSS, and JavaScript technologies allowed for the creation of an effective and engaging user interface that successfully met the project's requirements. Writing in mentioned programming languages was provided in the Visual Studio Code Integrated Development Environment (IDE).

4.3.1 Development of the HTML Web-Pages

Hypertext Markup Language (HTML) is a foundational technology used to structure the content of web pages and define their constituent elements, including headings, paragraphs, images, forms, tables, and lists (Moraes, 2020). HTML provides a standardized set of tags that enable the creation of a basic page structure, which can then be further refined and enhanced using Cascading Style Sheets (CSS).

CSS is a powerful tool for controlling the visual presentation of HTML elements on web pages, allowing designers and developers to modify font size, colour, spacing, background, and layout to create visually appealing and consistent user interfaces (MDN Web Docs, 2023). CSS also facilitates the separation of content and presentation, enabling web designers to maintain and update the page's design without altering its underlying structure.

HTML and CSS together form a strong foundation for prototyping user interfaces, which can be easily iterated and refined as necessary. These technologies are widely supported by modern web browsers, making them highly accessible and frequently used in the development of web-based applications. For instance, in a recent project focused on Supply Chain Management, 17 HTML pages were developed for various purposes, serving to test the practicality of theoretical hypotheses. Two distinct CSS styles were also created for the "insertion" (Figure 4. 18) and "selection" (Figure 4. 19) pages, helping to differentiate between pages used for entering data into a database and extracting data from it.

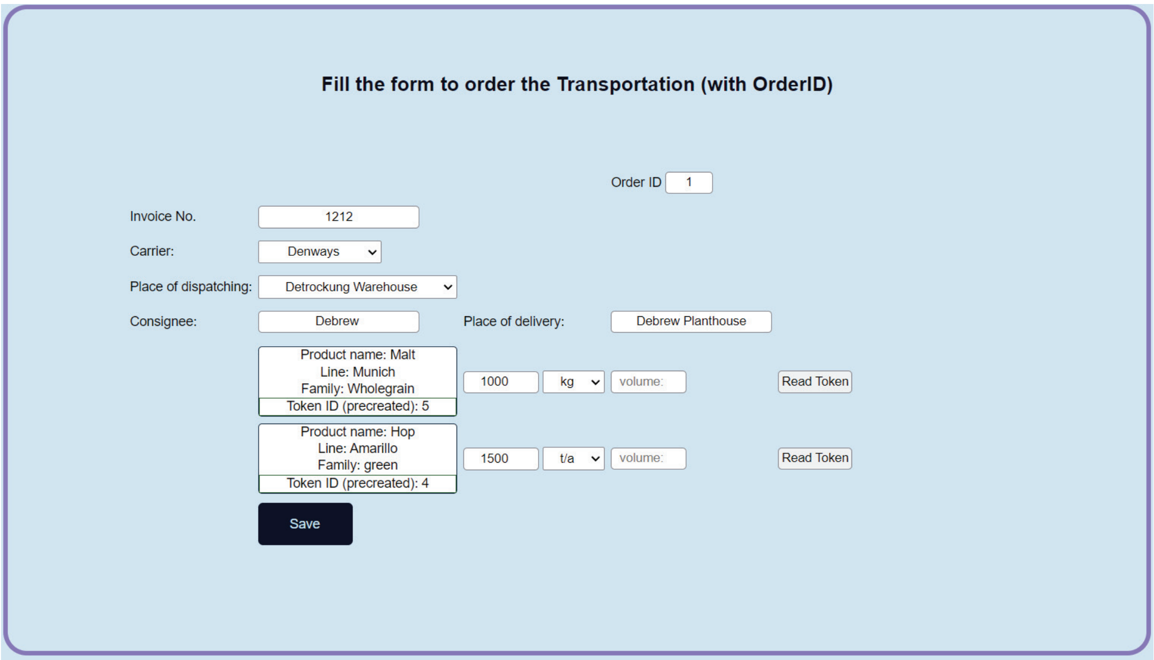

Figure 4. 18 Design of the "insertion" web-page

Figure 4. 19 Design of the "selection" web-page

The pages created for entering information into the database meet requirements in Chapter 2 and serve the following purposes:

1. Actor Information. This page allows the user to input information about a company that is part of the supply chain. As shown in the Figure 4. 20, user should provide the system with the name of the company and its role, and enter information about its primary important address. It can be a main office or manufactory where actor provides its activity.

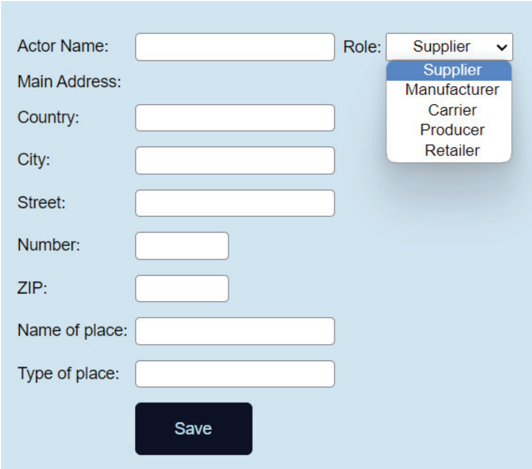

Figure 4. 20 Fields for entering information about member of the supply chain

2. Location Information. This page is used to add a new location for an existing actor.

3. Product Information. On this page, the user can add a new product item along with all its relevant characteristics, parameters, and information about the company that owns it.

4. Manufacturing Process Category. This page enables the manufacturer to add a new process category along with its bill of material. The user needs to provide information such as average duration, quantity of inputs and outputs, and comments.

5. Token Information. This page allows the user to create a new token for a product item. The token is represented by a QR code that is physically attached to the product and contains information such as quantity and unit of measure. For instance, it is possible that the supplier has created a token for a batch of 5 tonnes of malt, but it is also possible that this batch is later split into smaller batches of 500 kg each, each with its own token.

6. Ordering Information: This page is used to input all the necessary information required for placing an order.

7. Transportation Initiation (filled by actor who request for the shipment). Considering the complexity of shipment processes and the way of sharing the information between logistic or transportation companies and their customers, author takes into account that this step is difficult to implement in real world. However, the possibility of using different types of communication between different software such as API (Application Programming Interface), there are theoretical possibilities to get information from the carrier, but this issue is beyond the scope of this study. Therefore, the creation of several steps of transportation process was considered as an optimal solution for this work. Thus, it is considered, that firstly, actor who initiate the shipment (it can be done according to previous order or without order), provides an information about place of dispatching, receiver data required for carrier and the information

about products (which include tokens). It is mandatory to create a consignment note number for transport, which also can be called as invoice or transportation number.

8. Transportation Confirmation (filled by Carrier). After the previous page, we simulate that a carrier or transport company confirms a request for the delivery of goods using the specified information on the sender and recipient, consignment note, and goods, which was previously entered, and supplements this information with its own information on the mode of transportation as well as information on the vehicle. In this situation, the carrier may also specify which of the items included in the transport request it is able to carry as part of the same package. The person who completed the previous page (Transportation Initiation) must prepare a new waybill for the products that cannot be delivered in the current transport if the carrier is unable to deliver all or a defined number of goods in one shipment.

9. Manufacturing Process Information. This page is used by the manufacturer to input information about the manufacturing process, including inputs and outputs with tokens. We are also considering adding tokenless inputs when this is not possible.

10. Storage Information. Similar to the manufacturing process page, in this one actor enters the information about storage.

11. Access Control: This page is used to manage access to the system, specifying which user can access which information about specific product etc.

All of pages about processes are important for tracking and tracing products with tokens throughout the supply chain. On the other hand, the following pages have been created to retrieve and display information from the database:

1. Product Information. This page retrieves information about the available products within the current supply chain, allowing users to check which actor(s) offer a specific product with its described characteristics and parameters.

