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'Improving on supply chain performance regarding throughput time, by designing a Digital Chain that is based on the combination of IoT-sensors and blockchain technology'

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‘Improving on supply chain performance regarding throughput time, by designing a Digital Chain that is based on the combination of IoT-sensors and blockchain technology’

by

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Preface

Before you lies the result of my research towards improving supply chain performance, report number 2020.MME.8479. This research is performed as the final graduation project of the master program Transport Engineering and Logistics, a specialization track within the MSc Mechanical Engineering at the faculty of 3mE at the Delft University of Technology. The research is conducted in collaboration with Mieloo & Alexander, who have provided me with an internship, supervision, knowledge, insights, and laughter, among others. I was engaged in researching and writing this report from December 2019 to February 2021.

In truth, I could not have achieved my current level of success without the supervision and support I have received throughout this research. I would like to thank my supervisors for their guidance, support, and feedback during this process. To my academic supervisors, dr. W.W.A. Beelaerts van Blokland and prof. dr. R.R. L. Negenborn, thank you for all your feedback, council, and discussions during this research, as it helped me to produce research that is of proper academic standards.

I also like to show my gratitude towards my company supervisor, ir A. Pelser, as you have provided me with guidance, advice, insights, feedback, and much more throughout this research. To extend, I would like to thank all other colleagues at Mieloo & Alexander as well; you took me in, showing me what the business side of life is like. As a result, I was able to develop myself both on a professional level and as a person.

Lastly, I would like to thank my fellow TEL students, friends, family, and girlfriend, for your support during my time at the Delft University of Technology.

I hope you enjoy your reading. Cheers!

Uithoorn, February 2021

Index

Executive Summary

Introduction

In recent years market expansion and globalization have led to new market requirements, which resulted in more complex supply chains. Within these complex supply chains, the lack of visibility and cross-enterprise data-exchange on the whereabouts of goods has led to the occurrence of undesired dwell-time of products between processes, resulting in a decrease in supply chain performance with regards to throughput times. This research addresses the current lack of visibility and cross-enterprise data-exchange in supply chains, by designing a Digital Chain that is based on the combination of IoT-sensor technology and blockchain technology. Through the use of a Digital Chain, undesired dwell-time of goods is diminished, and therefore supply chain performance is improved concerning Service-Level Objectives regarding Throughput Times (SLOTT). A Digital Chain is a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. Digital Chains are expected to improve supply chain SLOTT performance as they provide for upfront, iterative forecasting of arrival times of goods. In this paper the following research question is answered:

- 'What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?'

In order to provide an answer to the above research question, first a literature review is conducted on both Digital Chains and blockchain technology. Afterwards, the design requirements for a Digital Chain are determined and an Efficiency and Performance Analysis Tool (EPAT) is designed and applied to a case-study, to achieve a current-state analysis. Consecutively, the design requirements, obtained theoretical knowledge and insights from the EPAT, are combined and transformed into a future-state design of a Digital Chain. Afterwards, the impact of the design on SLOTT performance is numerically estimated through scenario-testing of the results of the case-study. The research is finalized by providing conclusions regarding the impact of a Digital Chain on supply chain SLOTT performance and future-research recommendations.

Digital Chain

A Digital Chain is a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. The continuous data-updates between the physical and digital space enable a Digital Chain's explicit characteristics such as enhanced simulation, monitoring, analysis, diagnostics, and prediction of the flow of goods within supply chains. These enhancements allow supply chain participants to proactively optimize their operation decisions. Through utility of a Digital Chain, decision-making is improved, and an environment is provided that allows for process optimization and operational forecasting. In general, Digital Chain applications in supply chains are considered as value-adding, decision-making support applications that enable evolvement of supply chain management regarding SLOTT performance. A Digital Chain consists of three main aspects;

I. Data- collection through IoT-sensors
II. Continuous data-exchange of the collected data in real-time through use of blockchain technology
III. Connecting the data of multiple sensors through use of an intelligence layer, in order to produce a digital overview of the supply chain

I.) In order to achieve data-collection from each product that passes an IoT-sensor, each product needs to be individually identifiable by those sensors. This research is focused on performance of supply chains with regards to duration of the flow of goods, so it is of importance that both detection and identification of (individual) products is made possible, as well as the time and location of detection. Visibility of goods throughout the complete supply chain is achieved through the use of Automatic Identification and Data Capture (AIDC or Auto-ID) technologies such as barcodes, QR-codes, and Radio-Frequency Identification (RFID) tags.

II.) A major driving feature of a Digital Chain is the need for frequent and continuous data-exchange between the physical and digital world. Successful implementation of a Digital Chain is dependent on its ability to continuously update the current state of the system, which relates to continuous data-sharing between the physical entity and its digital counterpart. Current, centralized, legacy solutions are unable to handle, process, and exchange data in real-time, and blockchain technology has been identified by academics as a technology that could ensure real-time data-exchange. However research is currently lacking on combining IoT-sensors with blockchain technology in order to create a Digital Chain. During this research a future-state Digital Chain design is created that makes use of blockchain technology as a data-infrastructure middleware layer, in order to overcome the current knowledge gap.

Blockchain technology is a distributed ledger technology in which all transactions are encrypted, shared and recorded in a chronological order. A blockchain network consists of multiple participants, or nodes, that maintain a set of a shared state and modify that state by performing and validating transactions in a peer-to-peer system. Blockchain technology consists of multiple specific, distinctive characteristics that redefine how data-management is handled. Key characteristics of blockchain technology are; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions, and robustness of the system due to its fault-tolerance. All these characteristics combined establish a technology where trust is embedded into the system through use of cryptographical procedures. This enables the opportunity to generate trust-free operations between parties and provides an environment in which the current data-management architecture may evolve. As a result of this secure data-exchange and trustless operations, utilization of blockchain technology provides the opportunity for real-time, cross-enterprise data-exchange.

III.) The last main aspect of a Digital Chain is the intelligence layer. To enable provision of a Digital Chain, entities within the supply chain need to be connected to each other. Connecting the data together by means of an intelligence layer produces a digital overview that represents the physical supply chain. Within this model aspects such as relations, patterns, and flows between different sensors can be derived, and insights regarding performance of a supply chain are obtained.

During this research an EPAT is designed that functions as the required intelligence layer. This EPAT is based on Digital Chain design requirements, KPIs, is and specified to the analyzed case-study. After completion of the EPAT, a current-state analysis of the case-study was performed. From the results of current-state analysis of the case-study it became clear that current handling methods are insufficient with regards to proper and timely handling of incoming load, leading to the presence of undesired dwell-time in the supply chain, leading to a decrease in SLOTT performance.

Design

All obtained knowledge and insights are combined in order to produce a future-state design of a Digital Chain that combines blockchain technology, IoT-sensor technology and the EPAT as an intelligence layer. The philosophy of Digital Chains is translated into a future-state design that is intended to provide real-time visibility and data-exchange with regards to the whereabouts of goods within a supply chain, in order to enable forecasting of future arrival times of these goods and increase supply chain SLOTT performance. Unfortunately, time-limitations of this research did not allow for construction of a complete Digital Chain, but only certain components. Aspects that are included within the Digital Chain future-state design, but that are not covered to full extend during this research, are either based on knowledge obtained from literature or on current existing implementations of that particular technology.

The future-state Digital Chain design covers the complete range of steps necessary to achieve accurate forecasting, from the moment of detection of a tag by a sensor, to the provision of a forecast regarding future arrival times of incoming load. The design describes how data should be converted and implemented into a blockchain, as well as the construction of the forecast that follows from comparing new, incoming data to historical performance of the system. The design displays that once a Digital Chain of a supply chain is produced, through enhancements in simulation, analysis, and diagnostics of the system, insights are obtained with regards to performance and bottlenecks. The Digital Chain design provides the opportunity to compare new, incoming data to historical performance data, in order to predict future arrival/departure times of goods at a certain location. Through continuous updates from the IoT-sensors, the current state of the system is constantly being updated, and alongside it the forecast regarding future arrival times. Every time a transaction occurs on the blockchain, the intelligence layer derives this data and compares it to historical values in order to provide forecasts.

Since blockchain transactions occur every pre-determined period of time, the forecast is updated with every incoming transaction. This (near) real-time, data-exchange provides for continuous updating of the state of the system, enabling the possibility to generate iterative forecasting of incoming load, since the latest forecast is updated with every new blockchain transaction. The continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. When entities are prepared, for example providing sufficient handling capacity at the right time at the right place, transition phases between processes become more fluent and swift. Dwell-time is diminished and therefore the SLOTT performance of the supply chain increases.

Impact Design

After designing a qualitative future-state Digital Chain, the design is applied to the case-study in order to determine its actual impact on SLOTT performance in supply chains. Quantification of the impact of the design is achieved through a numerical estimation of the effect of a Digital Chain, by scenario-testing of the results of the case-study, using the EPAT. During these scenario-tests, the amount of dwell-time that is present at specific entities is reduced towards a level that agrees with the results of the EPAT, to display the impact of undesired dwell-time on supply chain SLOTT performance. Data-analysis of the current-state performance and future-sate performance enables comparison of the two and displays the potential impact of the design. When comparing the current-state performance and future-state performance, based on the available data from the case-study, it becomes clear that utilization of a Digital Chain, when able to diminish dwell-time, is able to improve the SLOTT performance of this particular supply chain between 14-55%, thereby ensuring that five out of eight sub-flows are able to meet the service-level requirements for the complete range of tags within the boundaries of the EPAT.

Conclusion

This research focused on obtaining an answer to the following research question; ‘What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?’. This paper demonstrates that a Digital

Chain-solution should be considered as an interesting proposition to improve supply chain Service-Level Objectives regarding Throughput Times (SLOTT) performance in the near future due to the advancements regarding visibility and business intelligence it accompanies. The combination of IoT-Sensors, blockchain technology, and an intelligence layer enables the design of a Digital Chain that provides for accurate, iterative forecasting of future arrival times of incoming load in supply chains. If a Digital Chain is able to receive continuous data-driven updates in real-time on the actual state of the supply chain, it is able to connect the data from individual sensors and produce forecasts regarding future arrival times of incoming load. The continuous updates, facilitated by data-collection through IoT-sensors and real-time data-exchange through utilization of blockchain technology, enable the ability to adjust a forecast if unforeseen delays occur during a process. These iterative forecasts provide participants of the supply chain with visibility on the whereabouts of products and enables the opportunity to prepare themselves upfront with regards to future incoming load, thereby facilitating for proper and swift transitioning and processing of goods. The insights gained in the performance of different entities, together with the ability to prepare upfront, result in a reduction of dwell-time of products within the supply chain, and therefore improves upon supply chain SLOTT performance. However, more research towards Digital Chain applications is necessary to provide a definitive answer on what the actual impact of Digital Chains on supply chain performance will be.

In order to understand the true potential of Digital Chains, the author recommends further research on various aspects concerning designing Digital Chains. More research towards applications of DT technology in supply chains is requested, to better understand the actual impact Digital Chains might have on processes, decision-making and performance, but also on the issues that present themselves alongside the transition towards utilization of Digital Chains.

During this research, the foundation of Digital Chains, which includes the steps necessary to transform raw data into forecasts, is provided. To explore further evolvement of the future-state design, the combination of the intelligence layer with data-driven 'intelligence' technologies such as Artificial Intelligence and Machine Learning should be researched to more extend, in order to achieve forecast optimization and aspects focused on providing an additional level of control, such as the enablement of dynamic asset and resource allocation based on the provided forecasts.

The last topic of recommendations regarding future research covers the results of the business-case. From the results of the EPAT it became clear that two types of improvements are present that would positively influence SLOTT performance of the supply chain; performance of internal processes of individual entities and overall efficiency of the complete supply chain. This research has focused on the overall SLOTT performance of the supply chain, however the design of the EPAT also provides the ability to focus on the performance of individual processes and/or entities. Conducting specific research on the internal processes of entities, such as in-depth analysis of the process-steps and performance as present within each entity, could lead to the identification and resolving of bottlenecks during the internal processes, leading to a higher level of supply chain performance.

List of Abbreviations

AI - Artificial Intelligence

AIDC - Automatic Identification and Data Capture

API - Application Programmable Interface

B2B - Business-to-Business

BB - Black-Box

CAD - Computer-Aided Design

CPS - Cyber-Physical Systems

DBFT - Delegated Byzantine Fault Tolerant

DT - Digital Twin

EPC - Electronic Product Code

EPAT - Efficiency and Performance Analysis Tool

ERP - Enterprise Resource Planning

IoT - Internet of Things

KPI - Key Performance Indicator

ML - Machine Learning

P2P - Peer-to-Peer

PoA - Proof-of-Authority

PoS - Proof-of-Stake

PoW - Proof-of-Work

RFID - Radio-Frequency Identification

RTI - Returnable Transport Items

SLOTT - Service-Level Objectives regarding Throughput Times

TPS - Transactions per Second

TX - Transaction

WMS - Warehouse Management Systems

List of Figures

List of Tables

Chapter 1 - Problem Definition

This chapter acts as an introduction to the research and illustrates the context of the research. First the problem description is displayed, including aspects such as current situation, problem identification, research gap and scope of the research. Consequently the research relevance and objective are explained, followed by the corresponding research question and sub-questions. The last part of this chapter covers the approach of the research.

1.1 Problem Description

1.1.1 Current Situation

Supply chains can be considered as one of the major cornerstones of both industries and society as present nowadays. A supply chain is a system that is designed to transport products or services between different participants. Parties involved within a supply chain might consist of organizations, enterprises, knowledge, information, activities and resources. Processes within a supply chain ecosystem involve designing, engineering, manufacturing and distribution of products and/ or services (Muckstadt, Murray, Rappold & Collins, 2001).

In recent years, market expansion and globalization have led to new market requirements, which resulted in an increase of intermediaries and therefore more complex supply chains. Due to an increased number of intermediaries between producers and customers, collaboration between parties in the supply chain becomes more difficult, which results amongst others in little knowledge and overview of the business processes that occur within the supply chain. Because of the increase in complexity within supply chains, current chains undergo three major forms of friction, namely information, interaction and innovation friction (IBM, 2017a). All of these friction points have a negative impact on overall performance of a supply chain. Information about the origin, shipping journey and processing of a product often remains limited, which leads amongst others, to dwell-time of products in the supply chain. Dwell-time in a supply chain is considered an undesired phenomenon, as it diminishes SLOTT performance, causing longer arrival times and delays with regards to delivery. As a result of little knowledge and overview of processes that occur within the supply chain, aspects such as visibility, track- and traceability, transparency of product flows and data-management are therefore some of the main challenges within current supply chain management (Kshetri, 2018).

An important aspect of the cause of increased complexity in supply chains is the presence of the digitalization trend, which lead to drastic producer and consumer behavior changes in current years (Botkina et al., 2018). An example of this is the transition to next day delivery, or even same day delivery, from items purchased on the internet. The requirements accompanying these behavioral changes have impacted supply chains and supply chain management, resulting in a continuous strive for further increasing performance. Up until this day, performance and efficiency in supply chains remains one of the main issues (Kshetri, 2018). This research aims to add value to supply chain management decision-making regarding performance of the flow of goods.

However, performance is too broad of an aspect to be addressed in one research, therefore this research is scoped on one major topic within performance. From literature it is derived that cross-enterprise communication should be addressed to enable further evolvement of SLOTT performance within supply chains (Badia-Melis et al., 2015), (Aung & Chang, 2014). The lack of communication between participants of an supply chain, for example regarding arrival times of products, leads to the occurrence of idle/ dwell time of goods between processes and entities, resulting in the occurrence of inefficiencies in a supply chain (IBM, 2017), (Kuo & Liang, 2016). This research focusses on producing an environment where real-time data-exchange is made possible, thereby overcoming communication issues and diminishing dwell-time within supply chains, leading to improved SLOTT performance.

1.1.2 Problem Identification

An example of a regular, basic, multi- entity supply chain is displayed in Figure 1.1. Often a supply chain consists of multiple tiers of suppliers, manufacturer(s), distributor(s), retailer(s) and customer(s). Note that transporters have not been concluded in this example, however they are usually present as entities are spread across different locations. An important aspect that should be noted from this figure are the black lines, including those with arrows, between consecutive entities. These lines are considered communication/data-exchange representation lines between entities. The number of lines present in Figure 1.1 indicate that numerous parties share information with each other. It becomes clear that data-exchange between participants is required numerous amounts of time before a product can arrive at the customer. If there is poor data-exchange between members of a supply chain on the time of arrival/ departure of products, transition process are misaligned and aspects such as provision of sufficient capacity to ensure proper handling of the incoming (peak)load might turn out to be insufficient. When insufficient capacity occurs, dwell time of the products occurs, the supply chain processes will stagnate and performance of the supply chain will decrease. The more complex a supply chain becomes, the more communication lines will be present and the chance of miscommunication between one or more of these entities grows.

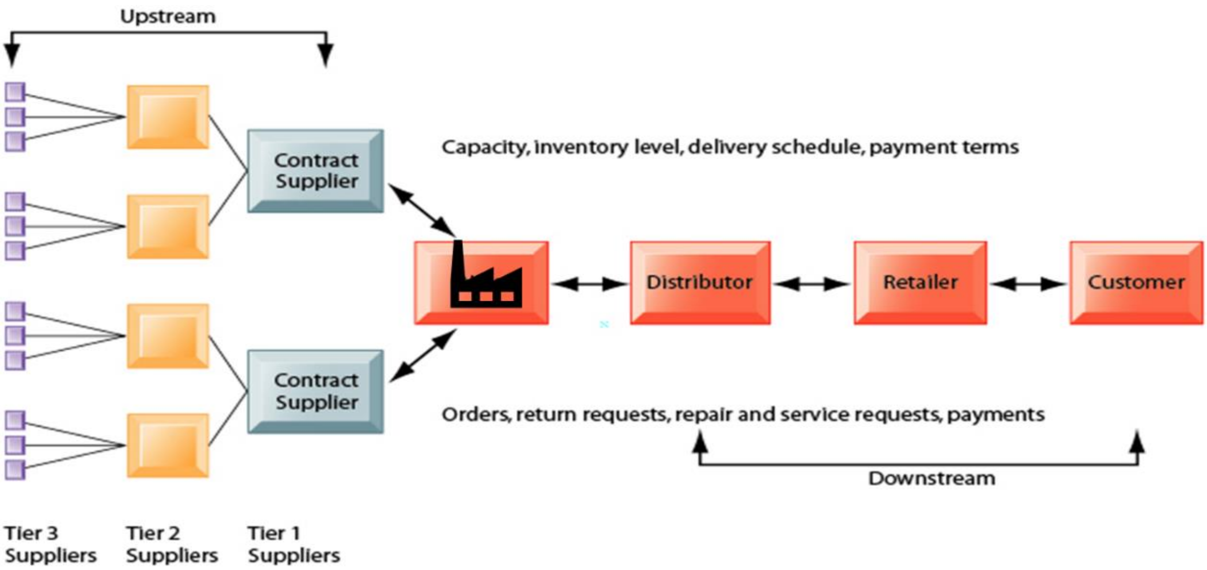


Figure 1.1 An overview of a generic supply chain (Laudon & Laudon, 2006)

In order to address data-exchange related issues, an entity must first be aware of which products are where at what time. Or in other words; an entity first needs to have visibility with regards to internal processes and the whereabouts of goods before communication to other supply chain participants is enabled. With the rise of Internet of Things (IoT) sensors, detection of products throughout a supply chain is more easily made possible and visibility may be automated. However, current enterprise systems are generally of a centralized nature, and this type of structure is regarded by academics to cause limitations to the applicability of IoT technology in the near future, as their data-management abilities will become insufficient (Boschi, Borin, Cesar Raimundo, & Batocchio, 2018), (Dorri, Kanhere

& Jurdak, 2016). These current centralized systems, which are often designed for in-house use, restrict further innovation regarding cross-enterprise information sharing such as visibility, transparency and real-time data-exchange (Liu et al., 2020), (Boschi, Borin, Cesar Raimundo, & Batocchio, 2018), (Biswas, Muthukkumarasamy & Tan, 2017). Without cross-enterprise visibility and data-exchange, it is not possible to diminish dwell-time and take the next steps with regards to improving supply chain SLOTT performance. Therefore, more research is requested towards new data-management technologies that enable the combination of IoT technology with aspects such as visibility and real-time data-exchange in supply chains.