2. Order Information. This page retrieves information about a specific order, identified by its unique ID. Future work could explore other approaches to improve the search process.

3. Process Inputs and Outputs. This page displays information about the inputs and outputs, as well as their quantity, of a specific process.

4. Manufacturing Process Information. This page contains details about a specific manufacturing process that has either been completed or is in progress. It includes information about the place, date, provider, and status of the process, as well as its inputs and outputs.

5. Transportation Process Information. This page provides the required information about the transportation process for products and their tokens. Users can access the page with token history based on the information provided here.

6. Token History: This is the most important page among all the previous ones, as it displays the complete history of a token throughout the supply chain, including its predecessors and successors, as well as all the processes in which it was involved.

Access to information on product characteristics contained on the created pages is regulated in accordance with the level of access granted by a particular actor-owner of a particular product. Within the scope of this project, it is simulated that an actor has logged in under their own licence and name and is viewing information about token-based products.

4.3.2 Enhancing User Interface with JavaScript

A variety of capabilities can be implemented on web pages using JavaScript, such as dynamically inserting rows for records and constructing dropdown lists using data from databases as it is done for the current work.

JavaScript uses an AJAX call to the server-side to obtain the necessary data in order to generate dropdown lists with data from a database (Figure 4. 21). After receiving the data, DOM (Document Object Model) manipulation techniques are used to dynamically populate the dropdown list with it. The most recent data from the database is then automatically updated in the dropdown list, guaranteeing that the user always has access to the most recent data.

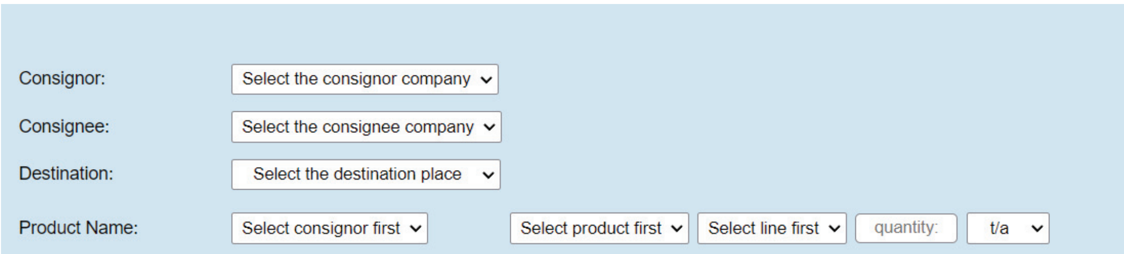

Figure 4. 21 Interconnected dropdown lists

Moreover, rows for records on a web page are dynamically added using JavaScript. This involves adding an event listener to a button (it also can be an input element) so that when it is pressed, it causes a function to be called that adds a new row to the HTML table or form. To construct a new row and fill it with the necessary data, the method employs DOM manipulation techniques. This method allows new records to be added dynamically without having to reload the entire page, which is very helpful for forms or tables that need to manage an unknown number of records. In Figure 4. 22– Figure 4. 25 depicted process of adding new row with example of QR-code scanning simulation.

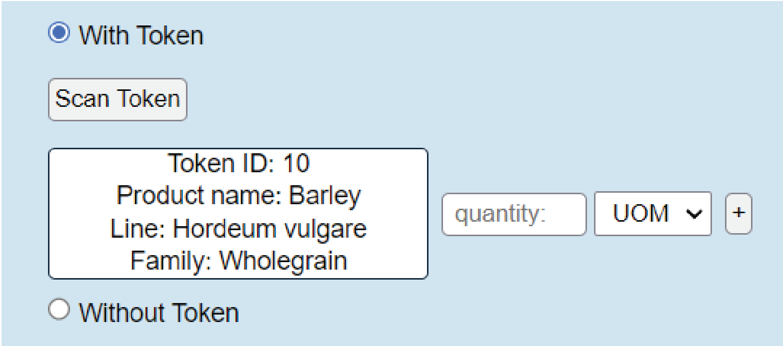

Figure 4. 22 Adding tokenized product for the process

The "Scan Token" button on the website switches to green (Figure 4. 23) after pressing the "+" button, making it clickable at that point.

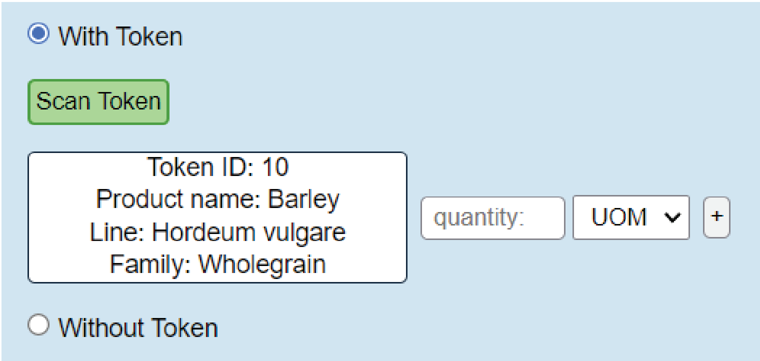

Figure 4. 23 Green "Scan Token" button after click on "+"

The "Scan Token" button causes a popup window to open when the user clicks on it (Figure 4. 24). The user can type the Token ID into the popup window to simulate scanning the token. After entering the Token ID, the system runs a query to get details about the relevant product from the database.

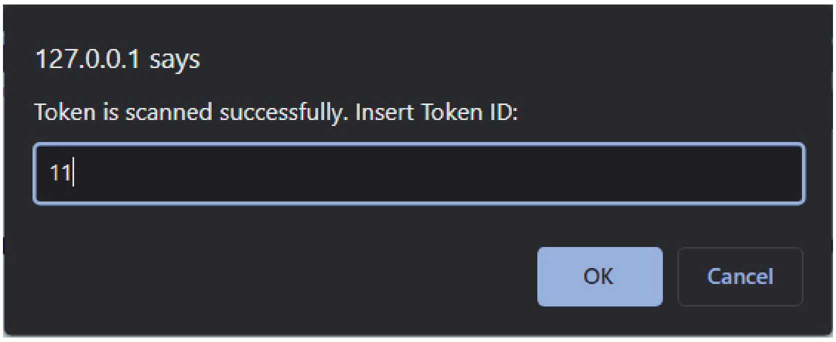

Figure 4. 24 Simulation of QR-code scanning

The product's name, line and family are provided in the respective field (Figure 4. 25).

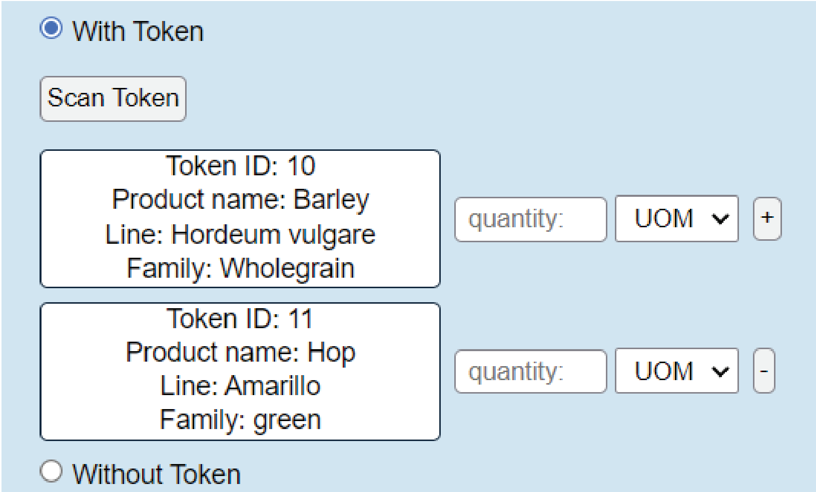

Figure 4. 25 Added a new tokenized product with the means of JavaScript

4.4 Datasets testing

To develop proficient comprehensive system, especially when it comes to SCM, we should consider its complexity and probable use cases. Different Supply Chain workflow scenarios were explored and tested, since current work is a prototype, 9 scenarios were tested (Figure A. *4*), although in real-world cases there are much more possible scenarios of possible ways of supply chain functioning which may also vary depends on type of the chain.