1.1.3 Research Gap

The lack of real-time data-exchange regarding future arrival times of goods between participants of a supply chain has been identified as an issue that restricts progress regarding improving SLOTT performance in supply chains. To enable further evolvement of supply chain management regarding performance, it becomes clear that possible solutions regarding the lack of real-time data-exchange need to be researched to more extend.

In order to enable swift and secure data-exchange, adequate data-management is required. Data-management includes numerous aspects such as data-sharing, data-storage, data-access and data-authenticity. Real-time data-exchange and secure data-management, especially in complex, multi-enterprise supply chains, is difficult since new data is continuously being supplied and processing of this data needs to be swift (Huang, Wang, Yan, & Fang, 2020).

Inadequate handling of data provides the base for the research gap that is currently present in literature, as it leads to issues regarding latency and processing of data.

From Table 1.1 it is concluded that current literature regarding performance in supply chains has identified multiple challenges with regards to data-management. A common, reoccurring aspect that is expressed by numerous scientists regarding the challenges of advancement of data-management is summarized as follows;

- Real-time data-exchange should be further researched.

Table 1.1 Multiple statements from academics regarding the current research gap

'Advancements in data storage & data transmission are required'	(Qi et al., 2019)
'Real-time data extraction is a challenge'	(Wärmefjord et al., 2017)
'Advancements regarding real-time data acquisition are requested'	(Qiu, Zhou, Liu, Gao, & Tan, 2019)
'Latency regarding processing of data'	(Lu, Liu, Wang, Huang, & Xu,2020)

New, emerging technologies have been identified by academics that might improve on data-management and are seeing an increase of attention (Qi et al., 2019). Examples of these technologies are blockchain technology, 5G, AI, edge & fog computing, Distributed File Storage systems, NoSQL- & NewSQL databases, and cloud storage systems. However, most of these technologies need to be explored further to provide insight on future impact. At the time of writing no clear solutions to real-time data-exchange issues are present that can be deployed on a large scale. Therefore further research is requested regarding new technologies that are able to mitigate the current data-management issues.

From literature, the following is concluded: The way current, centralized solutions handle data-management and exchange data cross-enterprise restricts further innovation in supply chain management regarding communication and visibility. This statement is in line with the view of numerous scientists, as they state that Industry 4.0 requires decentralized decision-making (Zheng et al., 2018), (Hermann, Pentek & Otto, 2016), (Schmidt & Wagner, 2019).

Blockchain technology has been identified by academics as a technology that could potentially overcome the issues regarding the lack of real-time data-exchange and data-management issues due to its specific characteristics (Laaper et al., 2017), (Yli-Huumo et al., 2016), (Zyskind, Nathan & Pentland, 2015), (Ramamurthy, 2016), (Huang, Wang, Yan, & Fang, 2020). Blockchain technology is a relatively new technology and more research needs to be conducted in order to understand its potential impact. Little research is especially present towards combining IoT-sensor technology with blockchain technology in order to overcome current supply chain issues regarding the lack of visibility and real-time, cross- enterprise data-exchange.

This research aims to add value to the academic world by conducting further research on combining IoT-sensor technology with blockchain technology, in order to provide real-time data-exchange in supply chains with regards to the whereabouts of goods at a specific time. Utilization of IoT-sensor technology is regarded to overcome the current visibility issues, while using blockchain technology as the main driver for real-time data-exchange is expected to solve communication- and data-management issues. The goal of the research is to improve on supply chain SLOTT performance, by diminishing dwell-time in-between processes.

1.1.3 Scope

The scope of the research objective consists of two parts, in order to further outline the research. The first part of the scope is regarding the flow of goods. Conducting research on SLOTT performance in supply chains through addressing the lack on visibility and communication already defines the nature of the research to some degree, however further narrowing the scope is necessary to be able to provide an in-depth research. Therefore, this research will focus on the flow of goods within supply chains. The flow of goods is one of the major components in supply chains and continuous research on this aspect is requested to keep up with increasing requirements because of the current digitalization trend. The flow of goods in supply chains is also big part of the business processes within Mieloo & Alexander, the company who facilitates this research. Within Mieloo & Alexander, extensive knowledge on supply chain management regarding the flow of goods is available, which will be beneficial during this project.

The next part of the scope is focused on technology. Throughout the years, the digitalization trend has improved performance in supply chains through computer-aided technologies such as computer-aided design (CAD), enterprise resource planning (ERP), Warehouse Management Systems (WMS) (Ross, 1960), (King, Jones & Simner, 2003), (Jacobs & Bendoly, 2003). However, as literature indicates, these technologies are currently unable to fully address issues regarding the lack of real-time (cross-enterprise) data-exchange. More research is requested regarding the implementation of new technologies to overcome the current issues. Both IoT technology and blockchain technology have been identified by academics to be a potential solution for these issues, as they take the digitalization trend to a higher level (Huang, Wang, Yan, & Fang, 2020), (Wang & Haghighi, 2016). Blockchain technology is a distributed ledger technology that is proposed by academics as a possible solution to improve on data-exchange in supply chains because its specific characteristics allow for real-time communication, while IoT-sensors provide for automated, objective, evidence-based data. However, knowledge is missing towards combining these technologies in order to increase SLOTT performance in supply chains. This research is intended to bridge the gap that currently exists regarding the combination of IoT-sensor technology and blockchain technology, by introducing the concept of a Digital Chain and producing a future-state design of such a Digital Chain, to improve supply chain SLOTT performance.

1.2 Research Relevance and Objective

The digitalization trend that has occurred in recent years has led to a difference in consumer behavior. This change in behavior resulted in higher requirements regarding supply chains in order to meet consumer demand. During this period, supply chains needed to adjust in order to fulfill the customers need. These adjustments have led to more complex supply chains, in which there are more participants present, while being spread over larger distances. Due to these complexities, visibility of the flow of goods across the entire supply chain becomes more difficult, the chance of miscommunications increases, and more potential points of friction, such as insufficient handing capacity, are present. All of these aspects have a negative impact on the performance in supply chains.

The objective of this research is improving on supply chain SLOTT performance with regards to the flow of goods, by addressing issues regarding the lack of real-time communication. These issues are addressed by combining two emerging technologies; IoT technology and blockchain technology. As mentioned before, performance is one of most important aspects in supply chains. Therefore, improving SLOTT performance in supply chains is the ultimate objective that was kept in mind during composition of this research. To improve SLOTT performance, this research is focused on addressing issues regarding the occurrence of dwell time of products that is caused by a lack of visibility and lack of data-exchange in supply chains.

1.3 Research Questions

From the objective of this research, the following research question was constructed:

- What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?

In order to enable a complete answer to this research question, the following research sub-questions are answered during this research:

Table 1.2 Overview of the research sub-questions and in which chapter they are answered

Research Sub-Question	Step in Approach	Answered in:
• What is a 'Digital Chain' and how will it impact supply chains? • Is blockchain technology able to provide real-time data-exchange in supply chains?	Exploration of Theory	Chapter 2
• What are the design requirements for a Digital Chain? • Wat is the current-state performance, through use of a case-study?	Design requirements of a Digital Chain & Current-State Performance	Chapter 3

• What should a Digital Chain design, that combines IoT-sensors and blockchain technology, look like?	Future-State Digital Chain Design	Chapter 4
• What is the impact of the design when applied to the case-study?	Impact of Design	Chapter 5

1.4 Approach

This research aims to overcome the current research gap that exists with regards to combining IoT technology and blockchain technology to increase SLOTT performance in supply chains. From theory a fundamental knowledge foundation is obtained regarding the characteristics of both of these technologies, and through use of a case-study a current-state performance analysis is executed. From the obtained knowledge and insights a future-state Digital Chain design is constructed based on the combination of IoT-sensors and Blockchain technology. Then a numerical estimation of the impact of the Digital Chain design is calculated, through data-analysis and comparison of current-state and future state performance of the case-study. Lastly the overall conclusion and recommendations are presented.

This research is structured as displayed in Figure 1.2, alongside the theory-oriented case-study methodology as proposed by Dul & Hak (Dul & Hak, 2007). First a literature study is conducted in order to introduce and define the problem. During this ‘Problem Definition’ phase, first a problem description is present in which the current situation -inefficiencies in supply chains- is analyzed and the problem -lack of real-time communication- is identified. This phase also displays the research gap -little research is present towards combining these technologies in order to increase performance in supply chains- and explains the scope and system boundaries of the research. Also the research objective and relevance are covered, including the research question and its sub-questions. During the ‘Exploration of Theory’, the concept of a ‘Digital Chain’ is introduced and a literature review is conducted on blockchain technology. During this phase the characteristics of these technologies are addressed, as well as their potential impact, current limitations and challenges. The obtained knowledge is then transformed into ‘Design Requirements’, where the requirements of a design solution are derived, the goal of the design is made clear, as well as identification of the KPIs. During this phase also a current-state analysis of a case-study is performed. In the next phase a ‘Future-State Digital Chain Design’ is constructed. From both theory and design requirements a future-state design is produced that combines IoT technology and blockchain technology to enable iterative forecasting, which improves upon the inefficiencies caused by the lack of visibility and data-exchange in supply chains. First an architecture design is constructed to enable an overview of the components of the solution, followed by a more specific, module design. During the ‘Impact of Design’ phase a numerical estimation of the impact of the future-state design on SLOTT performance is obtained through scenario-testing of the data obtained from the previously mentioned case-study. Data-analysis of the current-state performance and future-sate performance enables comparison of the two and displays the impact of the design. The last phase is the ‘Conclusion & Recommendation’ phase, in which the research question is answered and future research is recommended.

An overview of the approach and corresponding chapters of this research is displayed in Figure 1.2.

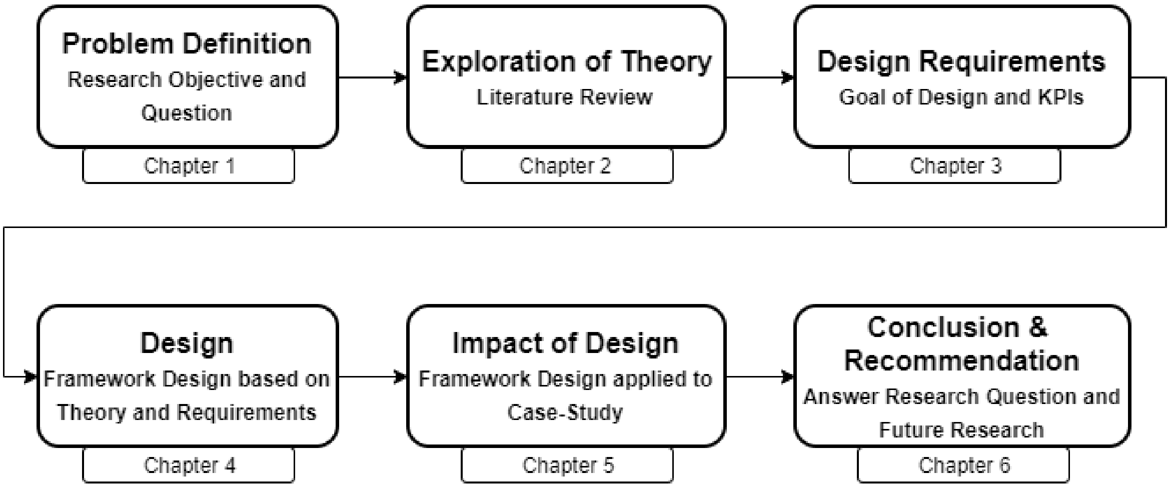


Figure 1.2 Overview of the approach of the research

Chapter 2 - Exploration of Theory

This chapter introduces and explains the concept of a ‘Digital Chain’. Through conducting literature review the first research sub-question is answered; ‘What is a ‘Digital Chain’ and how will it impact supply chains?’. During this chapter also knowledge is obtained regarding blockchain technology and its impact on supply chain SLOTT performance. The nature of blockchain technology is explained to more extend, its characteristics become clear and the following research sub-question is answered: ‘Is blockchain technology able to provide real-time data-exchange in supply chains?’.

2.1 Introduction of the ‘Digital Chain’

The digitalization trend in industrial systems as present in recent years can be divided into four stages; digital enablement, digitalization assistance, digital control and link, and cyber-physical integration (Qi et al., 2019). During these phases, industry networks have shifted from digital conversion of paper documents towards the aim of creating cyber-physical systems (CPS) that are able to merge the physical and digital world together. Through technologies such as Fieldbus, Ethernet, CAD and the current advancements regarding IoT, big data and AI, industrial networks are progressing more and more towards these cyber-physical systems (Lu, Liu, Wang, Huang, & Xu, 2020). A CPS possesses the ability to transform industries and business processes regarding simulation, monitoring and prediction (Rosen, von Wichert, Lo, & Bettenhausen, 2015), (Schleich, Anwer, Mathieu, & Wartzack, 2017), (Tao & Qi, 2019).

IoT technology combined with blockchain technology provides the next step in converging the physical and virtual world, bringing cyber-physical supply chains a step closer towards reality. The combination of blockchain technology, IoT-sensors, and an intelligence layer that connects the data, enables merging of the cyber- and physical space together, thereby opening-up the possibility for further advancement on the digitalization trend (Tao & Zhang, 2017), (Cheng, Zhang & Ji, 2018). Key aspects of a CPS are the connection regarding communication, interaction and exchange of information between the sensor and the intelligence layer. Continuous updating of state changes of the sensor-based data lays the foundation of a CPS. An example of the evolvement towards CPSs in manufacturing environments is present in the form of ‘Digital Twin’ (DT) technology, where the use of sensors and continuous updating is applied to hardware solutions such as analyzing an airplanes’ structural behavior digitally, with the intention of prediction it’s behavior (Tuegel, Ingraffea, Eason & Spottswood, 2011). However, DT technology is aimed at hardware applications, such as airplane engines and manufacturing machinery, and in its current form it is not suited for application in supply chains. Therefore the concept of a ‘Digital Chain’ is introduced, which builds upon both CPS and DT technology, and is focused purely on supply chain application. As displayed in Figure 2.1, a Digital Chain consists of three main aspects;

- Data- collection through IoT-sensors
- Continuous data-exchange of the collected data in real-time through use of blockchain technology
- Connecting the data of multiple sensors through use of an intelligence layer, in order to produce a digital overview of the supply chain

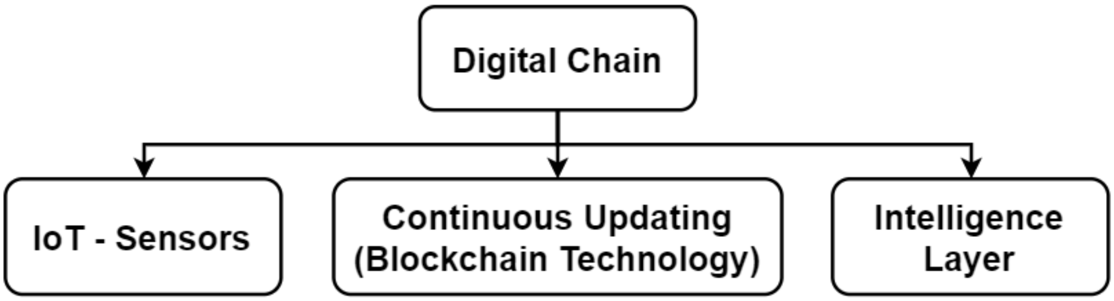


Figure 2.1 Main components of a Digital Chain

2.1.1 Data- collection through IoT-sensors

Sensor technology is a key aspect regarding the effectiveness of a Digital Chain; a Digital Chain is able to reflect the performance of its physical counterpart through continuous updates from sensor-data. Without these continuous sensor-data updates, the Digital Chain is no longer capable of proper representation of the physical world. The collection of data through IoT- sensors has the advantage that the data becomes evidence-based; all data origins from factual occurrences as sensors are only able to detect its actual surroundings. Sensors might monitor aspects such as torque, pressure, vibration, acceleration, voltage, current, temperature, humidity, speed, force, wear and deformation.

IoT technology is considered a major driver of a Digital Chain since it is both able to collect and store data from individual sensors, as well as transmission of this data to processing entities via the internet. All data collected by sensors needs to be transmitted to processing entities in order to enable analyzing of the data. This transmittance of data is enabled through communication technologies that generally make use of internet protocols (Schroeder et al., 2016). Without an internet connection, achieved through wired or wireless networks, no data exchange between sensor technologies and processing technologies would be possible. Wired data- transmission examples consist of coaxial cable transmission, fiber optic transmission and twisted-pair cable transmission, while examples of wireless transmission techniques consist of Wi-Fi, 4G, 5G, Bluetooth, Near Field Communication, and Ultra-Wideband (Lei, 2018).

When designing a Digital Chain of a supply chain with the intention of determining the SLOTT performance of the flow of goods, it is important that the products are tracked and traced. In order to achieve this each product needs to be individually identifiable by a sensor. Visibility of (the flow of) goods throughout complete supply chains can be achieved through use of automatic identification and data capture (AIDC or Auto-ID) technologies such as barcodes, QR-codes and RFID tags. Sensors that are able to detect these hardware Auto-ID components consist of cameras, scanners and antennas, among others. This research is focused on performance of supply chains with regards to the flow of goods, so it is of importance that both detection and identification of (individual) products is made possible, as well as the time and location of detection.

2.2.2 Continuous updating and communication through blockchain technology

A major driving feature of a Digital Chain is the need for frequent and continuous data-exchange between the physical and digital world. An important criterion is the processing architecture regarding latency of data. The performance of aspects such as real-time monitoring, analyzing and controlling are all dependent on latency; the higher the latency, the less accurate a system is. Without an adequate, time-sensitive data-synchronization mechanism, the connection between reality and its digital representation is lost. Successful deployment of a Digital Chain is therefore dependent on its high-performance data-transmission and data-processing abilities of time-series data (Lu, Liu, Wang, Huang, & Xu, 2020). An accurate Digital Chain requires high-performance, low-latency data-transmission that enables real-time communication between the physical and digital world. Due to is specific characteristics, blockchain technology is identified as a solution that provides for real-time communication of sensor-based data.

Blockchain technology in a Digital Chain is considered a data-infrastructure middleware layer that also acts as a data-management layer. The use of blockchain technology as a data-carrier enables real-time communication of sensor-data between the IoT sensor and an intelligence layer, ensuring the possibility for accurate representation of the current state of the system. An in-depth explanation of blockchain technology and how it achieves its specific characteristics, such as real-time communication, is found in paragraph 2.4 'Analysis of Blockchain Technology'.