Scenario №1. Simple Supply Chain Workflow:

In this scenario, a manufacturer orders raw materials, stores them in their storage place, and produces a product using the raw material. The product is then sent to the storage place before being shipped to the next customer. Next steps constantly recurring with further actors and products, going through storing, ordering, shipping and manufacturing process until it reaches retailer who sells finish product of the supply chain to the final customer. This is the most common and simple scenario of the supply chain workflow.

Scenario №2. Regular Agreement Workflow:

In this scenario, a manufacturer sends their product to the next customer without an ordering process. The product goes through the same shipment and storage process as in the first scenario, but there is no formal ordering process.

Scenario №3. Multi-Transportation and Storage Workflow:

In this scenario, the product can be transported using different modes of transportation, such as truck, train, airplane, or ship. It can also be stored at any storage place between the supplier and the customer places. This scenario allows for greater flexibility in the supply chain and can help to reduce transportation costs.

Scenario №4. Divided Transportation Workflow:

In this scenario, Customer №1 ordered 100 kg of Malt, but it cannot be shipped in one transportation task and needs to be divided into different transportations. There is only possibility to divide the 100 kg of Malt into three transportations, where two transports carry 70 kg and 25 kg respectively and the remaining 5 kg of Malt is shipped together with 65 kg of Barley for customer №2. The transportation with Barley and Malt goes to different locations and customers (Malt goes to the customer №1 and Barley – to the customer №2). Two of the cargos (70 kg and 25 kg) are stored together, but the remaining 5 kg travels with the Barley. After storage place, 95 kg of Malt is dispatched to customer №1's warehouse and the remaining 5 kg is delivered to the same warehouse.

Scenario №5. Mixed Transportation Workflow:

As was mentioned in the scenario 4, Carrier delivers 5 kg of Malt to customer №1's warehouse and after that, it then delivers 65 kg of Barley to customer №2. Customer №2 uses the Barley to produce Beer (output 1) and Treber (output 2). The batch of Beer goes further along the supply chain to the end customer same as the first scenario. On the other hand, the Treber batch is sent to a storage place and divided into two separate batches and goes by scenarios 6.

Scenario №6. Divided Dispatching Workflow:

The two batches of Treber, mentioned in the scenario 5, are delivered to two different customers. After they are dispatched, each of them goes further throughout the remaining way of the supply chain.

Scenario №7. Regular Agreement Workflow 2:

The product is sent to the customer without a specific ordering process but by a regular agreement. The product goes through the same shipment and storage process as the Simple Supply Chain Workflow

Scenario №8. Consolidated Shipment:

Here, three different products are ordered, all of each are collected and dispatched in one track as one transportation task. The next workflow follows the same steps as the first scenario, where the product is shipped to the storage place of the manufacturer, then to the next tier customer, and so on.

Scenario №9. Split Shipment:

There are three different products are ordered the same as in previous scenario. But in this case, one product is dispatched in one track, and the other two products are dispatched in another track. The two tracks with the products are delivered to one storage place. From the storage place, the next workflow follows the same steps as the first scenario, where the products are shipped to the next tier customer, and so on.

All the scenarios considered have been examined from a practical point of view, but given the scope of this work, the most common workflow scenario should be sufficient for description in order to check the logic of web pages and verify the correctness of the developed database for purposes of this work. As already mentioned, the author considers the first scenario to be the most common. This scenario is examined according to the specific supply chain within "MaltFungiProtein" project, depicted in Figure A. *1*. Although the solution in this paper is applied to a highly specialised industry, it is clear from Figure 2. 2 that the solution can be extended to other industries across different supply chains.

It's essential to enter all the relevant data in advance when working with a complicated supply chain system so that it can be used later. Fortunately, a user-friendly interface makes it simple to enter information on the supply chain's enterprises, their locations, the products they produce, and the various manufacturing processes and materials used. One thing to bear in mind, though, is that it is the system's developer's responsibility to put the various item types in the Item Class table. An example of the web page for entering information about product items and predefined categories in the dropdown list is depicted in Figure 4. 26.

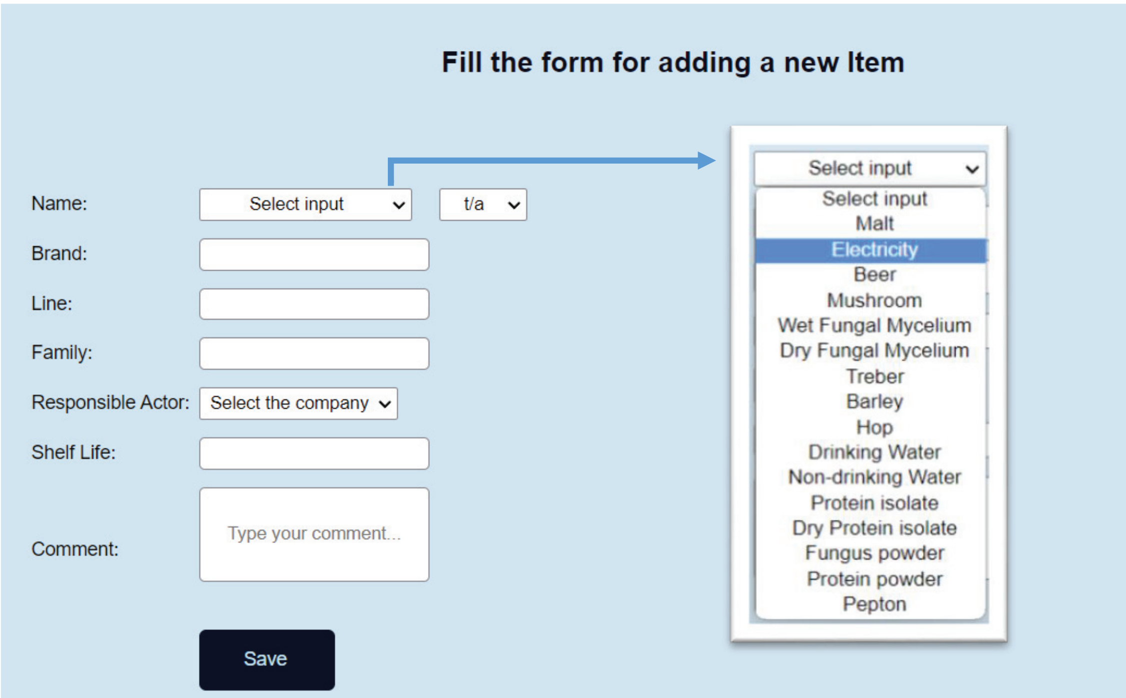

Figure 4. 26 Page with adding information about product with dropdown list

The system must be tested to ensure smooth operation after all the necessary data has been entered. The workflow of the system is made up of several connected processes that start with the submission of an order and end with the conclusion of the manufacturing process of the final product.

Placing an order is the first step in the procedure (Figure 4. 27). This comprises submitting a request to the supply chain system for products or services.