2.2.3 Connecting data together by means of an intelligence layer to produce a digital overview

To enable design of a Digital Chain, entities within the supply chain need to be connected to each other. If these connections are not present, visibility throughout the supply chain cannot be obtained and further evolvement regarding collaboration becomes difficult. Multiple initiatives in new information technologies are being researched to enable improved connectivity between entities. New information technologies that are often mentioned regarding Industry 4.0 are; Internet of Things (IoT), big data analytics, cloud- & fog-computing, Artificial Intelligence (AI) and blockchain technology (Vistacollege, 2019). The performance of a Digital Chain is dependent on these new information technologies, since these information technologies provide for innovation in regards to data-transmission, data-synchronization, data-storage and data -processing, to name a few. For example, new methods and techniques can be used to address latency issues regarding the processing of data.

Data is obtained from sensors in the physical space and communicated through the blockchain in real-time. The data that is obtained by individual, independent sensors can now be retrieved from the blockchain layer and connected to each other. Connecting the data together by an intelligence layer produces a digital model that represents the physical supply chain. Within this model aspects such as relations, patterns, and flows between different sensors can be derived, and insights regarding performance and efficiency of a supply chain become clear. The recognition and understanding of patterns leads to more intelligent and accurate decision-making, resulting in system optimization and a higher level of performance (Tao & Zhang, 2017), (Kuehn, 2019). Note: Utilization of a specific technology or program that acts as the intelligence layer as discussed above is out of scope during this research due to time-restrictions. The combination of a Digital Chain and emerging intelligence technologies such as AI, Machine Learning (ML), and Big Data is therefore identified as interesting future research, but no further research is conducted during this research.

2.2 Impact Digital Chain in Supply chains

The continuous updating of the as-is state of the supply chain through sensor-data enables frequent synchronization regarding the progress of products throughout the supply chain. Combining the data from different sensors together into a single model of the supply chain results in better understanding, learning and reasoning of the system's characteristics, providing better insights regarding performance of the system.

The combination of IoT devices, blockchain technology and intelligence technologies has the potential to lead to further evolvement of the digitalization trend, since it is able to analyze data from the past and convert it to predict future events. Benefits of such a Digital Chain are the enablement of enhanced; simulation, monitoring, analysis, diagnostics and prediction (Schleich, Anwer, Mathieu, & Wartzack, 2017), (Rosen, von Wichert, Lo, & Bettenhausen, 2015), (Zaccaria, Stenfelt, Aslanidou & Kyprianidis, 2018), (Cai, Starly, Cohen, Lee, 2017), (Boschert & Rosen, 2016). The continuous data-updates between the physical and digital space give a Digital Chain an iterative nature, adjusting the model according to the latest updates. Therefore it is able to represent the performance of a supply chain, including, simulation of the behavior of its physical counterpart, monitoring of the ongoing status, diagnosing of patterns, and prediction of future trends (Schleich, Anwer, Mathieu & Wartzack, 2016), (NIC, 2017) (Qi & Tao, 2018), (Angrish et al., 2017). Through utility of a Digital Chain, supply chain decision-making is improved, processes optimization occurs, and aspects such as anticipatory planning and predictive maintenance is enabled (Negri, Fumagalli, Macchi, 2017), (Rosen, von Wichert, Lo & Bettenhausen, 2015). Utilization of a Digital Chain provides the opportunity for prediction technologies to optimize physical processes, achieve data-driven operation monitoring, diversifying business models and value creation, and develop innovative services (Söderberg, Wärmefjord, Carlson, & Lindkvist, 2017), (Lu & Xu, 2019), (Tao et al., 2018), (Cai, Starly, Cohen & Lee, 2017), (Boschert & Rosen, 2016), (Tao, Zhang, Liu & Nee, 2018).

2.2.1 Chain optimization

The use of a Digital Chain provides entities involved in a supply chain with better understanding of the actions, processes, performance and operating conditions of a product during its supply chain lifecycle. Real-time data captured from sensors attached directly to the physical component enables a higher degree of situational awareness, operation resilience and flexibility. Another benefit is that data collection becomes evidence-based since data originates from sensors, resulting in the possibility for purely data-driven decision-making. These characteristics of a Digital Chain, combined with the recent advancements in operation technologies and information integration technologies, provide the next step regarding the development of smart manufacturing (Lu, Liu, Wang, Huang, & Xu, 2020). A Digital Chain connects the physical world with a virtual one, opening up the possibility for data-driven smart supply chain and/or manufacturing environments. Within this environment, a Digital Chain provides operational visibility and flexibility because of its sensor-connectivity and data-tracking characteristics.

Supply chains and production networks in the future will most likely be heavily affected by cyber-physical systems. In order to virtually represent a supply chain, a Digital Chain needs to connect entities, assets, people and services to each other. These connections between companies provide the opportunity to build digitally connected production networks, enabling optimization of visibility and therefore operational performance, as well as prediction models for future trends and needs in a network.

Through use of a Digital Chain, better understanding of the dynamic processes and working conditions can be achieved, and therefore decision-making can be improved regarding reasoning, planning and actions. Due to the increase in intelligence technologies, multiple Digital Chains can be combined and smart production networks can be constructed that are able to address processes with more flexibility and higher performance, mitigating risks and reducing costs along the way (Bauer, Wollherr & Buss, 2008). Once connected, aspects such as simulation and optimization of both single components and entire production systems are enabled. Aspects affected by smart production networks are planning, control, maintenance, logistics, factory lay-out and product lifecycles, among others (Tao, Qi, Wang & Nee, 2019).

Smart production networks are multiple connected cyber-physical systems that are able to operate together as one system that is capable of responding to dynamic changes in both local production systems throughout the supply chain and external factors (Lu, Peng & Xu, 2019). The high level of adaptiveness, flexibility and agility capabilities of smart production networks enable optimization regarding the complete supply chain; improved decision-making and higher levels of autonomous control can be achieved, resulting in the removal of dwell-times and increased SLOTT performance. Smart production networks are able to monitor, analyze, predict and plan processes based on real-time production statuses of products, and demand. Optimization throughout the complete network results in better performance regarding pre-defined goals by stakeholders; examples are high levels of performance and/or sustainability regarding economic, environmental and social impact.

2.3 Preliminary Concept Design

During previous paragraphs, numerous benefits of utilization of a Digital Chain with regards to supply chain performance are mentioned by academics. These statements from literature are now combined and connected in order to produce a preliminary concept design of a Digital Chain. Figure 2.2 displays this preliminary design.

Digital Chain applications in supply chains can be considered as value-adding decision-making support applications for a wide spectrum of operations (Qiu, Zhou, Liu, Gao, & Tan, 2019). The enhancement of simulation, monitoring, analyzing, diagnostics and prediction aspects allow entities to proactively optimize their operation decisions (Lu, Liu, Wang, Huang, & Xu, 2020). Examples of these optimizations are improved identification, analyzing and addressing of performance bottlenecks such as dwell-time. Other benefits of utilization of a Digital Chain, especially when combined with technologies such as AI and Machine Learning, consist of the ability to perform operational forecasting, which could lead to optimal allocation of assets and resources. A Digital Chain is expected to improve enterprise productivity and performance, reducing both costs and time.

A Digital Chain of a supply chain provides the ability to monitor processes and activities within that supply chain, leading to a higher degree of visibility. Increased visibility enables the possibility to both optimize single processes as well as the operational performance of the complete supply chain, since aspects such as process planning and -scheduling, asset and resource allocations etc. can be tuned until an optimum is found. Design of a Digital Chain provides the ability to optimize the performance of a supply chain through aspects such as simulation, monitoring, analyzing and prediction of different entities or processes. For example, when information regarding future incoming load is predicted beforehand, supply chain participants are able to prepare and optimize asset and resource allocations, production schedules, process- and production planning in advance. The possibility for preparation regarding incoming load in advance, together with continuous iteration regarding the current state of the system while passing through the processes, leads to less friction during transition phases in-between processes, therefore reducing dwell-time and improving on supply chain SLOTT performance.

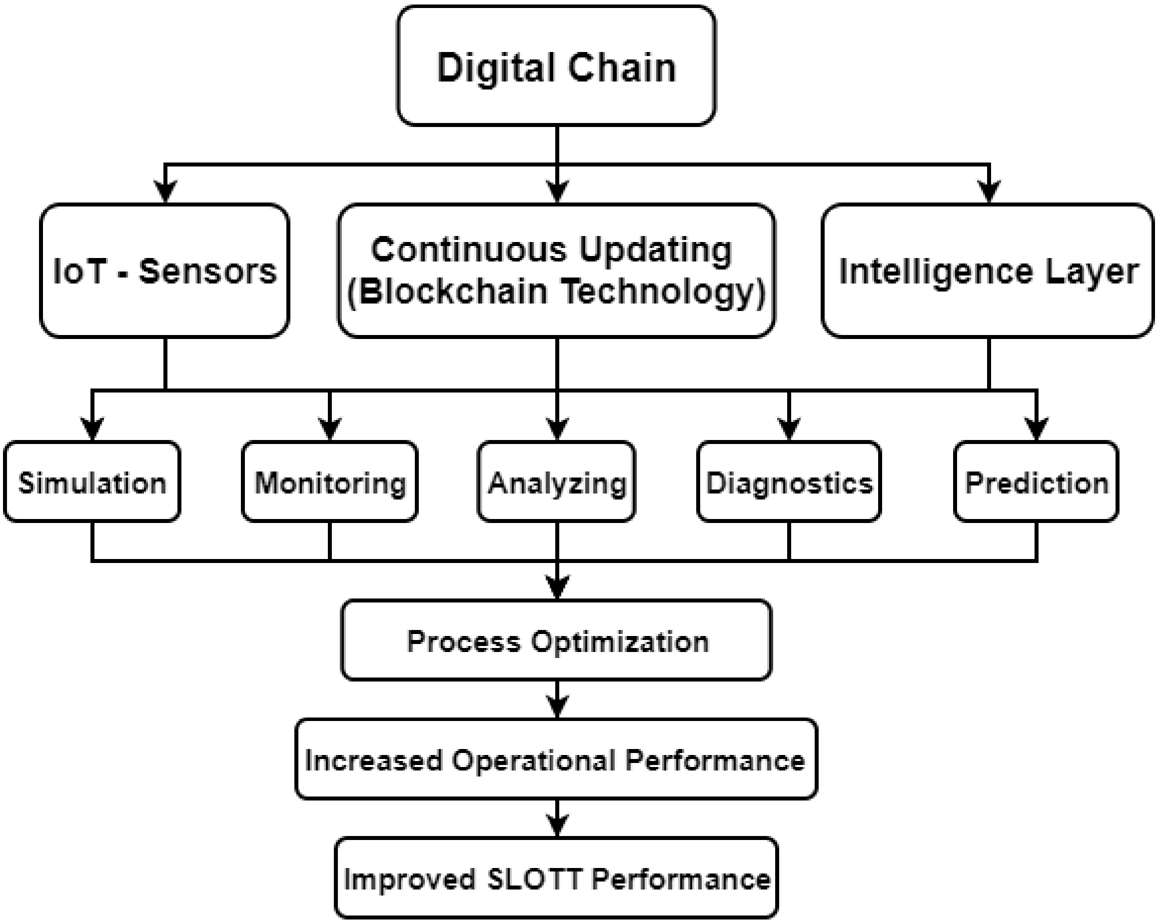


Figure 2.2 Preliminary concept design of a Digital Chain, including its main components, characteristics and impact on supply chains

2.4 Analysis of Blockchain Technology

2.4.1 General information

Blockchain technology emerged in 2008 after the Bitcoin whitepaper was published (Nakamoto, 2008). Benos et al. defined blockchain technology as: “a database architecture which enables the keeping and sharing of records in a distributed and decentralized way, while ensuring its integrity through the use of consensus-based validation protocols and cryptographic signatures” (Benos et al., 2017). Blockchain technology is a distributed ledger technology in which all transactions are encrypted, shared and recorded in a chronological order. A blockchain network consists of multiple participants, or nodes, that maintain a set of a shared state and modify that state by performing and validating transactions in a peer-to-peer system (Tien Tuan Anh et al., 2017). A transaction is a process that changes the state of the blockchain.

One of the biggest innovations blockchain brings to the table is its ability to publicly record, validate and distribute transactions in a decentralized, immutable, encrypted ledger, producing a trust-less environment in which dependency on legal contracts and third parties is no longer required (Swan, 2015), (Tapscott & Tapscott, 2017). Characteristics of blockchain technology, such as asymmetric encryption, chronological linking of blocks by means of cryptographic hashing algorithms, and a distributed communication mechanism are important aspects in construction of this trust-less environment (Schmidt & Wagner, 2019), (Novo, 2018). The distributed nature of the database and its communication network for example, removes the need for a central authority to maintain the ledger, resulting in a system without a single point-of-failure (Dorri, Kanhere & Jurdak, 2016), (Joshi, 2017).

Blockchain’s disruptive technology is considered to have a profound impact on both industries and societies, for example regarding data-management, since it allows organizations, individuals and machines to transact with each other in a different way compared to current legacy systems (Gaehtgens & Allan, 2017), (Novo, 2018). With the introduction of smart contracts, which are self-executing digital contracts, blockchain technology is able to impact even more industries. Embedding smart contracts within a blockchain results in a higher degree of automation, resulting in a reduction of required intermediaries, establishing a more efficient system.

However, since blockchain technology in its current form only exists for around a decade, it is still in the development stage and global adoption has not yet occurred. But during recent years, blockchain technology has already spread across a multitude of industries, including economics, insurance, medicines, supply chain, IoT and software engineering (Huckle, Bhattacharya, White & Beloff, 2016), (Hess, Malahov & Pettersson, 2017), (Yue et al., 2016), (Zhang & Wen, 2016), (Xu et al., 2016). For instance, Walmart has stated that the time required to trace the movement of a shipment of mangoes has been reduced from seven days to 2.2 seconds by implementing blockchain (Mckenzie, 2018). Another example comes from the energy sector, where a consortium of enterprises, including Shell and BP, are developing an blockchain based energy- commodity trading platform (Reuters, 2017).

Blockchain can be used as a registry and inventory system for transacting, recording, monitoring and tracing of assets. These assets can be of different natures, for example financial, physical, legal or electronic (Walport, 2015). Blockchain technology allows for the secure exchange of data within a distributed ecosystem, and therefore could impact the structure and governance of, for example supply chains, as well as relationship configurations and information sharing between different parties. Blockchain technology produces permanent, shareable and actionable records of products’ and services’ digital footprint through business processes and supply chains, leading to a higher degree of visibility (Wang, 2019).

Ownership management is another example of an industry that blockchain might disrupt. Ownership management is mainly used for managing and tracing of property rights and copyrights. Examples consist of real-estate, cars, music, digital publications and art. Difficulties within ownership management consist of product verification, transaction- security and reliability, and privacy protection. Deploying ownership management on a blockchain results in ensuring accurate contract execution trackability of assets. Ownership transactions are confirmed through timestamps and hashing algorithms, proving existence, authenticity and uniqueness of the transactions (Wang et al., 2019).

2.4.2 How does blockchain technology work?

As mentioned above, academic research has identified that utilization of blockchain technology may impact industries and societies to great extend (Gaehtgens & Allan, 2017). However, since blockchain is an emerging technology, in general there is a lack of knowledge on the subject. To see the potential of new technologies, it is important to understand how these technologies work, what it is able to do and what limitations it has. Therefore, this paragraph focusses on understanding blockchain technology, by breaking down the technology into multiple components and explaining each component.

Elements of a blockchain

Traditional databases provide adding, deleting, changing and querying of data. In blockchain systems, only adding and querying data is possible, therefore transactions stored on the blockchain become permanent and undeletable. This immutability and auditability are the result of combining multiple elements of a blockchain.

Three elements make up the core of a blockchain, as displayed in Figure 2.3. These elements are a distributed storage mechanism based on a peer-to-peer network, a time-stamp based chain-block structure, and a consensus mechanism based on decentralized nodes (Yuan & Wang, 2018). These three elements together produce the characteristics of a blockchain, which are cryptographically secured, append-only, immutability, auditability, transaction authentication and integrity, fault tolerance and trust-free operations (Bashir, 2017) (Makhdoom, 2019). These three elements will be explained in more depth. Before doing so, other important aspect such as nodes, transactions and blocks are explained briefly.

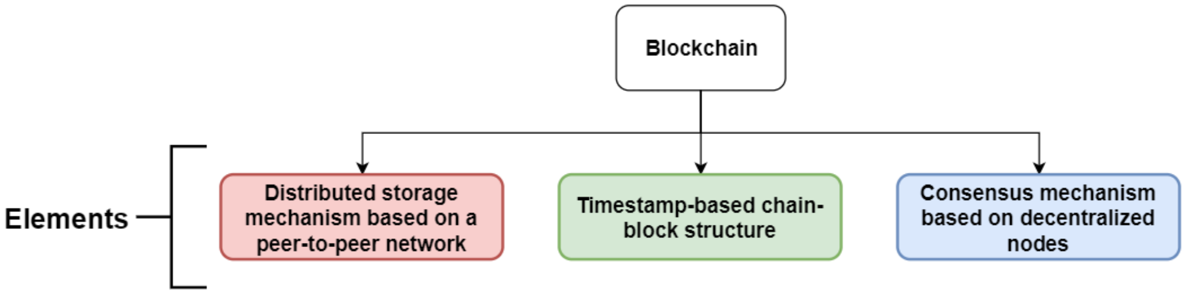


Figure 2.3 Elements of a blockchain

Distributed storage mechanism on a P2P network

The first key element of blockchain technology that is explained is a distributed storage mechanism based on a peer-to-peer (P2P) network. Figure 2.4 displays how a distributed P2P system works (left), compared to a centralized system (right). In the centralized system, five entities are present; four entities that conduct transactions and one central authority that is in control of the transaction ledger. The central authority, in this example represented by a clearing house, maintains and updates the ledger of all participants. All transactions go through this clearing house and it is not possible for entities to send transactions directly between them.

Blockchain technology does not make use of such a centralized structure. The communication and storage mechanism of blockchain technology is based on a distributed network, where all nodes are able to send and receive transactions directly. In a distributed network, there is no need for a central authority who is in control of maintaining the ledger. Instead, all entities have a copy of the ledger. After each transaction, an entity updates the ledger and broadcasts it to all nodes, ensuring that every node has the most recent version.