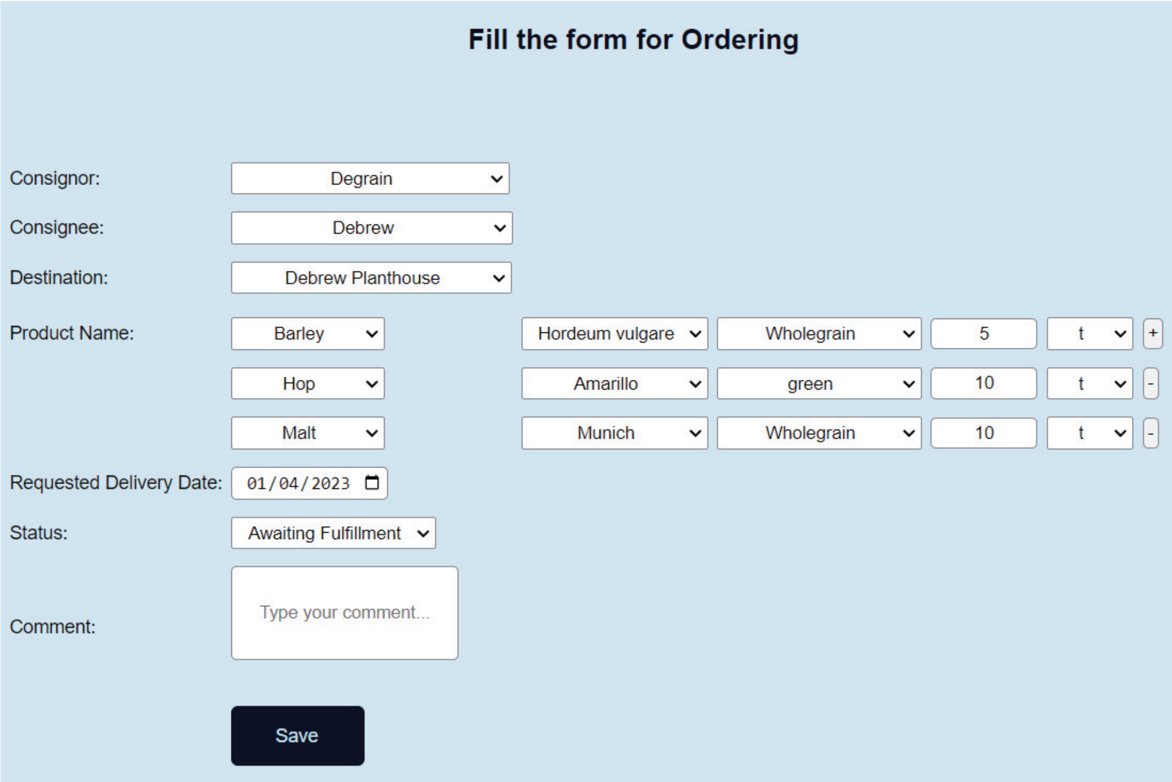

Figure 4. 27 Place an Order

Before providing next process within the supply chain, supplier creates Token for items he will send to the customer. Since supplier at this step is going to create tokens for so-called raw materials which do not have previously proceed product from which they would become as outputs, these items do not have "Parent token" or predecessor (Figure 4. 28).

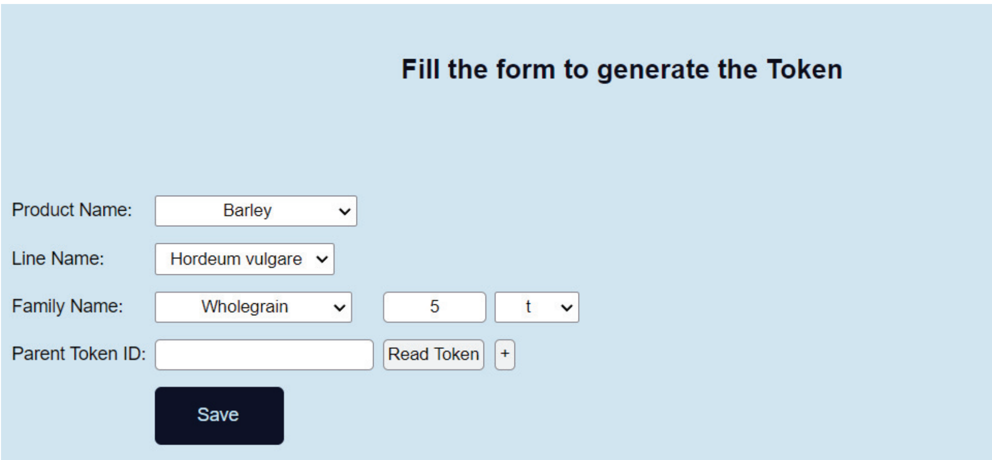

Figure 4. 28 Create a new Token for the product

In general supplier created three tokens for the products he is going to send according to the customer's order (Table 4.1). The Best Before Day is in case of token the time within which this token is valid.

Table 4.1 Tokens created for the transportation process

Token ID	Date	Quantity	BBD	Product
10	2023-03-20 12:23:24	5 t	2 years	Barley (Hordeum vulgare, wholegrain)
11	2023-03-20 12:24:05	10 t	2 years	Hops (Amarillo, green)
12	2023-03-20 12:24:19	10 t	2 years	Malt (Munich, wholegrain)

After the order is placed, the system moves on to the following stage, which involves finding and choosing the right delivery provider (Figure 4. 29). With entering Order ID required information auto retrieved from database. User only enter carrier, place of dispatching and products with tokens, which were created previously.

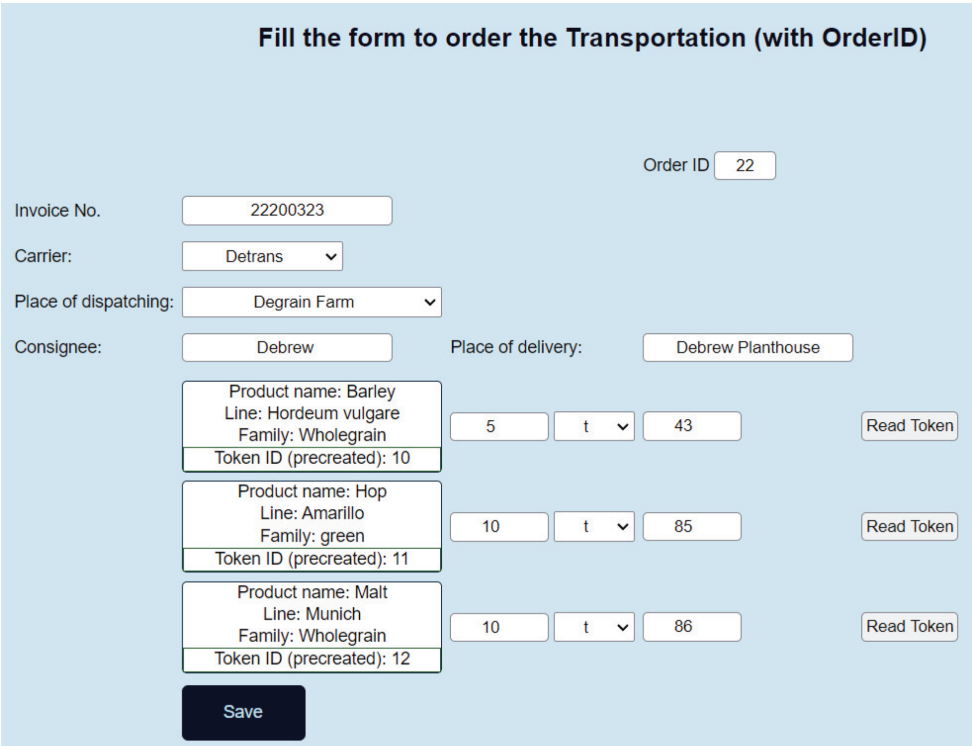

Figure 4. 29 Initiating of the Transportation by Supplier

Depending on variables including availability and cost, the shipping provider subsequently responds by approving or refusing the request (Figure 4. 30). With entering transportation number, all information retrieved from database, except estimate dates of dispatching and delivery, status and information about vehicle.