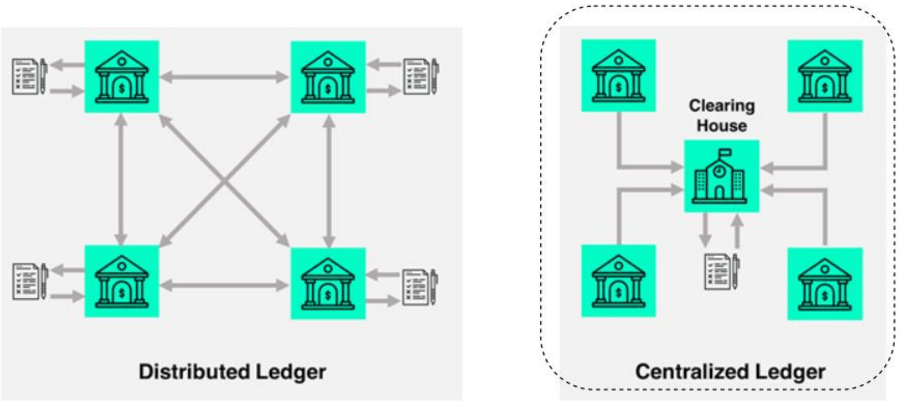


Figure 2.4 Elements of a blockchain - Distributed storage mechanism based on a P2P network (TradeIX Ltd, 2018)

In the centralized system, all nodes are dependent on the central authority. This dependency on a single entity leads to some undesirable vulnerabilities. First of all, it creates a single point-of-failure for the system. If for some reason (technical issues, software bugs, hardware problems, hacks, bankruptcy, etc.) the central authority is unable to maintain and update the ledger, or data is lost, the whole system is affected and may be unable to continue performing its activities. Second, the dependency on a central authority also empowers the central authority to a certain extend. Since the central authority controls the ledger, data- access is controlled by this authority; it is able to decide which transactions are approved, which transactions are denied, and may even restrict access to information or accounts. Another important aspect is the possibility for data-manipulation. Since the central authority is in control of the ledger, vulnerability is present regarding malicious actions of this entity such as data-alteration for personal benefit.

Blockchain technology is able to address these issues. In a distributed network, all nodes have a copy of the ledger and are able to directly communicate to each other. This removes the need for a centralized authority, and therefore vulnerability with regards to a single point-of-failure is eliminated.

However, the distributed storage mechanism on its own is not capable to address the issues regarding data-access management, validation and verification of transactions, and data-manipulation. Explanation of the time-stamped, chain-block structure and the consensus mechanism will provide understanding of how these aspects are managed. An in-depth explanation of these topics is found in Appendix III.

Timestamp-based chain-block structure

The second key element of a blockchain is a timestamp-based chain-block structure. Within this element aspects such as block structure, hashing algorithms, transaction structures and immutability are of importance. Appendix III focuses on explaining how blocks are formed and linked to each other, as well as how transactions are incorporated in these blocks and how transaction-immutability is achieved.

Consensus mechanism based on decentralized nodes

The third key component of blockchain technology is a consensus mechanism based on decentralized nodes. The consensus protocol of a blockchain is of great importance, since it is the core of the blockchain system. It forms the working entity, and both the security and the robustness of the system are provided by the consensus protocol. Implementing a correct and efficient consensus protocol ensures proper functionality of the blockchain and lays the foundation on which the system can grow. If there are flaws in the consensus protocol, malicious actions may occur. An example of malicious actions would be compromising of data recorded on the blockchain. Even worse, if the consensus protocol fails it could lead to cheating of malicious actors, or even a blockchain- fork (Baliga, 2017). Blockchain consensus is considered the agreement of common value among a group of a multitude of nodes within a blockchain system. The consensus protocol of a blockchain is its core element, since it determines the rules for broadcasting transactions, information sharing and replicating states (Viriyasitavat, 2019). Appendix III provides a more in-depth explanation of consensus mechanisms as used in blockchain technology.

2.4.3 Smart contracts

A smart contract is a piece of code deployed on the blockchain, which provides the ability to self-execute when a state change occurs within the blockchain. Smart contracts are series of commitments defined in digital form, who contain both execution conditions and execution logic. When the execution conditions are met, execution logic is carried out immediately and corresponding data is transmitted or released (Christidis & Devetsikiotis, 2016). From a technical standpoint, a smart contract is a web server that is built on top of a blockchain instead of on the internet. This means that smart contracts can host specific contract programs, which ensures a certain degree of automation (Yu et al., 2017). In smart contracts, the rights and obligations of participants, as well as the trigger conditions for execution of the smart contract and corresponding results are specified. Once appended to the blockchain, a smart contract will execute objectively and accurate. Before a smart contract is deployed on the blockchain, other nodes must first verify and validate on the inputs, outputs and states affected by this contract, to ensure that no errors will occur (Tien Tuan Anh et al., 2017). Smart contracts are able to communicate with each other through their individual addresses and application programmable interfaces (APIs) (Ethereum, 2017).

A smart contract will only execute when the change of state complies with the set of conditions that are predefined, via a programming logic, within the smart contract. The rules and consequences within a smart contract are defined similar to those of a traditional legal document, including obligations, benefits and penalties (Gupta, 2017). But since these contracts are written in programming code languages, they are able to auto-execute when triggered, leading to higher levels of automation and more streamlined processes (Barnard, 2017). Because a smart contract has the ability to self-execute, it is considered one of the most important and disrupting parts of blockchain technology (Swan, 2015), (Szabo, 1997a), (Szabo, 1997b).

When combining both blockchain technology and smart contracts, the result is an improvement of synchronization and automation of business operations and processes, which leads to the automation of transferring various types of ownership of assets, property and value (Luu et al., 2016). Applications of industries where smart contracts can be applied in consist of for example auto pay, digital rights management, financial services including loan mortgage and inheritances, supply chain management and smart grids (Huckle, Bhattacharya, White & Beloff, 2016), (Christidis & Devetsikiotis, 2016). Benefits of self-executing smart contracts are a reduction in the need for trusted intermediaries, since contractual conditions such as payment terms and confidentiality can be executed automatically when pre- defined conditions are met. Smart contracts provide users the freedom to ensure only authorized entities have access to their data, without having to trust third parties such as cloud service providers (Khan, Minhaj Ahmad, Salah & Khaled, 2018).

2.4.4 Permissionless vs Permissioned Blockchains

Blockchain networks can be classified in two main categories. These categories are permissionless blockchains and permissioned blockchains. The distinction between permissioned and permissionless blockchains lies in the scheme of ledger sharing, the number of validation nodes regarding the consensus protocol and the allowance to participate in the system (Buterin, 2014). Within the category permissioned blockchains there are also two options, private blockchains and consortium blockchains. More explanation on the characteristics, similarities and differences is found in Appendix III.

2.4.5 Limitations, Challenges and future research

Blockchain technology holds numerous advantages when compared to centralized systems. However, since this technology is still in the development phase, there are multiple issues and challenges that need to be addressed before blockchain technology and smart contracts can evolve to the next stage. Many of these technical hurdles lay within the development of blockchain, such as consensus mechanisms, chain structures, data- and storage management, interoperability and governance. Also regulations concerning blockchain technology are still to be decided. In the near future, issues regarding privacy, security, scalability, latency, transaction throughput and block size need to be addressed before the technology becomes mature. Within these issues and challenges numerous research possibilities can be found to understand blockchain technology better and improve on the current technology (Mougayar, 2016), (Xu et al., 2016), (Casey & Wong, 2017). Appendix III explains these issues to more extend and also provides a blockchain usefulness questionnaire that determines whether or not utilization of blockchain technology will be beneficial.

2.5 Impact Blockchain Technology

2.5.1 Advantages blockchain technology

Nowadays supply chain management consist of mostly centralized systems. Sectors as finance, healthcare and food act as examples; they are often controlled by third-party intermediaries who manage aspects such as decision-making, transactions and data-storage. However, due to the lack of visibility, traceability and transparency, centralized data-management systems are vulnerable to defects in reliability and data accuracy, as well as corruption, tampering and fraud (Abeyratne &

Monfared, 2016). When a supply chain is breached, the businesses within this supply chain will undergo damage. Often products will be recalled and businesses will receive negative publicity, resulting in a reduction of sales and/ or reputation loss. During investigation of the breach, until the origin is detected, related products are affected and sometimes businesses are even completely shut down (Kshetri, 2018). Because of lacking visibility, traceability and transparency within the supply chain, the economic impact of a breach can be quite severe.

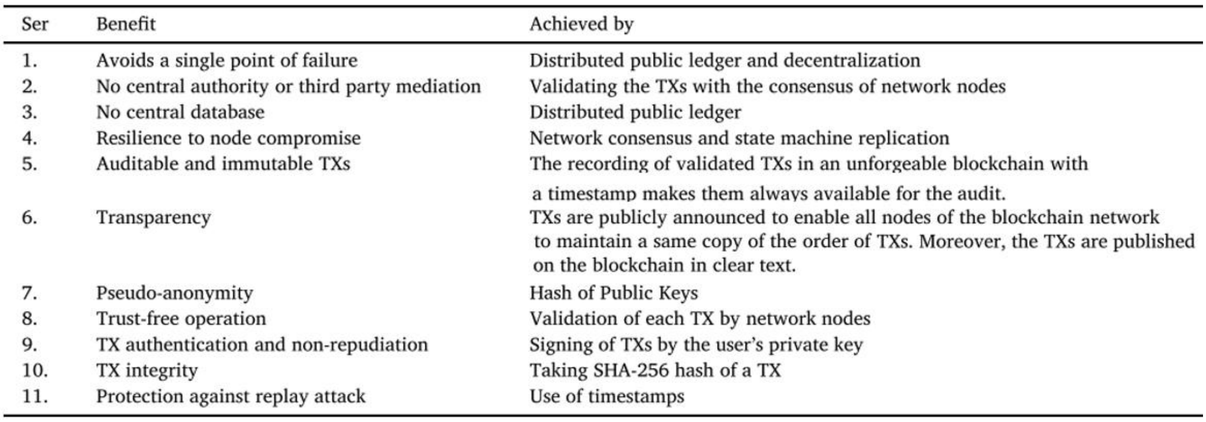
A good track- and traceability system aims to minimize the production and distribution of bad quality products by improving the labeling and tracking systems. Enhanced traceability could mitigate the high costs and risks of quality issues, such as recalls, reputation damage and the loss of revenue (Wang, 2019). In recent years, track and trace systems already have been improved by implementing sensors and transitioning their data management from paperwork to the internet (Aung & Chang, 2014), (Badia-Melis et al., 2015). Track and trace systems used nowadays have improved traceability over the recent years, but because of their centralized nature, they still cannot guarantee the integrity of collected and shared data from/ with other supply chain participants, nor can they update the systems' state in real-time.

Eliminating centralized authorities, by using a distributed ledger system, improves on these aspects. Blockchain technology combines data that was originally stored in local databases of proprietary stakeholders to a single ledger, thereby improving on visibility and flexibility. This results in a more dynamic supply chain with improved business resources (Swan, 2015), (IBM, 2017a). Blockchain enhances tracking and tracing from origin till destination, while maintaining a formal registry from all transformations during this process. An example of this registry is capturing the environmental conditions of a product during transportation, such as temperature and humidity (Reid, 2015).

Implementing a blockchain system, combined with smart contracts, results in a more efficient system regarding production, logistics and cash flow operations. No more traditional labor intensive actions are required to update the flow of goods, since these operations can be incorporated within a single database-layer. Notifications are send to participants near real-time when a state change in the system has occurred. Logistic operations are improved since notifications of status alterations are delivered to stakeholders in real-time, at nearly the exact moment of execution, which results in a reduction of dwell-time in-between processes. Integrating certain control points during the processes further enhances the tracking, tracing and visibility of the goods. Shipping times, shipping conditions and delivery statuses are examples of implementations of these control points.

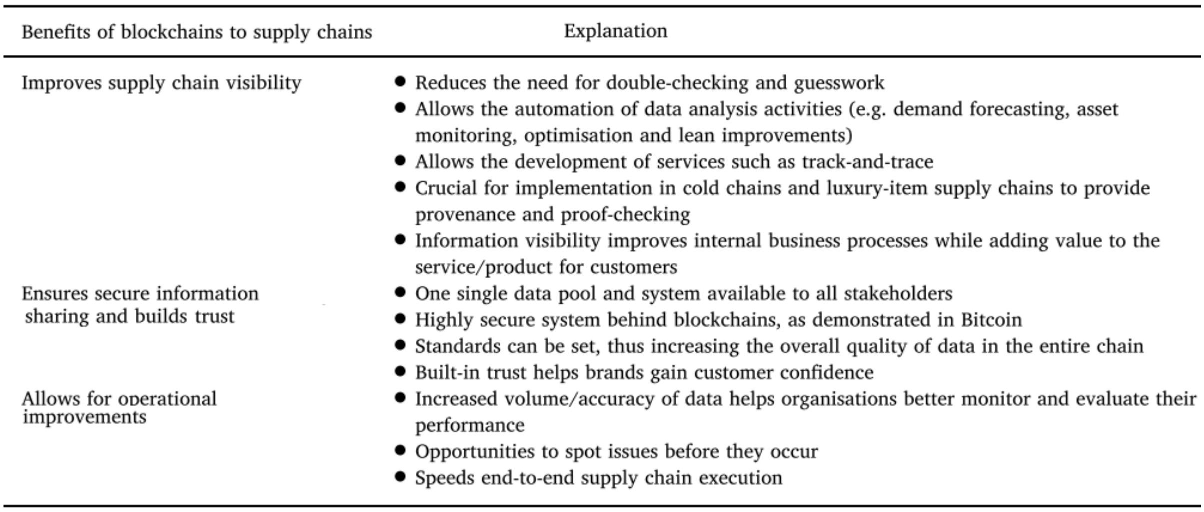
Blockchain technology can be constructed to provide cross-organizational traceability in which participants such as producers, suppliers, distributors, retailers and quality supervisors could all benefit. Within supply chains, relationship management can be improved by using blockchain technology, since it is able to cope with the complexity and diversity that occurs when engaging with multiple shareholders (Casey & Wong, 2017). Because data can be collected real-time, participants can view the production processes, transportation and sales of the products, which results in an improvement of trust between the participants and therefore a stronger multi-party alliance (Chen et al., 2016). Table 2.1 and 2.2 give an overview of numerous benefits of blockchain technology in general, and in supply chains.

Table 2.1 Benefits of blockchain technology (Makhdoom, 2019)



Ser	Benefit	Achieved by
1.	Avoids a single point of failure	Distributed public ledger and decentralization
2.	No central authority or third party mediation	Validating the TXs with the consensus of network nodes
3.	No central database	Distributed public ledger
4.	Resilience to node compromise	Network consensus and state machine replication
5.	Auditable and immutable TXs	The recording of validated TXs in an unforgeable blockchain with a timestamp makes them always available for the audit.
6.	Transparency	TXs are publicly announced to enable all nodes of the blockchain network to maintain a same copy of the order of TXs. Moreover, the TXs are published on the blockchain in clear text.
7.	Pseudo-anonymity	Hash of Public Keys
8.	Trust-free operation	Validation of each TX by network nodes
9.	TX authentication and non-repudiation	Signing of TXs by the user's private key
10.	TX integrity	Taking SHA-256 hash of a TX
11.	Protection against replay attack	Use of timestamps

Table 2.2 Benefits of blockchain technology in supply chains (Wang, 2019)



Benefits of blockchains to supply chains	Explanation
Improves supply chain visibility	● Reduces the need for double-checking and guesswork ● Allows the automation of data analysis activities (e.g. demand forecasting, asset monitoring, optimisation and lean improvements) ● Allows the development of services such as track-and-trace ● Crucial for implementation in cold chains and luxury-item supply chains to provide provenance and proof-checking ● Information visibility improves internal business processes while adding value to the service/product for customers
Ensures secure information sharing and builds trust	● One single data pool and system available to all stakeholders ● Highly secure system behind blockchains, as demonstrated in Bitcoin ● Standards can be set, thus increasing the overall quality of data in the entire chain ● Built-in trust helps brands gain customer confidence
Allows for operational improvements	● Increased volume/accuracy of data helps organisations better monitor and evaluate their performance ● Opportunities to spot issues before they occur ● Speeds end-to-end supply chain execution

2.5.2 Impact Blockchain Technology in Supply Chains

Data-management

The purpose of data-management is to keep data accessible, integrity-driven and confidential. Sometimes trade-offs between enhancing transparency and preserving privacy are required (Dinh et al., 2018). Within supply chains that use local, internal, centralized databases to store data, the accessibility of data depends on communication between different participants, since this is the only way to obtain required non-locally stored information (Xu et al., 2016).

Nowadays, long term financial and relational commitments are often required to build trust within a supply chain (Schoenherr, Narayanan & Narasimhan, 2015). To counteract corruption, tampering and fraud without these long term commitments, an ecosystem embedded with trust needs to be established between different parties within the supply chain. Due to the characteristics of the blockchain a more transparent, authentic and trustworthy environment can be ensured (Laaper et al., 2017). To achieve security, both reliability and authenticity must be established. The data integrity of a blockchain ensures this security (Yli-Huumo et al., 2016). Blockchain also ensures access control and tracking of products and services across borders among supply chain participants, as well as activity logging and transfer of proprietary property (Ethereum, 2017). For example, blockchain technology allows for shipping notifications, invoices, purchasing orders, change orders receipts, inventory data and other trade related documents, (Wang et al., 2019). Product and shipping details are collected and validated, after which they are recorded on the blockchain. Once added on the blockchain, because of its immutability, the record becomes permanent and cannot be altered (Zyskind, Nathan & Pentland, 2015), (Ramamurthy, 2016).

Because of the presence of numerous intermediaries, an extensive amount of manual labor actions, paper-based transactions and business frictions are required to share data within a supply chain. This results in a low service efficiency of the supply chain (Kuo & Liang, 2016). Efficiency can be gained by digitalizing document transfers and acceleration of dataflow, especially within an supply chain in which cross-border activities occur. Traditionally, to track a cross-border shipment, a lot of steps have to be taken. There are numerous partners present, who often use their own IT systems and databases, making integrating of these systems very difficult (Wang, 2019). An example can be found within the shipping industry. In 2014, Maersk tracked a shipment of refrigerated goods from East Africa to Europe. During this transport, more than 200 different interactions and communications between nearly 30 participants were required to be able to deliver the goods. Each interaction within this process is vulnerable to errors, delays and fraud to documents, resulting in an inefficient and unreliable system (Barnard, 2017), (IBM, 2017b).

A typical supply chain is displayed in a simplified manner in Figure 2.5, including the flows regarding goods, information and money. As mentioned before, tracking and tracing play a major role within supply chain management and are considered the key components on which business logic and processes are build. Traditionally, local databases are often used and maintained by individual enterprises. Therefore tracking and tracing require a lot of labor resources and manual operations to update and confirm a process status. Methods such as email, phone calls, web- based services, and ERP are typically used by enterprises to manage and exchange data between different parties, both internal and external (Min & Zhou, 2002). Exchanging data, due to these self-owned local databases, often becomes time consuming and expensive. These time consuming and labor intensive tasks result in a system where real-time tracking is near impossible (Chang, 2019).