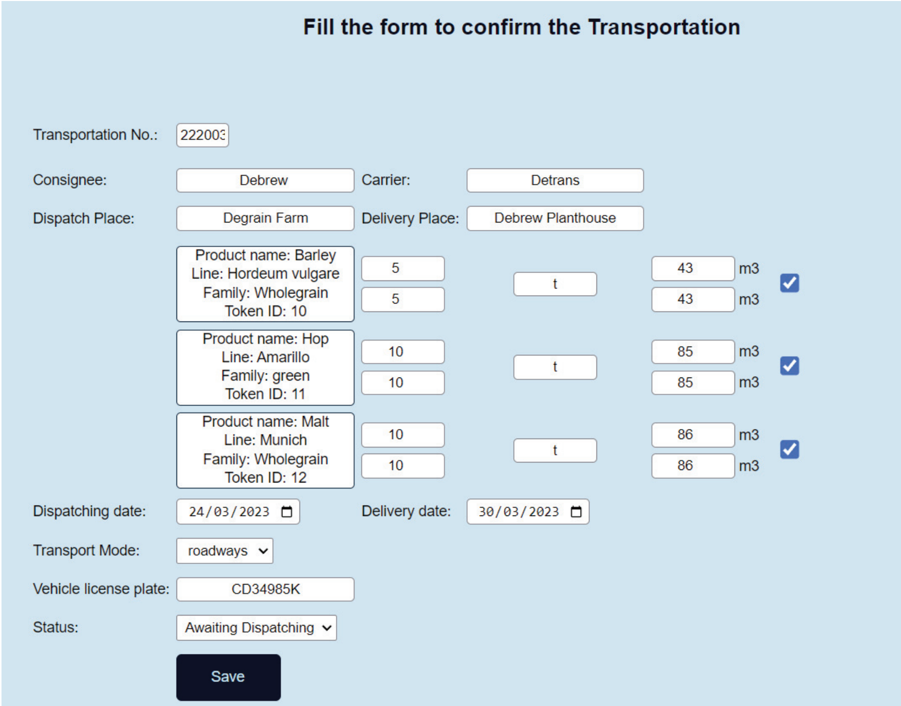

Figure 4. 30 Confirmation of the Transportation by Carrier

Once the products are delivered, either the carrier or the customer is responsible for providing a database with relevant information about the delivered goods. For the purposes of the current work, the transition from the transportation stage to the storage stage is considered an adequate indicator of successful product delivery. Thus, the delivered products are transferred to the company's warehouse, from where they are subsequently transferred to the production process. This stage involves careful allocation of appropriate warehouse space and implementation of effective inventory management strategies to optimise the production process (Figure 4. 31).

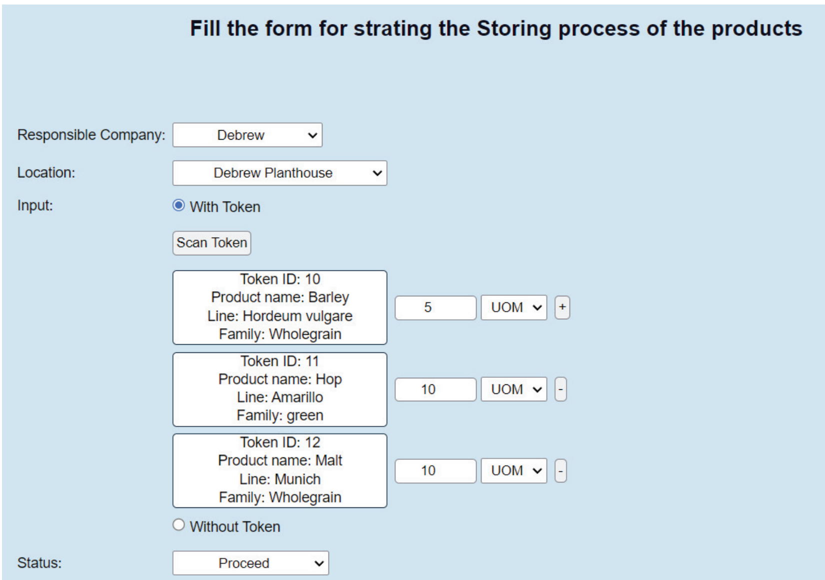

Figure 4. 31 Storing process

The system then advances to the manufacturing stage, where the products are created from the product items which were delivered previously. The brewing process is provided at this stage, but the same manufacturer can provide multiple processes. As it is mentioned in the supply chain scheme (Figure A. *1*), after Brewing the same supplier provides also Fermentation and Separation processes. When a company produces new products during the manufacturing process, it creates new tokens for the outputs of the process. The possibility to use inputs with tokens and without tokens is depicted in Figure 4. 32. And there are outputs that can be with and without tokens in Figure 4. 33. For example, in our case, Beer is beyond our tracking and tracing system, therefore, the manufacturer does not create a token for this product even though it was produced. But this approach has disadvantages such as that without a token it becomes impossible to track this product further.

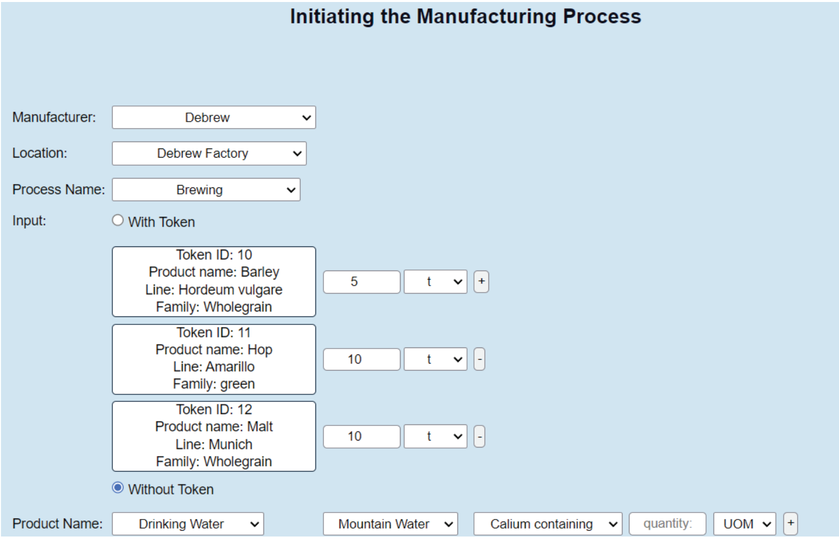

Figure 4. 32 Manufacturing process with input components

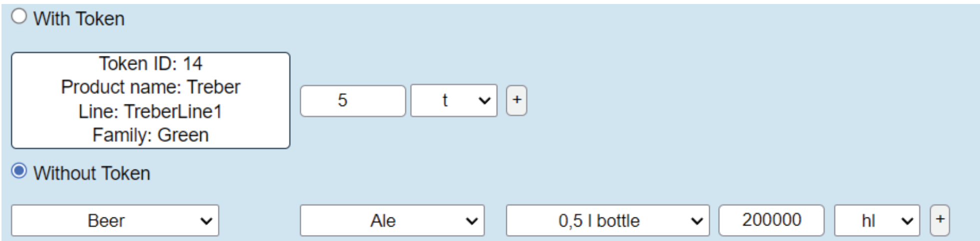

Figure 4. 33 Outputs of the Manufacturing process

Further moving through the supply chain repeat all previous actions, therefore, we can go further by all the next steps according to the supply chain depicted in Figure A. *1* in order to go to the main part of this work – validate that using the centralised system with tokens which represent physically attached QR-codes to the products in the system is sufficient to track and trace products from the very first supplier to the final customer.