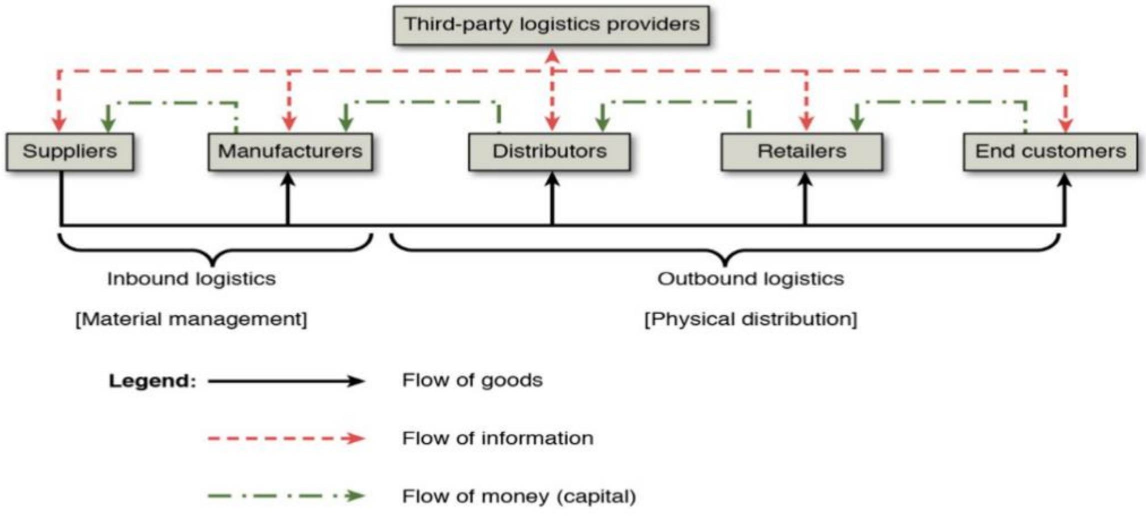


Figure 2.5 Typical, multi-entity supply chain (Min & Zhou, 2002)

Track and trace systems, based on AUTOID technologies like RFID, combined with blockchain technology, are considered the next step in the evolution of the supply chain. Data collected through IoT-sensors is stored on the blockchain to produce a transparent, reliable and secure platform that ensures quality, authenticity and information credibility. Malicious actors are no longer able to disrupt the supply chain and in case of an emergency, measures can be taken directly to prevent the risk of hazard spreading (Tian, 2016).

2.6 Preliminary Concept Design (Extended)

The advantages of utilization of blockchain technology are now included within the preliminary concept design of paragraph 2.3. As a result, an extended preliminary concept design is constructed that includes; the components of a Digital Chain, the role of blockchain technology, advancements regarding insights due to the specific characteristics of a Digital Chain, and the impact a Digital Chain has on supply chains. Figure 2.6 displays this preliminary concept design.

Four major aspects that define blockchain technology are; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions and robustness of the system due to its fault-tolerance. These characteristics of blockchain technology enable the ability to provide trust-less operations. These trust-less operations result in evolvements with regards to data-accessibility, enabling aspects such as real-time data-exchange throughout the supply chain.

The combination of data-collection through use of IoT-sensors and utilization of blockchain technology as a data-infrastructure middleware layer to facilitate real-time data-exchange lead to provision of continuous updating of the current state of the supply chain. When continuous updating is combined with an intelligence layer that connects the data of individual sensors into one digital overview of the complete supply chain, the concept of a Digital Chain is realized and its' advancements regarding supply chain optimization may be displayed.

Design of a Digital Chain provides the ability to optimize the performance of a supply chain through aspects such as simulation, monitoring, analyzing and prediction of different entities or processes. For example, when information regarding future incoming load is predicted beforehand, supply chain participants are able to prepare and optimize asset and resource allocations, production schedules, process- and production planning in advance. The possibility for preparation regarding incoming load in advance, together with continuous iteration regarding the current state of the system while passing through the processes, leads to less friction during transition phases in-between processes, resulting in process optimization. As a result of the increased visibility and data-exchange regarding the whereabouts of goods at a specific time, operational performance increases, dwell-time is diminished and supply chain SLOTT performance is improved.

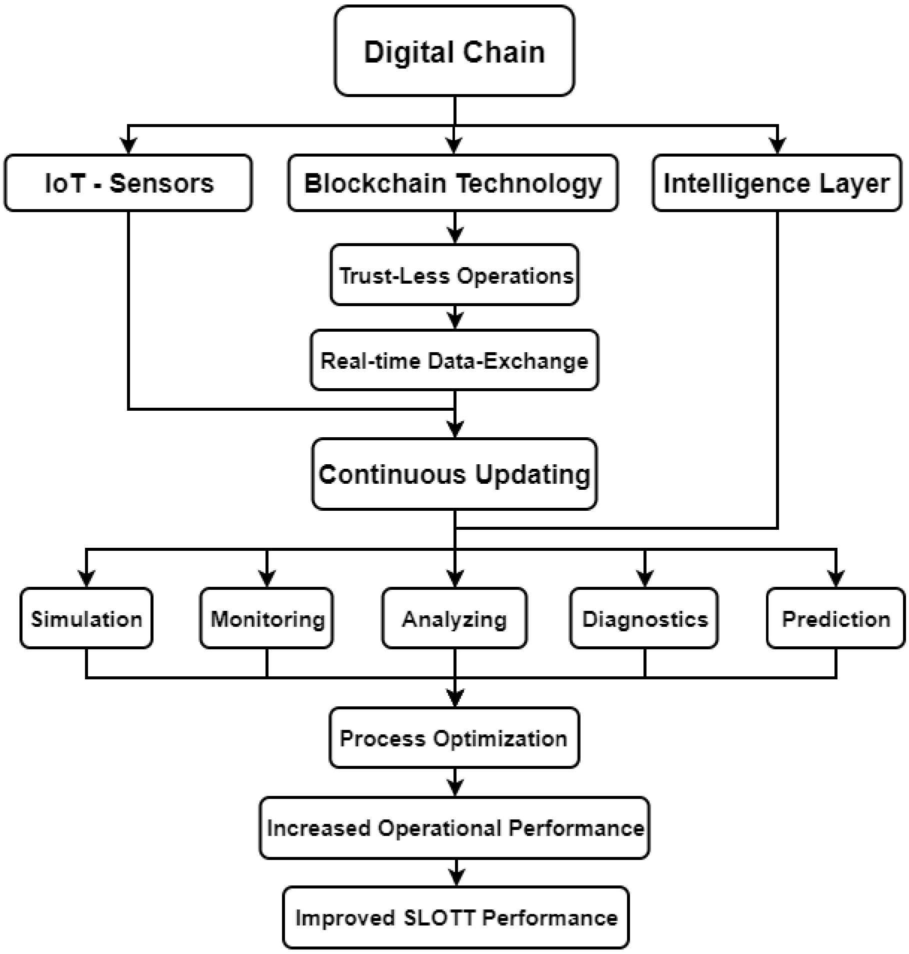


Figure 2.6 Extended preliminary concept design of a Digital Chain, including its main components, characteristics and impact on supply chains

This paper focusses on designing a Digital Chain that provides for an environment where supply chain SLOTT performance is improved by reducing dwell-time that occurs in-between processes of different entities. In order to achieve this goal, the advancement regarding predictions is further explored by designing a Digital Chain that allows for upfront forecasting on future arrival times of goods at a specific location.

The preliminary concept design provides a foundation on which the next steps towards supply chain SLOTT performance optimization may be built. When a Digital Chain is able to receive continuous data-driven updates in real-time on the current state of the supply chain, it is able connect the data from individual sensors and compare it to historical performance. The result of this comparison provides the opportunity to produce forecasts regarding future arrival times of incoming load at a certain location. As the state of the system is continuously updated, it becomes possible to achieve iterative forecasting of incoming load, as the latest forecast is updated with every new incoming transaction. These continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. When entities are prepared, transition phases between processes become more fluent and swift. Dwell-time is diminished and therefore the SLOTT performance of a supply chain improves. The following chapter displays the design requirements necessary to produce a Digital Chain that is able to create forecasts based on real-time information provided by RFID-sensors, in order to improve on SLOTT performance.

2.7 Conclusion Exploration of Theory

This chapter answered the following research- sub questions: ‘What is a Digital Chain and how will it impact supply chains?’ and ‘Is blockchain technology able to provide real-time data-exchange in supply chains?’. During this chapter knowledge is obtained from literature on both Digital Chains and blockchain technology. Their specific characteristics and advantages are explained, as well as their impact on supply chains. This chapter explains that a Digital Chain consists of three main components;

I. Data- collection through IoT-sensors

In order to achieve data-collection from products that pass an IoT-sensor, each product needs to be individually identifiable by a sensor. This research is focused on performance of supply chains with regards to duration of the flow of goods, so it is of importance that both detection and identification of (individual) products is made possible, as well as the time and location of detection. Visibility of goods throughout the complete supply chain is achieved through use of AIDC, or Auto-ID, technologies such as barcodes, QR-codes and RFID tags.

II. Continuous data-exchange of the collected data in real-time through use of blockchain technology

A major driving feature of a Digital Chain is the need for frequent and continuous data-exchange between the physical and digital world. Successful implementation of a Digital Chain is dependent on its ability to continuously update the current state of the system, which relates to continuous data-sharing between the physical entity and its digital counterpart. Current, centralized, legacy solutions are unable to handle, process and exchange data in real-time, and blockchain technology has been identified by academics as a technology that could ensure real-time data-exchange. However research is currently lacking on how to combine data from IoT-sensors with blockchain technology in order to design a Digital Chain. During this research a future-state Digital Chain design is constructed that makes use of blockchain technology as a data-infrastructure middleware layer.

Through literature, it became clear that blockchain technology consists of multiple specific, distinctive characteristics that redefine how data-management is handled. Key characteristics of blockchain technology are; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions and robustness of the system due to its fault-tolerance. All these characteristics combined construct a technology where trust is embedded into the system through use of cryptographical procedures. This enables the opportunity to produce trust-free operations between parties and provides an environment in which the current data-management architecture may evolve. As a result of this secure data-exchange and trustless operations, utilization of blockchain technology provides the opportunity for real-time, cross-enterprise data-exchange.

III. Connecting the data of multiple sensors through use of an intelligence layer, in order to produce a digital overview of the supply chain

The last main aspect of a Digital Chain is the intelligence layer. To enable design of a Digital Chain, entities within the supply chain need to be connected to each other. Connecting the data together by means of an intelligence layer produces a digital overview that represents the complete physical supply chain. Within this model aspects such as relations, patterns, and flows between different detection points are derived, and insights regarding SLOTT performance of a supply chain become clear.

Based on obtained knowledge and statements from academics regarding Digital Chains, a preliminary concept design of a Digital Chain is constructed that includes; the components of a Digital Chain, the role of blockchain technology, advancements regarding insights due to the specific characteristics of a Digital Chain, and impact a Digital Chain has on supply chains. A Digital Chain is a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. The continuous data-updates between the physical and digital space enable a Digital Chain's explicit characteristics such as enhanced simulation, monitoring, analyzing, diagnostics and prediction of the flow of goods within supply chains. These enhancements allow entities to proactively optimize their operation decisions. Through utility of a Digital Chain, decision-making is improved, and an environment is produced where aspects such as processes optimization and operational forecasting are enabled. In general, Digital Chain applications in supply chains are considered as value-adding, decision-making support applications that enable evolvement of supply chain management regarding SLOTT performance.

This research is focused on designing a Digital Chain that provides for an environment where supply chain SLOTT performance is improved by reducing dwell-time that occurs in-between processes. In order to achieve this goal, the advancement regarding predictions is further explored by designing a Digital Chain that allows for upfront forecasting on future arrival times of goods at a specific location. After obtaining knowledge on the key aspects of a Digital Chain, the next step towards design of a Digital Chain is translation of the preliminary concept design into actual design requirements. The following chapter covers these design requirements, as well as the translation of these design requirements towards actual supply chains, through current-state analysis of a case-study.

Chapter 3 - Design requirements of a Digital Chain & Current-State Performance

So far this research has covered the potential impact Digital Chains may have on supply chains as described by academics. During this chapter the knowledge obtained from previous chapters is combined and transformed into specific design requirements for a Digital Chain framework design that can be used in actual supply chains. This chapter answers the following research sub-questions: 'What are the design requirements for a Digital Chain?' and 'Wat is the current-state performance, through use of a case-study?'

3.1 Design Requirements

The goal of the Digital Chain is to produce an environment where SLOTT performance is improved by reducing dwell-time that occurs in-between processes. From the goal of reducing dwell-time to improve on SLOTT performance, multiple requirements become clear:

- Performance is based on time spend in the supply chain, therefore measurements with regards to time are required

During this research, performance is purely based on the amount of time goods spend in the supply chain. The shorter the amount of time goods spend in a supply chain, while processes remain equal, the higher the performance of a supply chain. In order to determine the time goods spend in the supply chain, measurements with regards to time need to be performed on at least the initial entering and final exiting of goods present in the supply chain. However, utilization of multiple checkpoints throughout the supply chain is preferred as they provide more insights on performance of individual parts of the supply chain. Other aspects related to SLOTT performance, such as economic efficiency in the form of labor costs and/ or costs related to operation of assets and resources, are not taken into account during this research. Although cost-efficiency is a major factor in businesses, it is left outside of the scope during this research.

- Use of IoT sensors is required to provide visibility of the flow of goods throughout the supply chain

In order to enable reduction of dwell-time that is present in-between processes, first the existing processes need to be identified and understood. If it is unclear which processes are present within the supply chain, as well as the sequential order of goods passing through these processes, it is not possible to determine if and where dwell-time occurs. The flow of goods need to be made visible in order to enable further supply chain performance optimization. Designing a Digital Chain of a supply chain to enable performance optimization therefore requires the presence of strategically placed sensors/detection points throughout the supply chain, in order to both visualize the flow of goods and divide the supply chain into multiple sections. As derived from literature, AUTOID technology is currently the go-to technology when it comes to identification of individual products.

IoT-sensors that accompany the use of AutoID solutions require fixed positioning in order to function properly. This means that they are static once installed, and unable to move during operation. Since they are static, it is important to position them strategically within the supply chain to ensure precise, useful insights of process durations, such as beginning and end of value-add processes. By strategically placing these detection points, duration and/ or dwell-time between processes/ locations can be made visible. During detection of an AUTOID tag two aspects are of importance; identification of the tag and precise moment of detection. The possibility of identification of individual tags allows for connecting different sensor-data together, since the data can be assigned to a specific tag. By connecting data from different sensors, relations are made visible and performance can be calculated.

During this research the performance of entities present in the supply chain is evaluated. In this research performance is calculated based on time. Each location has two detection points where tags are being detected. The moment of first detection at an inbound process at location i is called Location i IN, while the moment of first detection at an outbound process is called Location i OUT.

Figure 3.1 displays a generic overview of a supply chain that consists of multiple entities, spread across 'N' locations. Besides the locations, also transport is present between two locations.

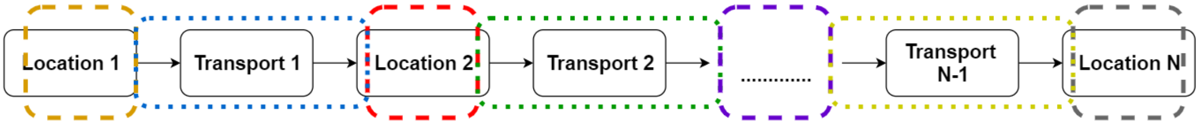


Figure 3.1 Generic overview of a supply chain, including detection points (vertical lines)

- Data acquired by individual sensors is send to an intelligence layer in order to connect data from multiple sensors together and display SLOTT performance of specific parts of the supply chain, as well as the complete the supply chain.

In order to reduce dwell-time that is present in-between processes within the supply chain, first the performance of different parts of the supply chain need to be obtained. This comes down to acquiring data regarding throughput time of different processes or sections by connecting the data from all individual sensors into a single digital overview. This digital overview is created through utilization of an intelligence layer. This intelligence layer is of key importance, as it provides for visibility of the flow of goods and enables for calculation of supply chain SLOTT performance and efficiency.

The vertical, colored, dotted lines in Figure 3.1 at each location show the moments of detection of that particular entity. The left vertical line of a rectangle displays the inbound, or 'IN', moment of detection, the right vertical line of the same rectangle displays the outbound, or 'OUT', moment of detection. By subtracting the values of both of these detection moments, the time-difference/ throughput time of that entity is obtained. Note that the moments of detection do not have to match the exact moment of arrival of departure of products at an entity; they might be installed at the beginning of end of specific value-add services or key processes.

One of the key features during this research is the design of an Efficiency and Performance Analysis Tool (EPAT) that act as an intelligence layer. This EPAT is of significant importance during analysis of performance of a supply chain, as it provides for measuring of the SLOTT performance. The EPAT is explained to more extend in the coming paragraphs.

3.1.1 KPIs

This research is aimed at improving SLOTT performance of the supply chain. In this regard, the goal of the design is to easily display the performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. The design serves as a data-analysis tool and provides insight in the duration of the flow of goods throughout the supply chain. In order to achieve these goals the following key performance indicators are required:

- Performance of the individual entities of the supply chain, based on time [h]
- Performance of the complete supply chain, based on time [h]
- Efficiency of the complete supply chain, compared to current service-levels [%]

Combining the sensor-placement explanation to the above KPIs leads to the following formulas:

- Actual performance of the individual entities of the supply chain, based on time [h]
    - Performance internal process of individual entity

$$(t_{Location\ i\ OUT} - t_{Location\ i\ IN}) \qquad , i \geq 1$$

    - Performance of cross-enterprise transition process

$$(t_{Location\ i\ IN}) - (t_{Location\ i-1\ IN}) \qquad , i \geq 2$$

- Actual performance of the complete supply chain, based on time [h]

$$\sum_{i=1}^{N}(t_{Location\ i\ OUT} - t_{Location\ i\ IN}) + \sum_{i=2}^{N}(t_{Location\ i\ IN} - t_{Location\ i-1\ OUT}) \qquad , N \geq 2, i \geq 1$$

In the formulas, ‘t’ represents the moment of detection, and ‘i’ represents the number of a specific location within the sequential flow. ‘N’ equals the number that belongs to the last location-entity present in the supply chain during the summation.

The actual performance of the complete supply chain is calculated by adding up all the outcomes of the individual entities instead of subtracting $t_{Location1\ IN}$ from $t_{LocationN\ OUT}$. The KPI is calculated this way to provide for more accurate throughput times, since the values of numerous detected tags over a relative long period of time may need to be sorted and combined to diminish outliers and provide a duration period that reflects reality most accurately. Figure 3.2 below shows how the KPIs are combined and displayed per tag. When a large number of tags is detected over an extensive period of time, the performance of the individual entities as well as the complete supply chain is displayed in percentiles to provide a clear overview of the general performance.

	$\Delta t_{Location1}$	$\Delta t_{Transport1}$	$\Delta t_{Location2}$	$\Delta t_{Transport2}$	$\Delta t_{Location3}$	Δt_{Total}
Tag 1						
Tag 2						
…						
Tag X						

Figure 3.2 Exposition of KPI display-structure after calculation

- Efficiency of the complete supply chain, compared to current service-levels [%]

In order to display the effect of utilization of a Digital Chain, the current efficiency needs to be compared to the efficiency after application of a Digital Chain. To ensure that both the current and future efficiency are compared to a stationary benchmark, they are both compared to the current service-level. The service-level can be considered as a predefined goal set by high-level decision-makers. It is assumed that large amounts of goods will pass through the supply chain, resulting in obtaining large amounts of data. In order to ensure that the data remains clear, the data is divided into percentiles. These percentiles are compared to the service-level to provide a quantification of the efficiency of the supply chain. The formula is displayed below;

$$\frac{\Delta t_{\text{Service-level}}}{\Delta t_{\text{Total\_percentileX}}} \quad \text{X } 100$$

3.2 Current-State Performance (EPAT)

In order to display the impact of utilization of a Digital Chain, the future state should be compared to the current state. Therefore, the KPIs of the current state should be calculated first. In order to compare the current performance to the performance after application of a Digital Chain, this research makes use of a case-study to enable quantification of the impact of a Digital Chain.

As mentioned before, one of the key features during this research is the design of an Efficiency and Performance Analysis Tool (EPAT) that acts as an intelligence layer. This EPAT is of significant importance during analysis of performance of a supply chain, as it provides for measuring of the SLOTT performance. The goal of the EPAT is to easily display the performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. The EPAT serves as a data-analysis tool that provides insight in the duration of the flow of goods throughout the supply chain, by transforming the design requirements into measurable Key Performance Indicators (KPIs). Note that an EPAT is specific for a particular supply chain.

M&A has provided a case-study from their repository in which IoT sensors are already installed, to ensure a Digital Chain can be produced. Also blockchain usefulness is checked through the questionnaire found in Appendix III. This particular supply chain consists of multiple entities that are scattered over different locations. Within their supply chain, multiple different, consecutive stages are equipped with RFID technology, and transport is present between each of the locations.

In the current situation, there is no overview of the duration of processes of the supply chain and therefore the KPIs as necessary do not exist. In order to provide proper KPIs of the supply chain, an EPAT needs to be designed based on sensor-data from RFID tags that pass the supply chain.

Before continuing with an explanation of the EPAT, an important aspect must be noted. The data from this company, as well as their identity, will be kept confidential during this report. All results from the EPAT are anonymized and indexed, no sensitive information is present that can be linked to the company.

3.2.1 Case-Study Analysis Steps

An important aspect of this research is aimed at gaining insights in the SLOTT performance of the supply chain and to identify if and where possible improvements might be possible. The goal of the EPAT is to easily display the SLOTT performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. The EPAT serves as a data-analysis tool and provides insight in the duration of the flow of goods throughout the supply chain.

The following steps are undertaking in order to design a EPAT of which the output is equal to the KPI’s:

- General analysis of the inland inbound supply chain

During this general analysis understanding of the supply chain on a high level is achieved. The flow(s) of the supply chain are identified, as well as the number of participants, the order of which products pass through the supply chain and where RFID detection points are installed.

- The next step is to determine which detection points should be used during the analysis

Not all data from installed readpoints might be useful during this analysis. Therefore, during this step the readpoints that provide necessary information are identified. In addition to identification of useful readpoints, also more insight is provided on important aspects that should be taken into account when using a specific readpoint, as well as the impact it might have on the results of the EPAT.

- Filtering out excessive data

The raw data as provided by the company is not sorted and includes useless, unwanted data. During this step the data is filtered until it suits a format that enables proper functioning of the EPAT.

After the data is filtered, the EPAT is able to calculate the actual values for each of the entities of the supply chain. These values are incorporated in the framework in order to become part of the KPIs.

- Combining all results in order to produce the required KPIs

Once all values are obtained, they are combined to produce the required KPIs and therefore enable insights in the current performance and efficiency of the supply chain, including the ability to identify if and where possible improvements are possible.

Important: The analysis is based on real data from a listed company and might include sensitive data. Approval of usage of this data was given under the condition of an NDA that prohibited public access to this data. Therefore all results and all information regarding this company have been generalized. The actual results from this analysis are found in Appendix I & II for those authorized.

3.2.2 General Analysis of the Inland Inbound Supply Chain

This paragraph explains the different flows, readpoint placement at locations and theoretical duration times in more detail, in order to provide more insights in the processes.

Flows

As discussed before, the inland inbound supply chain can be divided into two main flows, as displayed in Figure 3.3.

- Flow 1:

- Flow 2:

Figure 3.3 Overview of the flows present within the supply chain of the business-case

As derived from Figure 3.3, both flows start at Location 1. From Location 1, by means road transportation, all products are transported to Location 2 for a first round of internal processes. Location 2 is a hub for most of Europe, which means that products that are inbound at Locations may have destinations all across Europe. At Location 1, resources regarding sorting of products and customs is lacking, therefore all products must go from Location 1 to Location 2. At Location 2 the first sorting steps take place, for example separating products based on inland or foreign destination. Also customs is present at Location 2. Since both customs and the first sorting steps take place at Location 2, it is not possible to go from Location 1 straight to one of the other locations.

This research focusses on the inland inbound supply chain, so from this point on this paragraph will disregard tags that have a foreign destination; it will focus only on tags that are detected at inland locations.

The two flows start to differentiate from the moment Location 2 is left. Flow 1 consists of tags that go from Location 2 (,through road transport,) straight to one of the final inland locations. There are five local locations, also referred to as local sorting centra, present in this country. This means that during the analysis, Flow 1 is divided into five different sub-flows. The steps of each sub-flow are displayed below:

- Location 1 → Location 2 → Location 3
- Location 1 → Location 2 → Location 4.1
- Location 1 → Location 2 → Location 4.2
- Location 1 → Location 2 → Location 4.3
- Location 1 → Location 2 → Location 4.4

Note that the final locations consist of the numbers, 3, 4.1, 4.2, 4.3 and 4.4. The difference between number 3 and the numbers 4.X originates from the difference between Flow 1 and Flow 2. Within Flow 1, location 3 is one of the final destinations of this supply chain. However, regarding Flow 2, Location 3 functions as an additional, necessary step in the supply chain.

Flow 2 differs from Flow 1 since it incorporates an extra sorting step. This sorting step takes place at Location 3. Taking in consideration that Location 3 is also present as a final location in Flow 1, the sub-flows of Flow 2 consist of:

- Location 1 → Location 2 → Location 3 → Location 4.1
- Location 1 → Location 2 → Location 3 → Location 4.2
- Location 1 → Location 2 → Location 3 → Location 4.3
- Location 1 → Location 2 → Location 3 → Location 4.4

3.2.3 Determining detection points

In order to conduct a proper analysis of the supply chain, it is important to understand where in the process tags are being detected and what can be concluded from these readpoint placements.

Location 1

Figure 3.4 displays the layout of Location 1. From this figure is derived that two different readpoints are utilized to the flow of goods. The readpoint deemed Location 1 IN is indicated with the most upper of the two orange squares, and covers a readpoint on a conveyor. This readpoint is selected as starting point of the supply chain mainly because of the high accuracy of the RFID reader compared to the readers located at the docking doors at inbound; The read accuracy of readpoint Location 1 IN is around 98%. The readpoint Location 1 OUT is located at the outbound docking doors, indicated with the lower of the two orange squares at Figure 3.4.

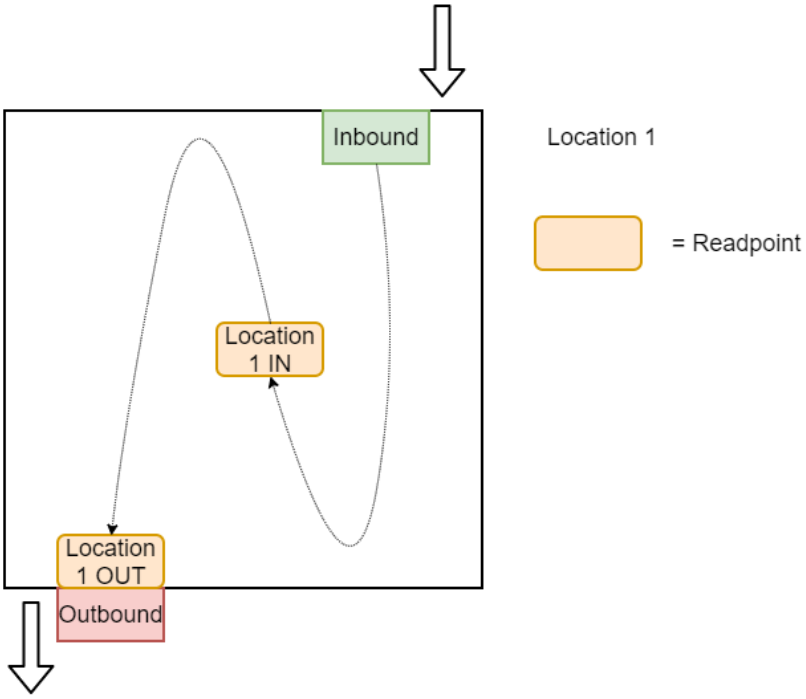


Figure 3.4 Schematic overview of placement of readpoints of location 1

From Figure 3.4 it becomes clear that a few aspects should be taken into account due to the placement of the readpoints at Location 1. These aspects are:

- ‘Black box’ regarding starting point of EPAT and starting point in reality

In the EPAT, the starting point of the analysis is when a tag is first detected at readpoint Location 1 IN. However, in reality the starting point would be at the moment a tag enters the facility through one of the docking doors. So the time between passing through the docking doors and first detection at readpoint Location 1 IN are not taken into account. This means that in reality the time a tag is present at Location 1 is higher than the outcome of the EPAT. However, due to the lack of objective measurements regarding this time period it remains unclear what the difference might be. Therefore the assumption is made that the time between these starting points is negligible compared to the duration of the total supply chain.

- Location of readpoint Location 1 OUT

Readpoint Location 1 OUT is located right above the docking doors of the outbound loading area at Location 1. Location 1 OUT is measured at the exit point of Location 1. Due to the limited range of the RFID antenna, most likely tags are detected at the moment they are being loaded into a truck for transportation. Therefore, possible dwell time at Location 1 will occur outside of the range of the RFID reader. As a result, the time a tag spends at Location 1 is assumed to be relatively high because of the inclusion of possible dwell time.

Location 2

Within Location 2 there are numerous RFID readers present, as displayed in Figure 3.5.

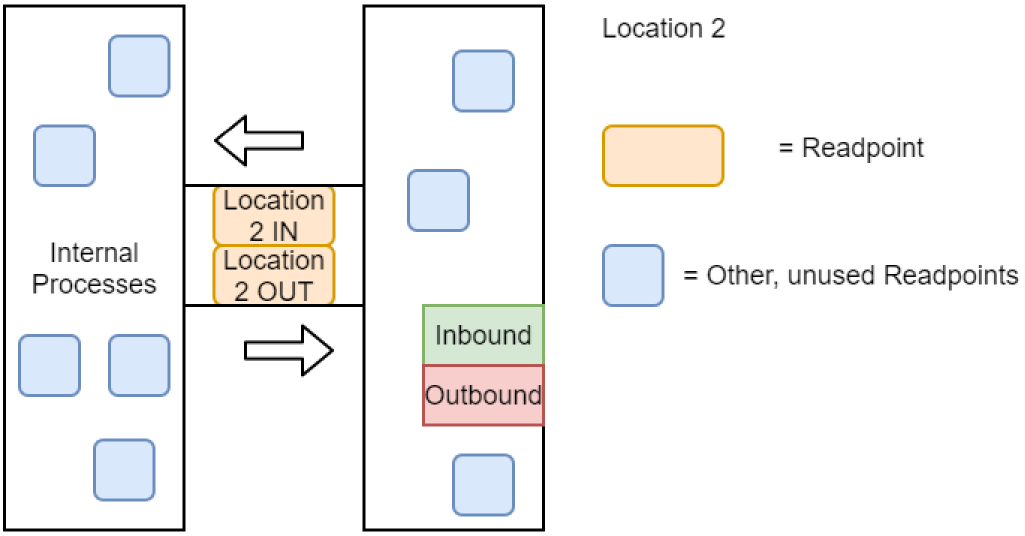


Figure 3.5 Schematic overview of placement of readpoints of location 2

The research behind the analysis of this supply chain is focused on both displaying the efficiency and performance of cross-enterprise supply chain processes, as well as identifying where inefficiencies may be present. In order to achieve insights in the SLOTT performance of the supply chain, it is important to recognize where and when value-add processes start and stop. The value-add processes at Location 2 start and stop at a particular readpoint. This readpoint is indicated in Figure 3.5 with the orange squares, and besides its beneficial geographic location it also has the benefit that all products pass this detection point. This readpoint is located in a hallway that connects the loading/unloading area (right of readpoint) with the internal, value-add processes (left of readpoint). Due to the specific position of this readpoint, both Location 2 IN and Location 2 OUT are measured at this point. Location 2 IN equals the first time a tag is detected at that readpoint, while Location 2 OUT equals the last time a tag is detected while 'Bizstep= Entering'. The term 'Bizstep= Entering' is explained in the paragraph 'Filtering of the raw data', further down this chapter.

From Figure 3.5 it becomes clear that a few aspects should be taken into account due to the placement of the readpoints at Location 2. These aspects are:

- Dwell time at Location 2

The choice to use that particular readpoint as detection point for both Location 2 IN and location 2 OUT enables the EPAT to incorporate possible dwell time at the loading and unloading areas at Location 2. Within the EPAT different tag reads are connected to each other, and by combining the use of the chosen readpoint at Location 2 with applying logic, it is possible to identify dwell time at specific locations. A more detailed explanation of how logic is applied is found during the paragraph 'Results', further down this chapter.

- Internal processes are considered a 'black box'

The numerous RFID readpoints installed inside of Location 2 provide the opportunity to gain insight in the performance of the internal processes. However, this research is focused on global supply chain SLOTT performance and therefore internal processes are out of scope. The internal processes of Location 2 are considered as a ‘black box’ and are not part of this in-depth analysis of the supply chain.

Location 3

At Location 3 only one readpoint is utilized, as displayed in Figure 3.6. This readpoint is located at the end of the loading/ unloading area and forms the border between inbound/outbound processes and the internal processes. All products at this location pass this detection point.

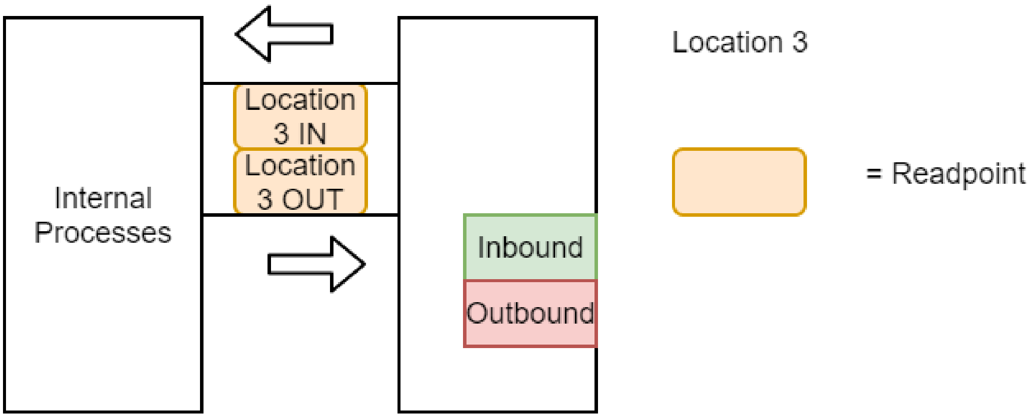


Figure 3.6 Schematic overview of placement of readpoints of location 3

From Figure 3.6 it becomes clear that a few important aspects should be taken into account due to the placement of the readpoints at Location 3. These aspects are:

- Time spend within Location 3

Both the inbound and outbound flow of products occurs at only one loading/ unloading area at Location 3. This means that tags should pass the readpoint at least two times. These multiple detection moments enable the EPAT to calculate the time a product spends within Location 3.

From Figure 3.6 it becomes clear that one important aspect should be taken into account due to the placement of the readpoint at Location 3;

- Dwell time during inbound operations at Location 3

The placement of the readpoint enables the EPAT to incorporate possible dwell time at the loading and unloading area at Location 3 during inbound operations. Within the EPAT different tag reads are connected to each other, and by combining the use of the readpoint at Location 3 with applying logic, it is possible to identify dwell time at specific locations.

Location 4.X

Locations 4.1, 4.2, 4.3, 4.4 all have similar schematic lay-outs, see Figure 3.7. Equal to Location 3, the RFID readpoints are placed at the end of the loading/ unloading area, forming the boundary between inbound/ outbound operations and internal value-add processes.

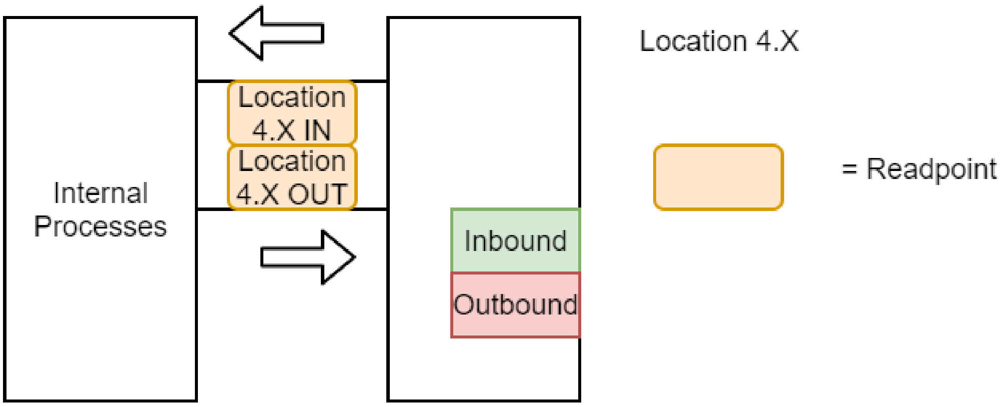


Figure 3.7 Schematic overview of placement of readpoints of location 4.X

From Figure 3.7 it becomes clear that a few important aspects should be taken into account due to the placement of the readpoints at Locations 4.X. These aspects are:

- Time spend within the locations

Both the inbound and outbound flow of products occurs at only one loading/ unloading area at the locations. This means that tags should pass the readpoint at least two times. These multiple detection moments enable the EPAT to calculate the time a product spends within that particular location.

- Dwell time during inbound operations

The placement of the readpoint enables the EPAT to incorporate possible dwell time at the loading and unloading area at the locations during inbound operations. Within the EPAT different tag reads are connected to each other, and by combining the use of the readpoint at Location 3 with applying logic, it is possible to identify dwell time at specific locations.

- Outbound detection last point of measurement

The readpoints at the Locations 4.X are the final locations of this analysis. After leaving location 4.X, a product still needs to pass some more processes before it reaches its final destination. However, no RFID readpoints are present after leaving on of these locations, and therefore no RFID tags will be detected after leaving location 4.X. This analysis is based on objective, RFID-based sensor-data, and because there is no trustworthy data available after leaving location 4.X, the analysis stops after the last time an outbound tag is detected at one of these locations.

3.2.4 Filtering Out Excessive Data

The actual filtering steps and results from this step are found in Appendix I for those who are authorized. Some specific aspects the author deems worth mentioning that are covered during this paragraph are depicted below:

- Raw data was obtained from all of the readpoints that are installed at the different entities in the supply chain. The raw data covered a period of approximately one year, from April 2019 – March 2020.

- The last filtering steps consist of removing tags that fall outside of contractual obligations and of tags of which the data is incomplete or illogical. For example, obligations regarding maximum allowed time spend in a particular part of the supply chain only apply for business days, and not for weekends. Therefore, only tags that are detected first at Location 1IN between Monday 01:00 hours and Friday 18:00 hours are included. Tags that are detected outside of this time period are excluded from the analysis.
- Items that pass through customs at Location 2 are part of different contractual agreements, therefore different rules apply to them with regards to the period of time they are allowed to spend within specific parts of the supply chain. In general these tags take longer to run through the supply chain compared to ‘normal’ tags, since they can be stationary at customs for quite some time. In order to ensure proper analysis of the ‘normal’ flow of the supply chain, tags that pass through customs are filtered out since they may influence/ pollute the data
- Lastly also tags that represent returnable transport items (RTI’s) were filtered out, as they pollute the data.