With a special page where we can retrieve specific information about the products with tokens. In Figure 4. 34 is shown that according to Token ID, we retrieve the information about the product to which this token is attached, the processes to which it was involved, and for sure about its predecessors and successors.

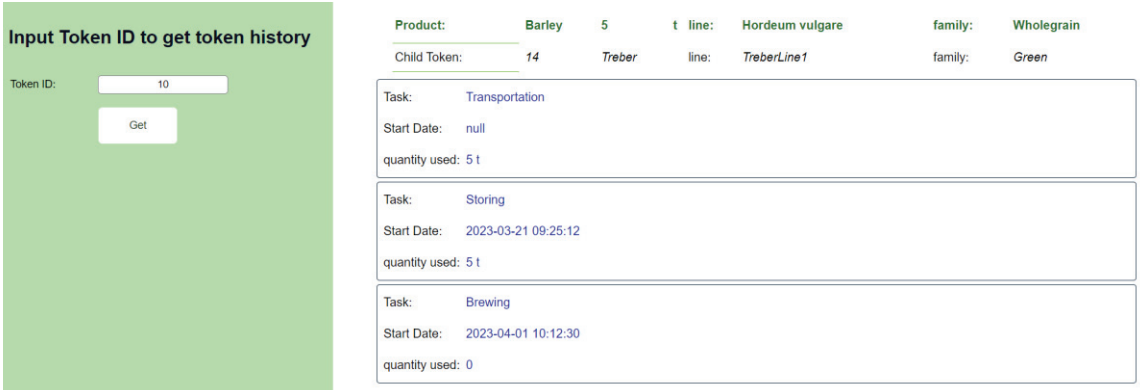

Figure 4. 34 Information about Token 10 (Barley)

The history of token changes is possible to verify by going through each previous or next token. For example, in Figure 4. 35 we can see a successor of the first token, which in its turn, except the Token with ID 10, has also other predecessors, which means that the Token with ID 14 is an output of a combination of three other tokens.

Figure 4. 35 Token 14 - successor of Token 10

Along the entire supply chain, we can see details about all related products that came before and after. For instance, in Figure 4. 36 the information about a product named "Protein Isolate" is shown, which was produced at a certain point of the supply chain.

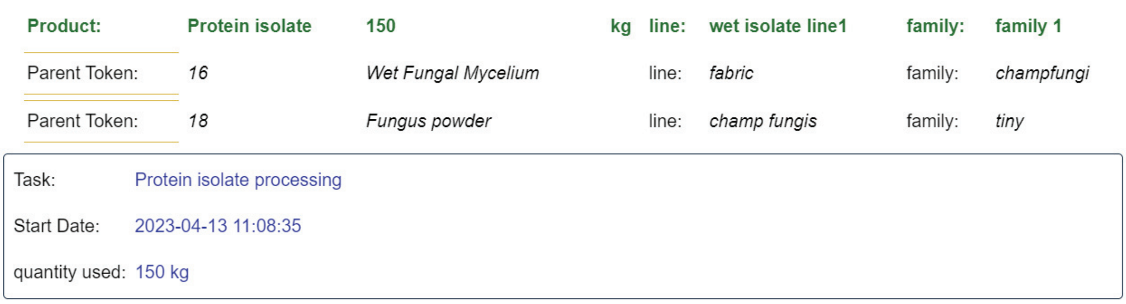

Figure 4. 36 Information about product at some point of supply chain

5 Conclusions and Future Work

A tracking and tracing system prototype using a centralised database and QR codes was created as a result of this research. The technology attempts to enhance supply chain transparency, boost productivity, and lower the possibility of fraud or tampering. The examination of the state of present traceability systems, the creation of a centralised prototype, and the testing of the system in a simulated supply chain environment all contributed to the research's success in achieving its goals.

Globalization and technological development nowadays put forward demands to supply chains all over the world. The larger the supply chain becomes, the more risks and disruptions tend to happen along this chain. Such interruptions might be caused by a variety of reasons, starting with natural disasters and finishing the IT or technological disruptions. Therefore, the development of an efficient system that can help SC's specialists to manage or even lower the amount of such disruptive events, is a vital task for responsible persons or organizations. Additionally, as the number of participants in the supply chain grows, the issue of the validity of data on goods, transactions, and processes becomes important. In this case, the supply chain must be equipped with a traceability system that can provide confidence to all participants and consumers that the product is safe and complies with all regulations. This issue is especially relevant in the context of the food supply chain. There are many supply chain traceability solutions available today, but most of them rely on decentralised databases and relatively expensive elements such as IOT, RFID, etc. Unlike the other solutions, this paper investigated and tested the possibility of applying a relatively low-cost, but nevertheless effective solution using a centralised database and QR codes.

The results of the solution provided in this work demonstrated that the prototype is efficient in preserving information flow across all supply chain nodes and lowering the danger of data manipulation.

This study makes a significant contribution to the field of supply chain management by showing how centralised tracking and tracing systems can increase transparency and lower the likelihood of fraud. These results can be used as a foundation for future research to create more sophisticated and scalable supply chain tracking and tracing solutions. However, there are still issues that must be resolved, such as the requirement for safe data storage and the incorporation of decentralised or clustered systems to guarantee the system's scalability and robustness. At the same time, this prototype should be expanded and modified to meet the needs of each particular supply chain industry. The research conducted in this paper, such as algorithms for generating unique token values, and the use of access levels, can be used to improve and extend this prototype for practical applications and further research. In addition, more work needs to be done to improve the system's protection against hacking and injection by third parties.

Tracking and tracing the food supply chain holds enormous potential for future research, and there are numerous directions that might be taken in this direction. The creation of models with many functionalities, which can assist maximize the use of big data from the food supply chain network, is one potential field of research (Balaji and Arshinder, 2016). With the inclusion of sophisticated and intelligent models or algorithms, such as deep machine learning, it is possible to define several objectives and choose the appropriate data for each objective function. Future research could also examine the implementation of these models in real-world settings and evaluate their effectiveness in improving food traceability and reducing risks in supply chains.

Second, the usage of digital devices in E-commerce logistics generates a lot of data that could contain insightful information to help firms make more informed decisions. Big Data Analytics is viewed as a future perspective in upgrading E-commerce logistics in order to efficiently and effectively analyse this enormous data. Because it provides for shared access to resources, data, and information across the internet, cloud computing can provide a solution. Future studies can look into how cloud computing is used in food traceability systems, especially in terms of how it might enhance data processing and decision-making. *(Yu et al., 2016).*

Investigating the viability and efficiency of integrating cutting-edge models and cloud computing into food supply chain tracking and tracing systems may be valuable for future study in this subject. More investigation into the use of deep machine learning techniques and cloud computing infrastructure might be necessary for this. Future research may also find interest in investigating how these technologies can be integrated with the tracking and tracing systems already in use for the food supply chain. Overall, there is a great deal of room for further research and development in the area of tracking and tracing the food supply chain, and there is a great deal of potential for future developments in this subject.

Finally, the current study showed that the usage of centralised databases and QR codes can offer an effective and efficient way of traceability in the food supply chain. Future study, however, can look into how traceability systems can incorporate decentralised strategies like blockchain technology along with centralised one. This might improve data security and transparency while lowering the possibility of data tampering. Moreover, clustered systems for centralised supply chains, as employed by large firms, can be researched to see if they are appropriate for small to medium-sized businesses.