3.2.5 Combining and Visualizing of KPIs

During this chapter the different flows, as well as readpoint placement at specific locations and theoretical duration times have been discussed isolated from each other. Combining these different aspects provides a base for the analysis and produces a reference framework that enables visualization of the KPIs. Figures 3.8 and 3.9 visualize the combination of all three aspects.

- Flow 1:

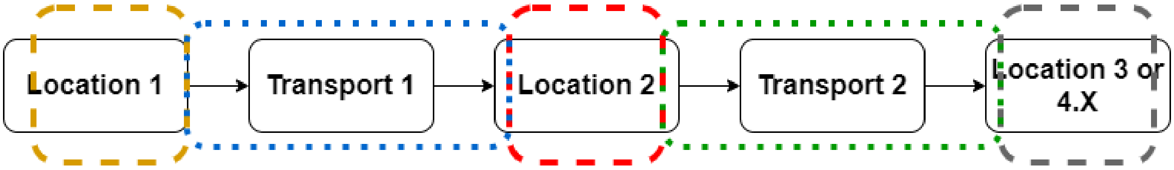


Figure 3.8 Visualization of the components of Flow 1

- Flow 2:

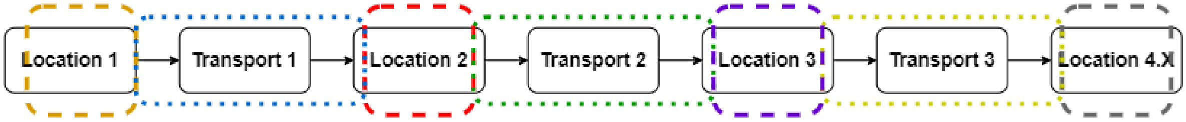


Figure 3.9 Visualization of the components of Flow 2

From Figure 3.8 and 3.9 a few aspects should be derived:

- The order of how products pass through the inland inbound supply chain.

The sequence of processes as present in the supply chain is indicated by a block scheme connected through arrows. The left side of each block represents the arrival of products at a specific point within an entity, while the right side of each block represents the departure of products from a specific point of an entity.

- The colored, dotted rectangles display the exact moment of tag detection with regards to the processes that occur at that particular entity.

Through the presence of two vertical boundaries per colored rectangle it becomes clear that each step in the supply chain generates two key detection moments. From these boundaries two items should become clear:

- Ability to measure time-difference

At each step in the supply chain two different timestamps are obtained, one that equals start of internal processes and one that equals end of internal processes. The time difference between these two timestamps represents the time a product has spent in that part of the supply chain

- Displays the detection moments compared to the time spend within an entity

The majority of entities present in the supply chain enables detection of tags at the start of their internal, value-add processes. However, the time of value-add processes may not match the time spend at that particular entity. The placement of the vertical boundaries equals the moment of detection of a tag within an entity, displaying whether a possible occurrence of dwell time within that entity may occur. For example, detection point Location 1OUT (right, dotted, vertical, orange line at Location 1) is on top of the boundary of Location 1 itself. This indicates that the moment of detection of readpoint Location 1Out is equal to departure from entity Location 1. When looking at Location 2, it becomes clear that the block of Location 2 is wider than the tag detection box (red dotted rectangle). This indicates that the time a tag spends on Location 2 may differ from the detected moments during the start or ending of the internal value-add processes. This difference provides the opportunity to identify possible dwell time and therefore displays inefficiencies and /or bottlenecks within the supply chain.

By combining all the aspects that are mentioned above a template is constructed that easily visualizes the KPI's. At this stage all preparations are completed. It is now time to run the EPAT and incorporate the results into the framework to achieve the required KPI's.

3.3 Results Analysis Current-State Performance

While running the EPAT, raw data is combined, ordered and processed in such a way that it enables production of the KPI's. For each entity in each flow the data is first collected separately, and afterwards combined to enable an overview of the entire sub-flow.

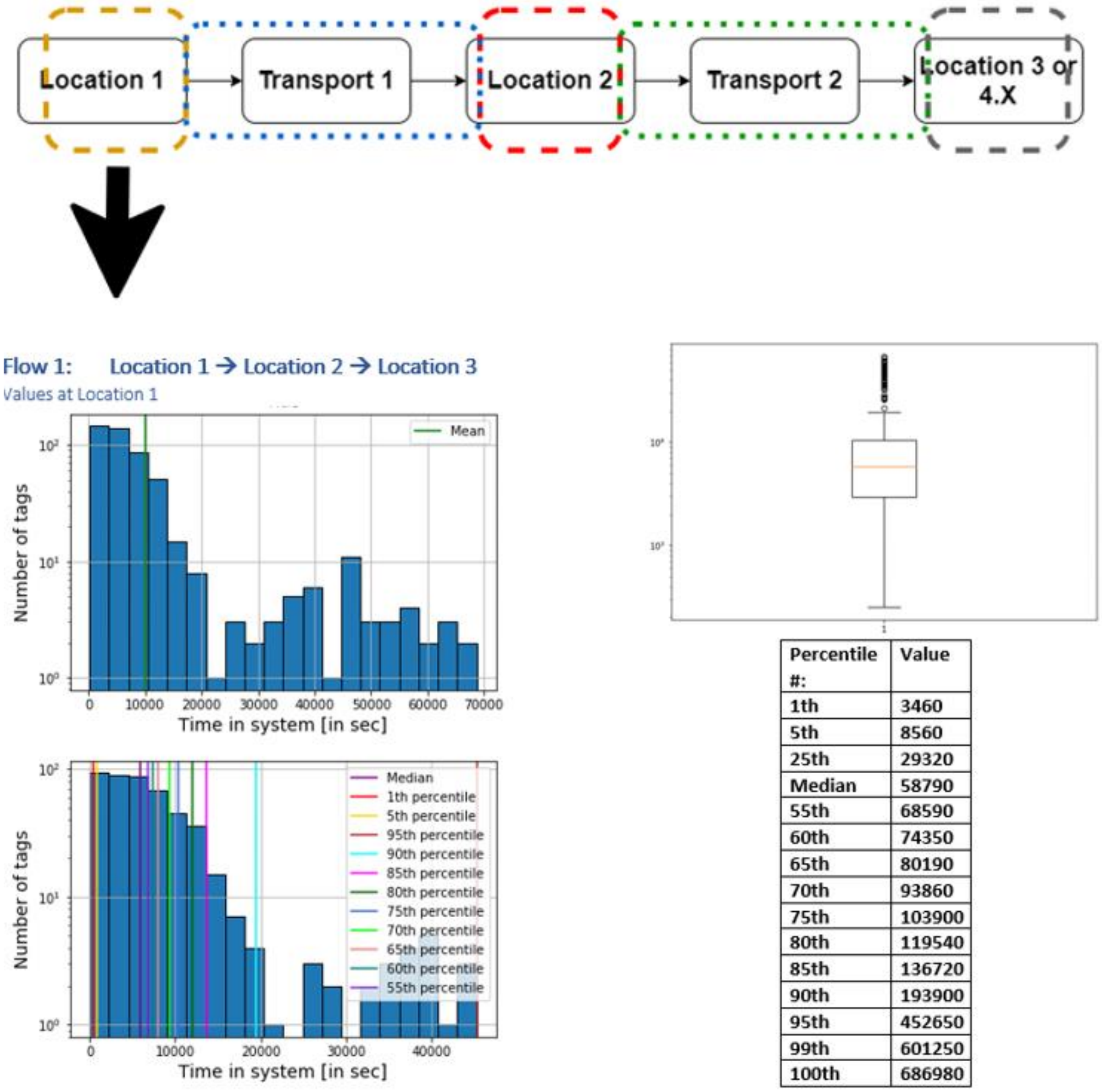
3.3.1 Use of Percentiles

This section will explain the choices made during analysis of the data and shows the results of this analysis. All nine sub-flows were analyzed under the same rules and conditions, therefore the approach is shown only for one of these sub-flows. All graphs and diagrams of each of the sub-flows are found in Appendix II. The KPIs of all sub-flows are present within this report; they are found in the paragraph 'Results Sub-Flows'.

The sub-flow used to explain the steps is:

- Flow 1: Location 1 → Location 2 → Location 3

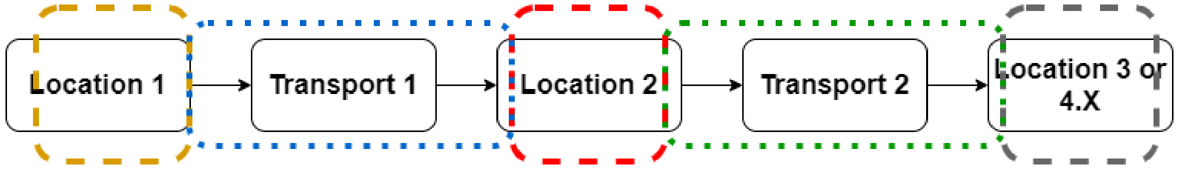
This flow has been chosen because it contains the highest number of suitable tags for comparison, covering a number of 494 tags. The EPAT calculates the time difference for each step of a sub-flow. This means that for all sub-flows of Flow 1 five different steps are calculated, while sub-flows belonging to Flow 2 consist of seven steps. The result of the EPAT for one particular step is displayed in Figure 3.10 and represents the time all appropriate tags have spent at that location. Figure 3.10 displays time spend at Location 1. Note that the vertical axes have a logarithmic scale. From the upper left graph it becomes clear that the mean value is not representative for this data set, as the outliers influence the value greatly. Therefore, further analysis of the data is done through the use of percentiles, as is common in data analysis (Thoughtco, 2020). The right side of Figure 3.10 displays the boxplot of this dataset and the value of numerous percentiles in seconds.



Percentile #:	Value
1th	3460
5th	8560
25th	29320
Median	58790
55th	68590
60th	74350
65th	80190
70th	93860
75th	103900
80th	119540
85th	136720
90th	193900
95th	452650
99th	601250
100th	686980

Figure 3.10 Display of the data-output of every individual entity in a sub-flow

These steps have been performed for every entity within that sub-flow, and after gathering al the results they are combined into one table, as displayed in Figure 3.11. The column ‘Total Time’ is the result of adding up all values per row, and transforming it into hours instead of seconds.



	🟨	🟦	🟥	🟩	▩	
	Location 1	**Transport 1**	**Location 2**	**Transport 2**	**Location 3**	
Percentile #:	**Value [s]**					**Total Time [h]**
5th	8560	34390	38280	38250	58430	49
10th	14640	36600	46900	43390	71390	59
15th	18860	38950	61180	46830	83460	69
20th	23360	41200	77390	51740	90440	79
25th	29320	42930	96540	57250	101900	91
30th	38510	44580	109930	60400	119160	103
35th	43580	46570	124200	63400	140350	116
40th	46990	48600	133800	68290	160920	127
45th	52380	50230	145910	72150	186780	141
Median	58790	52520	161900	75330	210950	155
55th	68590	54080	182780	81970	230910	172
60th	74350	55620	205420	92250	249020	188
65th	80190	57160	220130	106150	263940	202
70th	93860	59780	243600	123580	290110	225
75th	103900	62070	281400	155990	314770	255
80th	119540	66150	411230	191490	344900	315
85th	136720	71410	751670	305380	368700	454
90th	193900	81840	1092340	628390	444520	678
95th	452650	99030	87582020	2409570	1136940	25467
100th	686980	76774030	230666360	254307200	4295850	157425

Figure 3.11 Overview of the data-output of each sub-flow

3.3.2 Verification & Validation EPAT

Now that the total time of tags spend in that particular sub-flow is calculated by the EPAT, it is time to verify these values. During the verification, the output of the EPAT is compared to the data it was based on. In order to enable this kind of verification, first the reference data needs to be acquired. This reference data is obtained by measuring the first time a tag is detected at Location 1IN and the last time a tag is detected at a local sorting centra. Note that these measurements are based on ‘Bizstep = Entering’. Extracting the timestamp of first detection from last detection provides a timespan in which the tag was present in the system, while all in-between processes remain a ‘Black-Box’. This measurement is done for all appropriate tags, and after collecting the data it is also divided into percentiles. The blue, left columns of Table 3.1 show the results of these Black-Box (BB) measurements. The orange columns on the right of Table 3.1 display the results of the EPAT. The results of the EPAT were also verified through an expert analysis, executed by employees of the company of the case-study which are responsible for supply chain management.

Table 3.1 Overview of measured total time compared to the total time that results from the EPAT for Flow 1, Location 1 → Location 2 → Location 3

BB Measurement		**EPAT**	
Percentile #:	Total time [h]	Percentile #:	Total time [h]
5th	87	5th	49
10th	103	10th	59
15th	117	15th	69
20th	125	20th	79
25th	133	25th	91
30th	140	30th	103
35th	149	35th	116
40th	153	40th	127
45th	160	45th	141
Median	167	Median	155
55th	187	55th	172
60th	211	60th	188
65th	270	65th	202
70th	320	70th	225
75th	370	75th	255
80th	546	80th	315
85th	826	85th	454
90th	1437	90th	678
95th	25242	95th	25467
100th	70689	100th	157425

The results of both the EPAT and actual measurements are now compared and therefore verified. Figure 3.12 below shows a line graph of these results; the blue line shows the results of the actual measurements and the orange line represents the results of the EPAT. If both lines are close to each other, it means that the EPAT is able to reflect reality well and the EPAT is suited for analysis. When the lines are diverging it means that the EPAT is unable to follow the actual flow, and nothing trustworthy can be derived from the EPAT. From Figure 3.12 it becomes clear that the divergence after the 75th percentile increases significantly. Therefore the author has decided that the EPAT for this particular sub-flow is able to represent reality up to an upper bound that is equal to the 75th percentile.

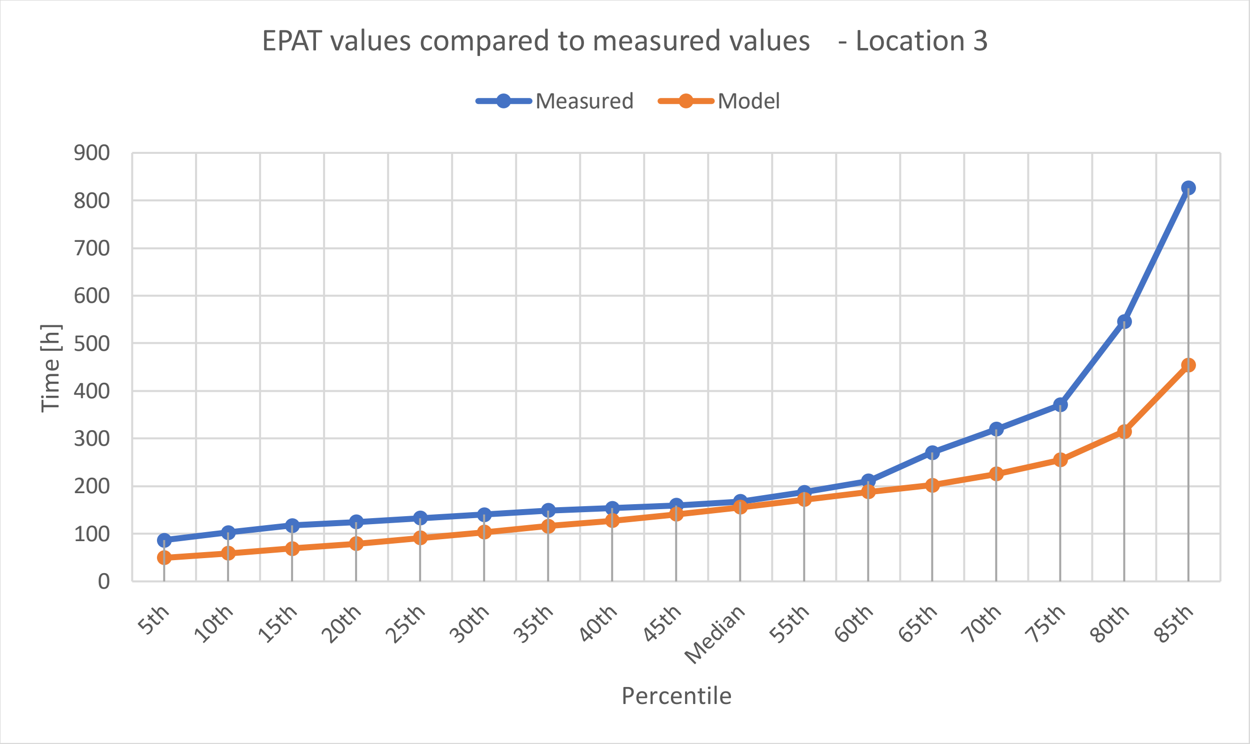


Figure 3.12 Display of verification through comparison of EPAT values to measured values for Flow 1, Location 1→ Location 2 → Location 3

Validation of the EPAT is performed through scenario-testing. Through adjusting parameters, and comparing the actual results of the EPAT with the expected results, it becomes clear that the EPAT behaves as desired. The results of four of these scenarios are displayed in Table 3.2. An explanation of each of these scenarios is found below;

- Scenario A

During scenario A, the value of throughput time within Location 1 is set to a constant of 1 second, simulating that each product passes through Location 1 in exactly the same time. The result should display both a lower value for each percentile, compared to the Original result, as well as a wider gap between original value and scenario A value along the increase of percentiles. A lower value for each percentile is expected since the constant value of 1 second is significantly lower than would be possible in reality. Since there is now a constant time throughout all percentiles of Location 1, instead of a higher number along the increase of percentiles, a wider gap between original value and scenario A value should occur along the increase of percentiles. From Table 3.2 it becomes clear that both of these expected results are indeed present in the results of Scenario A.

- Scenario B

In scenario B, the time-difference at Location 2 is multiplied by a factor 10. Processes within Location 2 take up a relative large amount of time, therefore adding a multiplier to the throughput time of Location 2 should increase the total time to large extend. Similar to scenario A, the gap between the Original value and scenario B value should increase along an increase in percentiles. Table 3.2 displays that the values of scenario B are in line with the expected values; the total time at the low percentiles is approximately three times larger, while the difference at high percentiles spreads up to around six times larger.

- Scenario C

During scenario C, the top 10% of goods within this sub-flow, with the highest total time spend in the supply chain are removed from the analysis. It is expected that removal of these products leads to significant lower values of the highest percentiles when compared to the Original results, while the low percentile values remain equal to the Original values. Table 3.2 shows that this scenario is able to perform as expected.

- Scenario D

In scenario D, the opposite of scenario C is tested. Scenario D removes the top 10% of goods with the lowest total time spend in the supply chain from the analysis. As the lowest values are no longer present, a shift in the value of all percentiles to the upside is expected, meaning that all percentiles in scenario D are expected to have a higher value when compared to the values of the Original scenario. Note that also the high percentiles are expected to increase in value, as the sample size becomes smaller and therefore the high percentiles are closer towards the maximum measured value. From Table 2 it becomes clear that the results of scenario D are in accordance to the expectations.