Appendix A

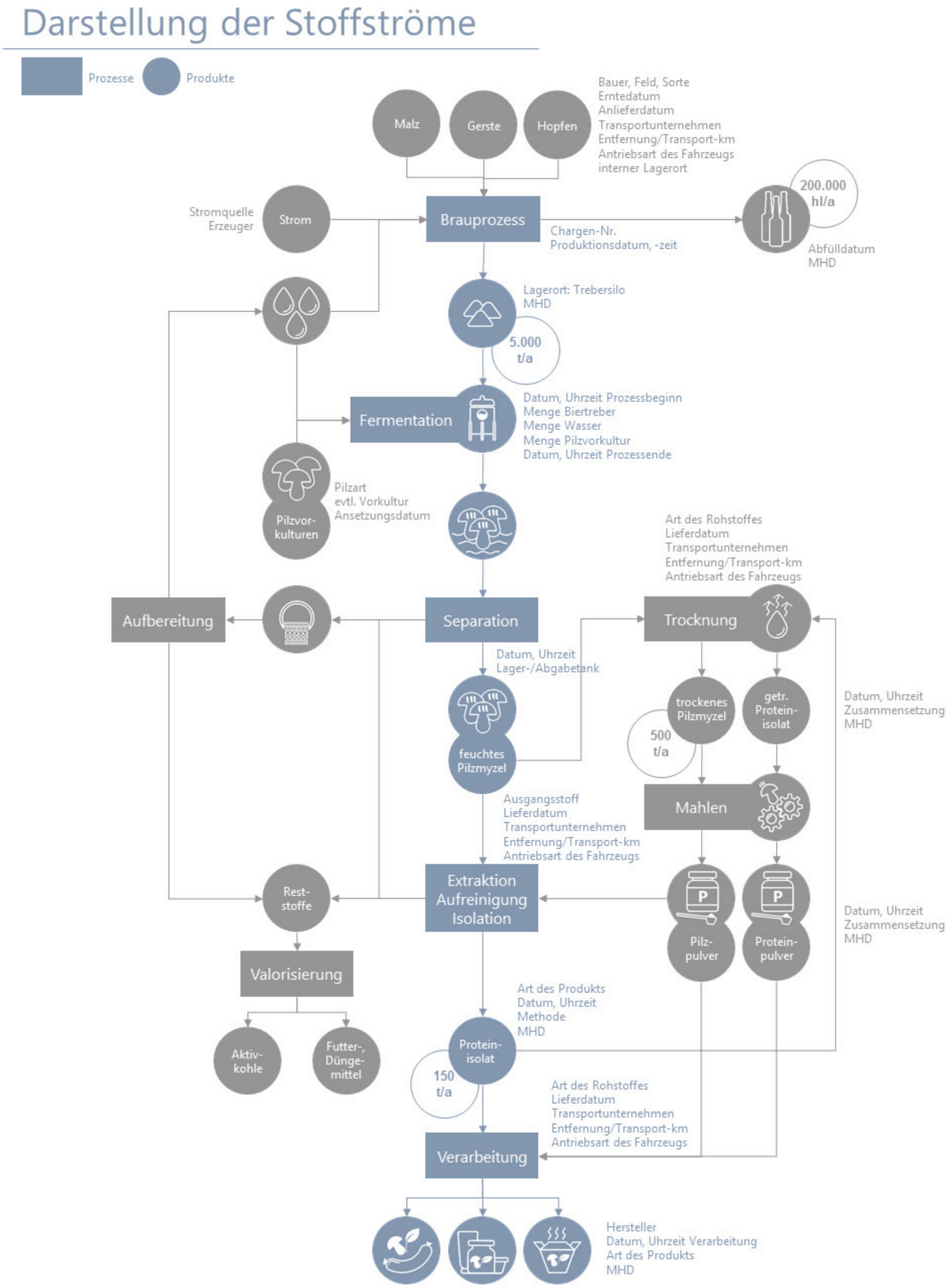

Figure A. 1 Supply Chain scheme from Visutronik GmbH

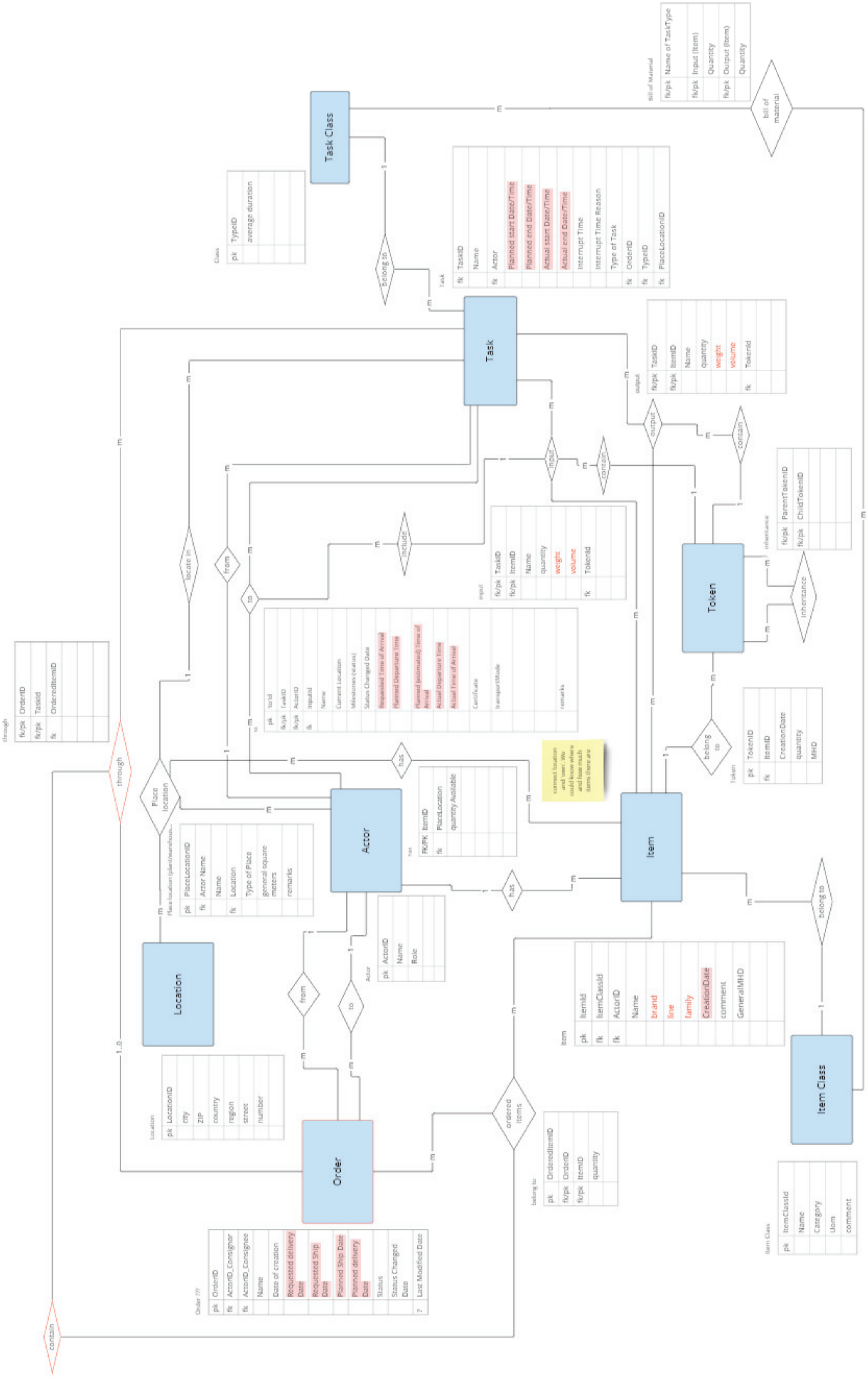

Figure A. 2 Logical Data Model

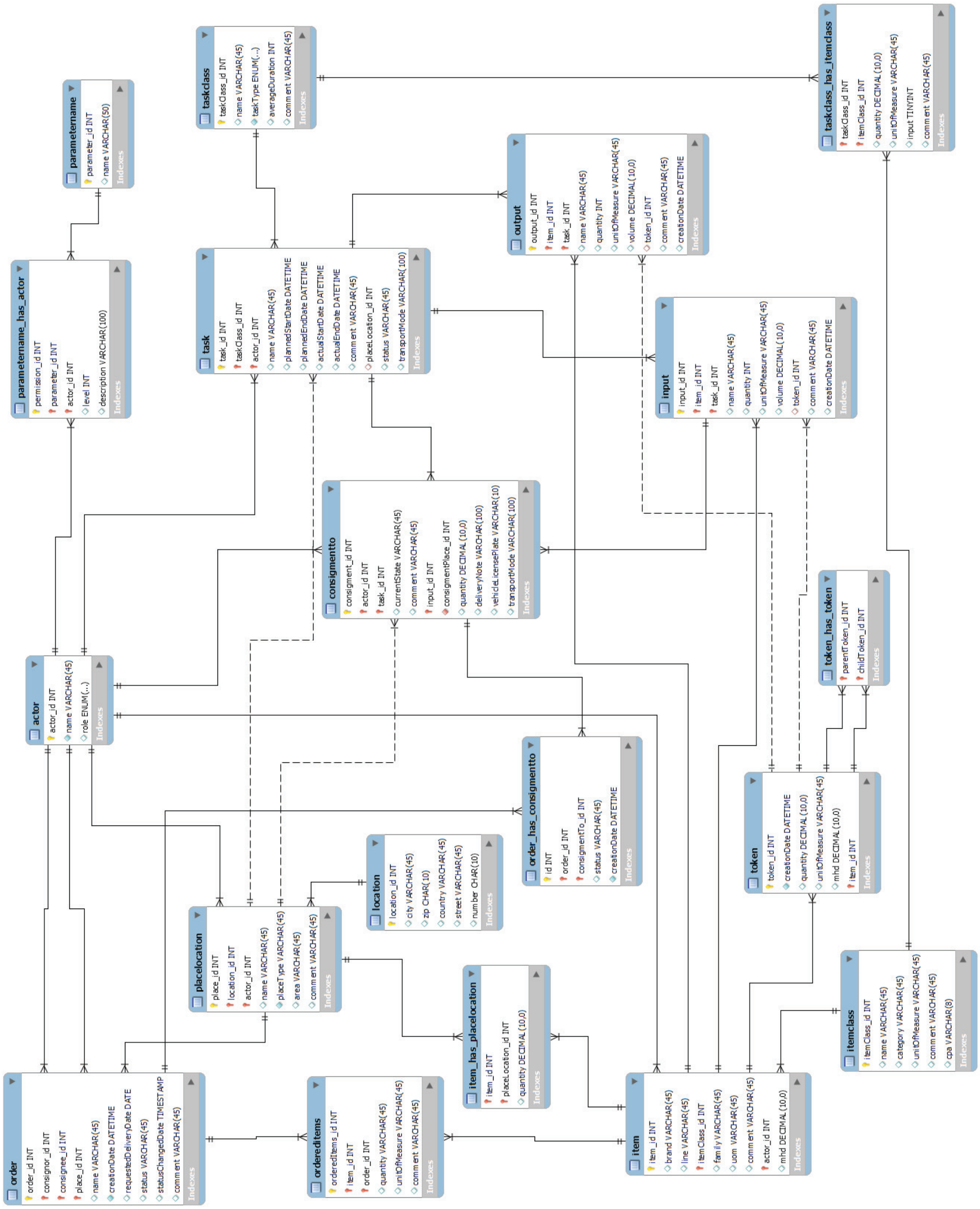

Figure A. 3 Physical Data Model

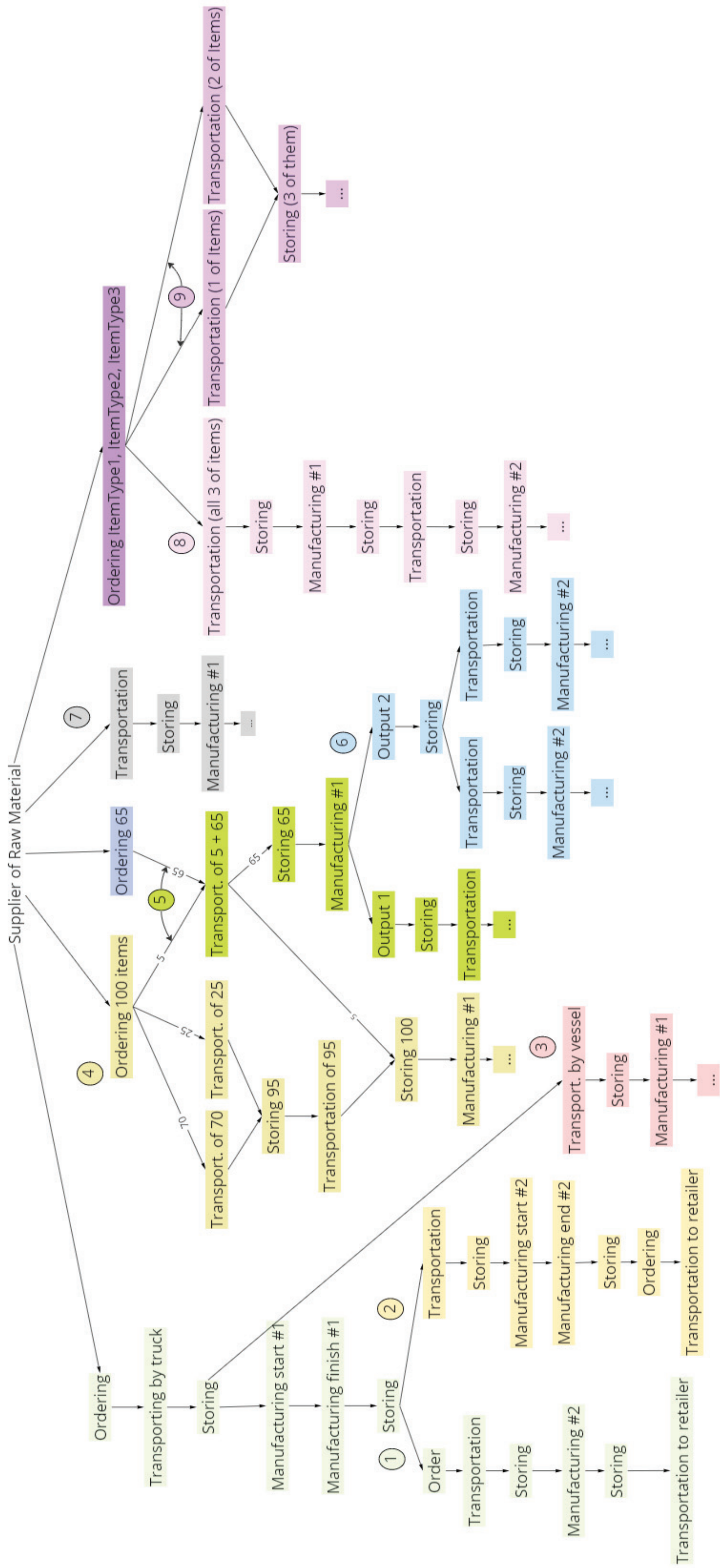

Figure A. 4 Scenarios of the Supply Chain workflow

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Declaration for the Master's Thesis

I confirm that this Master's thesis is my own work and I have documented all sources and material used. This thesis was not previously presented to another examination board and not been published.

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Veronika Shvets, Neubrandenburg, 21.04.2023