Table 3.2 Results of validation through scenario-testing

	Original		**Scenario A**	**Scenario B**	**Scenario C**	**Scenario D**
Percentile #:			**Total Time Spend in Supply Chain [h]**			
5th	49		47	143	49	51
10th	59		55	172	58	65
15th	69		64	217	69	75
20th	79		72	266	78	87
25th	91		83	324	88	100
30th	103		93	368	101	114
35th	116		104	415	112	126
40th	127		114	449	124	139
45th	141		126	491	136	152
Median	155		139	544	148	169
55th	172		153	610	163	183
60th	188		167	681	177	198
65th	202		180	730	195	213
70th	225		199	808	211	242
75th	255		226	930	236	271
80th	315		282	1310	266	387
85th	454		416	2295	302	498
90th	678		624	3355	477	910
Do the results of scenario-testing match the expected results?			√	√	√	√

3.3.3 Service-Level & KPI Visualization

The value of a percentile displays the percentage of tags of which the maximum time spend in the supply chain is equal to this value. As derived from Figure 3.13, the value of the 75th percentile is equal to 255 hours. This means that 75% of the tags pass through the supply chain in 255 hours or less. Figure 3.13 displays the performance of this sub-flow, where the percentiles are plotted against the total time spend in the supply chain. The blue bars in Figure 3.13 show the values, of different percentiles, of which the EPAT is representative to reality, while the black bars are included to show the rise of throughput time at higher percentiles. The horizontal red line indicates the current service-level, which can be considered as an approximative target time as set by the company. The current service-level of this supply chain is set to 240 hours by its policy makers. This service-level is considered the benchmark of SLOTT performance of the supply chain, and both current- and future-state results are compared to the service-level in order to obtain their efficiency.

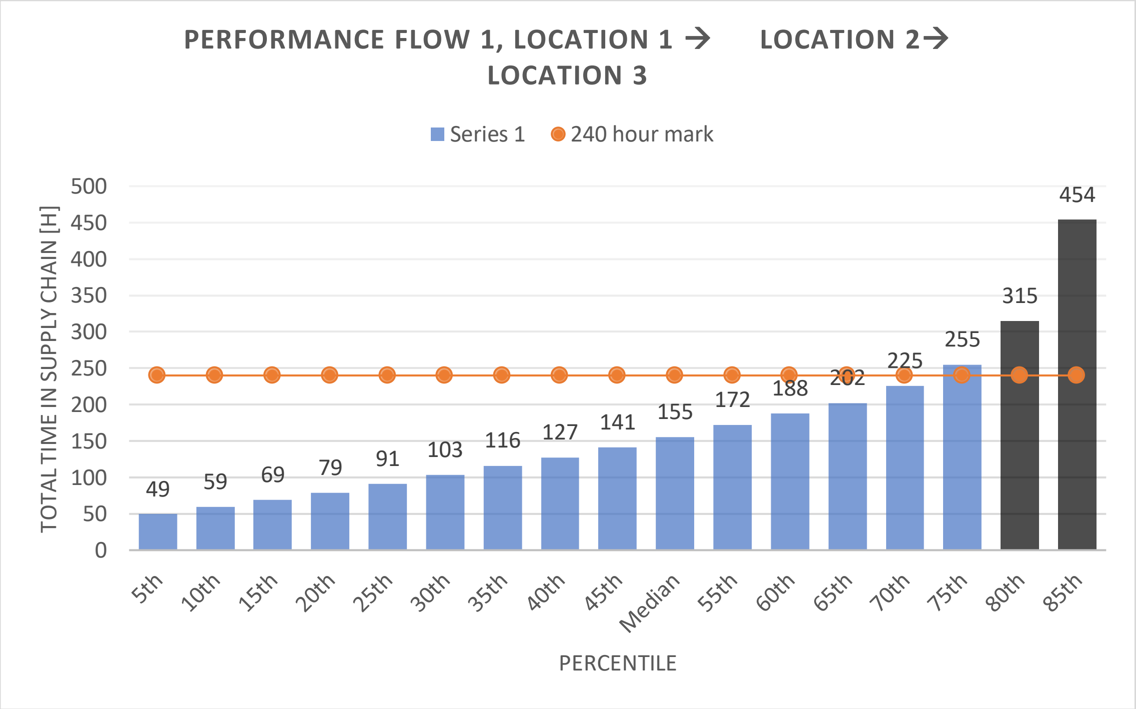


Figure 3.13 Overview of the performance per percentile of Flow 1, Location 1 → Location 2 → Location 3

Through verification it has been confirmed that the EPAT is able to represent the total throughput time of tags up until the 75th percentile for this particular sub-flow. However, in order to achieve the pre-determined KPIs, more detailed information is required than just total throughput time. The KPIs require the duration of every step, as well as the performance of the complete supply chain, compared to current service-levels.

Utilization of the EPAT ensures calculation and visualization of all of the KPIs, as displayed in Table 3.3. However, from Table 3.3 a few aspects need to be explained to more extend; only the values of the median and the upper bound percentile are taken into account. The reason for exclusion of the results of most of the percentile has to do with the usefulness of these results during further analysis; they have little additional value when the benchmark value and the upper bound value are known. When calculating throughput time while making use of percentiles, one important aspect regarding the characteristics of percentiles should be taken into account; the values are ranked from low to high. When the values of each of the individual entities is divided into percentiles, and afterwards summed up to calculate the total duration of goods in the supply chain, both the lowest and highest percentiles might give unrepresentative values, as they could contain outliers that pollute the data. From the in-sample verification performed during paragraph 3.3.2 'In-Sample Verification' it became clear that because of these outliers the model is only able to represent reality till a certain upper bound. But in order to determine an 'average' throughput time of products passing through the supply chain, a baseline value is necessary. Therefore, the median is assumed as the average throughput time of the supply chain that will acts as a baseline during future comparison of performance. The median-value results have been verified as a suitable baseline through an expert-analysis conducted by operators that work in the company of the analyzed supply chain.

Table 3.3 Display of the KPI of Flow 1, Location 1 → Location 2 → Location 3

Percentile #:	**Duration (in hours)**					**Total time [h]**	**Efficiency* [%]**
	Location 1	**Location 1 → Location 2**	**Location 2**	**Location 2 → Location 3**	**Location 3**		
Median	**16**	**15**	**45**	**21**	**59**	**155**	**155**
Upper Bound	**29**	**17**	**78**	**43**	**87**	**255**	**94**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

In Table 3.3 the particular sub-flow covered is shown, including the performance of each of the entities for the median and upper-bound. Also efficiency of the median and upper-bound is displayed. This efficiency is calculated relative to the service-level of 240 hours, which is considered 100% efficient. This means that if the total time of the median and/or the upper-bound is lower than 240 hours, the performance will be higher than 100%, and vice-versa. When the efficiency is above 100%, the cell is colored green, as the system performs better than the requested service-level. If the efficiency is below 100%, the cell is colored red to indicate that the service-level objective is not met.

It becomes clear that the throughput-times of the median and upper-bound differ quite significantly, with a total time of 155 hours and 255 hours, respectively. Since the processes are equal for both the median and upper-bound, and the data has been collected during a period of a whole year, it can be concluded that dwell-time is present during the processes that causes a decrease in SLOTT performance of the supply chain.

The analysis as conducted to this sub-flow has also been applied to the other sub-flows of the supply chain. The KPIs that follow from this analysis are displayed in Table 3.4 – 3.11 below.

Flow 1

Table 3.4 Display of the KPI of Flow 1, Location 1→Location 2 →Location 3

Percentile #:	TD (in hours)					Total time [h]	Efficiency* [%]
	Location 1	Location 1→ Location 2	Location 2	Location 2 → Location 3	Location 3		
Median	16	15	45	21	59	155	155
75th	29	17	78	43	87	255	94

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.5 Display of the KPI of Flow 1, Location 1→Location 2 →Location 4.2

Percentile #:	TD (in hours)					Total time [h]	Efficiency* [%]
	Location 1	Location 1→ Location 2	Location 2	Location 2→ Location 4.2	Location 4.2		
Median	16	15	73	104	174	382	63
85th	102	21	138	1145	719	2124	11

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.6 Display of the KPI of Flow 1, Location 1→Location 2 →Location 4.3

Percentile #:	TD (in hours)					Total time [h]	Efficiency* [%]
	Location 1	Location 1→ Location 2	Location 2	Location 2→ Location 4.3	Location 4.3		
Median	13	15	58	19	89	195	123
85th	30	18	107	29	332	515	47

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.7 Display of the KPI of Flow 1, Location 1→Location 2 →Location 4.4

Percentile #:	TD (in hours)					Total time [h]	Efficiency* [%]
	Location 1	Location 1→ Location 2	Location 2	Location 2→ Location 4.4	Location 4.4		
Median	11	14	66	29	83	202	119
85th	24	18	231	38	556	868	28

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 2

Table 3.8 Display of the KPI of Flow 2, Location 1→Location 2 →Location 3 →Location 4.1

Percentile #:	TD (in hours)							Total time [h]	Efficiency* [%]
	Location 1	Location 1 → Location 2	Location 2	Location 2 → Location 3	Location 3	Location 3 → Location 4.1	Location 4.1		
Median	**17**	**15**	**31**	**18**	**31**	**17**	**69**	**198**	**121**
70th	**25**	**16**	**57**	**21**	**54**	**20**	**85**	**279**	**86**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.9 Display of the KPI of Flow 2, Location 1 → Location 2 → Location 3 → Location 4.2

Percentile #:	TD (in hours)							Total time [h]	Efficiency* [%]
	Location 1	Location 1 → Location 2	Location 2	Location 2 → Location 3	Location 3	Location 3 → Location 4.2	Location 4.2		
Median	**13**	**14**	**31**	**16**	**28**	**17**	**35**	**154**	**156**
80th	**28**	**18**	**54**	**26**	**53**	**20**	**74**	**273**	**88**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.10 Display of the KPI of Flow 2, Location 1 → Location 2 → Location 3 → Location 4.3

Percentile #:	TD (in hours)							Total time [h]	Efficiency* [%]
	Location 1	Location 1 → Location 2	Location 2	Location 2 → Location 3	Location 3	Location 3 → Location 4.3	Location 4.3		
Median	**18**	**16**	**28**	**18**	**41**	**13**	**85**	**218**	**110**
70th	**26**	**17**	**49**	**21**	**55**	**14**	**90**	**274**	**88**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

Table 3.11 Display of the KPI of Flow 2, Location 1 → Location 2 → Location 3 → Location 4.4

Percentile #:	TD (in hours)							Total time [h]	Efficiency* [%]
	Location 1	Location 1 → Location 2	Location 2	Location 2 → Location 3	Location 3	Location 3 → Location 4.4	Location 4.4		
Median	**20**	**14**	**25**	**17**	**29**	**25**	**24**	**155**	**155**
70th	**29**	**16**	**49**	**24**	**48**	**28**	**52**	**247**	**97**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

3.3.4 Overview Current-Performance all Sub-Flows

In order to provide a single overview that displays the performance [h] of all analyzed sub-flows, Table 3.12 is produced. In Table 3.12 the two main flows of the supply chain are divided, and the number in the second row of each of these parts indicates which sub-flow it covers. For each of the sub-flows the total performance [h] of the percentiles between the median and upper-bound is displayed.

The background colors of each cell indicates how the value it contains compares to the service-level of 240 hours. If the total time of that cell is equal to or beneath the 240 hours, it outperforms the requested service-level and the background color is green. If the value of a cell is higher than the service-level, the background color is red. The grey background colors indicate the percentiles of which the EPAT is unable to represent reality, no useful conclusions can be derived from these values. Figures 3.14 and 3.15 are included to illustrate which components are present in both of the main types of flow.

- Flow 1:

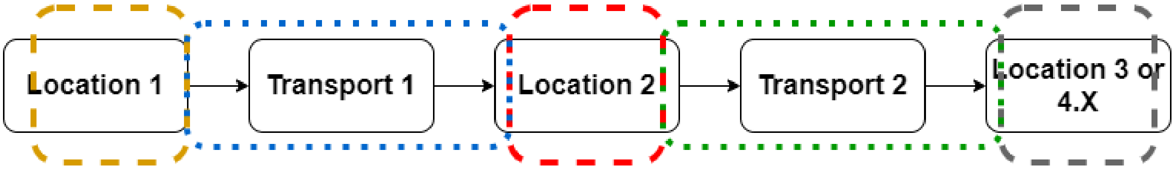


Figure 3.14 Visualization of the components of Flow 1

- Flow 2:

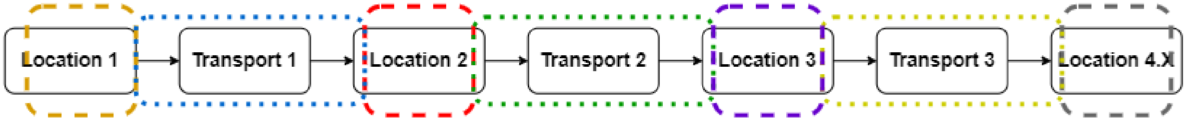


Figure 3.15 Visualization of the components of Flow 2

Table 3.12 Overview of the performance of all sub-flows, divided into percentiles, including comparison towards required service-level

		Flow 1					Flow 2			
		3	4.2	4.3	4.4		4.1	4.2	4.3	4.4
Percentile #:		Duration [h]					Duration [h]			
Median		155	382	195	202		198	154	218	155
55th		172	512	201	332		217	193	232	167
60th		188	651	212	371		235	215	243	205
65th		202	1006	347	385		258	228	260	232
70th		225	1123	426	417		279	249	274	247
75th		255	1311	449	469			261		
80th			1695	474	642			273		
85th			2124	515	868					
90th										
95th										
100th										

From Table 3.12 it becomes clear that for the median value of most of the sub-flows, the requested service-level is reached. However, looking at the upper-bound performance of these flows paints a different picture; none of the upper-bound values is able to reach the requested service-level. This leads to the following conclusion: Since the processes are equal for both the median and upper-bound of a sub-flow, but their performance differs significantly , it is concluded that dwell-time is present during the processes that causes a decrease in SLOTT performance of the supply chain. In addition to this conclusion, the fact that the data has been collected during a period of a whole year enforces this state, as it shows a structural difference and cannot be caused by single-events.

3.4 Conclusion Design requirements of a Digital Chain & Current-State Performance

During this chapter the following research sub-questions were answered:

- What are the design requirements for a Digital Chain?
- Wat is the current-state performance, through use of a case-study?

The goal of the Digital Chain is to produce an environment where SLOTT performance is improved by reducing dwell-time that occurs in-between processes. In order to achieve this goal, specific design requirements for a Digital Chain design are composed to enable upfront forecasting on future arrival times of goods in actual supply chains. The following design requirements were obtained:

- Performance is based on time spend in the supply chain, therefore measurements with regards to time are required
- Use of IoT sensors is required to enable visibility of the flow of goods throughout the supply chain
- Data acquired by individual sensors is send to an intelligence layer in order to connect data from multiple sensors together and display SLOTT performance of specific parts of the supply chain, as well as the complete the supply chain.

These design requirements were transformed into KPIs that are able to easily display the SLOTT performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. These KPIS cover the performance [h] of both the individual entities of the supply chain and the complete supply chain, as well as the efficiency [%] of the complete supply chain, compared to current service-levels.

Mieloo & Alexander has provided a suitable case-study from their repository on which a current-state analysis is applied. During the current-state analysis, a numerical foundation is obtained regarding both the presence and impact of undesired dwell-time on SLOTT performance, as well as comparison between performance of the current-situation to the future-state performance, which will make use of the Digital Chain design.

In order to obtain and display the KPIs of the supply chain of the case-study, an Efficiency and Performance Analysis Tool (EPAT) was designed. The EPAT, specified to the analyzed case-study, is used as the required Digital Chain intelligence layer during this research, both for the current-state analysis and during the future-state design. This EPAT is of significant importance during analysis of performance of a supply chain, as it provides for measuring of the SLOTT performance. The EPAT is based on sensor-data from RFID tags that pass through the supply chain. The design of the EPAT is necessary since the current situation does not provide an overview of the duration of individual processes of the supply chain and therefore the KPIs as necessary do not exist. The goal of the EPAT is to easily display the performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. The EPAT serves as a data-analysis tool that provides insight in the duration of the flow of goods throughout the supply chain, by transforming the design requirements into measurable Key Performance Indicators (KPIs). The results of the EPAT were verified through both a 'Black-Box' comparison and an expert analysis, executed by employees of the company of the case-study whom are responsible for supply chain management of that enterprise.

From the results of the current-state performance the following conclusion is derived: Since the processes are equal for both the median and upper-bound value of a sub-flow, but their performance differs significantly, it is concluded that dwell-time is present during the processes that causes a decrease in performance of the supply chain.

In order to overcome the presence of dwell-time in supply chains, a design must be produced that is able to predict arrival times of products, in order to provide participants of the supply chain with the ability to prepare assets and resources upfront. The ability to prepare upfront ensures smooth and swift transitions between consecutive processes, and as a result dwell-time is diminished. The following chapter covers the construction of a future-state Digital Chain design that is able to provide iterative forecasts, to diminish dwell-time in supply chains and therefore improve on SLOTT performance.

Chapter 4 Future-State Digital Chain Design

This chapter covers the design of a Digital Chain-framework that combines blockchain technology, IoT-sensor technology and the EPAT as an intelligence layer. The framework acts as a future-state design; as both IoT technology and blockchain technology are new, emerging technologies, little knowledge is currently present on combining these two technologies to diminish dwell times in supply chains.

During the creation of the future-state design, in which blockchain and IoT sensor technology are combined, the knowledge obtained from both theory and the case-study is now converted into a conceptual framework design, to display how a Digital Chain could operate in the near future. The goal of the design is to produce an initial assessment on the possible impact of Digital Chains, as time limits of this research do not allow for an in-depth design that works out every detail of all components present, for example use of specific programs and/or writing of all required code. Therefore it has not been possible to produce a complete Digital Chain, but only certain components. Aspects that are included within the Digital Chain future-state design, but that are not covered to full extend during this research, are either based on knowledge obtained from literature or on current existing implementations of that particular technology.

This design is intended to provide real-time data-exchange and therefore visibility, with regards to the whereabouts of goods within a supply chain, in order to enable forecasting of future arrival times of these goods. During this chapter, the philosophy of Digital Chains is translated into a future-state design that includes the required steps necessary to make it tangible and applicable for real-life cases. This chapter answers the following question: 'What should a Digital Chain design, that combines IoT-sensors and blockchain technology, look like?'. First an architecture design is produced, followed by a more in-depth module design that covers all necessary steps. The consecutive part of this chapter covers the impact of the future-state design, while the last part of this chapter indicates which aspects of the Digital Chain design are covered to more extend during this research.

4.1 Architecture Design

From theory on Digital Chain technology and Part 3 'Design requirements' it becomes clear that data-gathering, based on sensor-data from IoT sensors, lays the foundation of a Digital Chain. In short this means that the design starts with the detection of products at locations where sensors are present, and ends with displaying information regarding future arrival times of products at certain locations. In order to provide structure to the steps required to transform raw-data into a forecast, the architecture design is divided into multiple layers.

As sensor-based data forms the input for the complete system, the use of sensors provides the base for the architecture design structure. The general idea of a sensor is that is able to detect (physical) events or changes within the environment it is designed for (Balluf, 2020). Due to this fact, sensors are assigned to the 'Detection Layer', as displayed in Figure 4.1. From Figure 4.1 it becomes clear that during the design the sensors are already specified towards AUTOID sensors.

A major aspect within this design is enabling visibility of the flow of goods through a supply chain. In order to achieve visibility and/ or track- & traceability of products, they need to be (individually) identifiable throughout the processes. In order to achieve identifiable products, each of the products needs to have a tag attached to it that contains a unique identity. Nowadays, a common method to achieve identifiable products is through the use of AUTOID technology, which for example consists of barcodes, QR-codes and RFID-tags. So, the Detection Layer consists of AUTOID-tags and AUTOID-sensors.

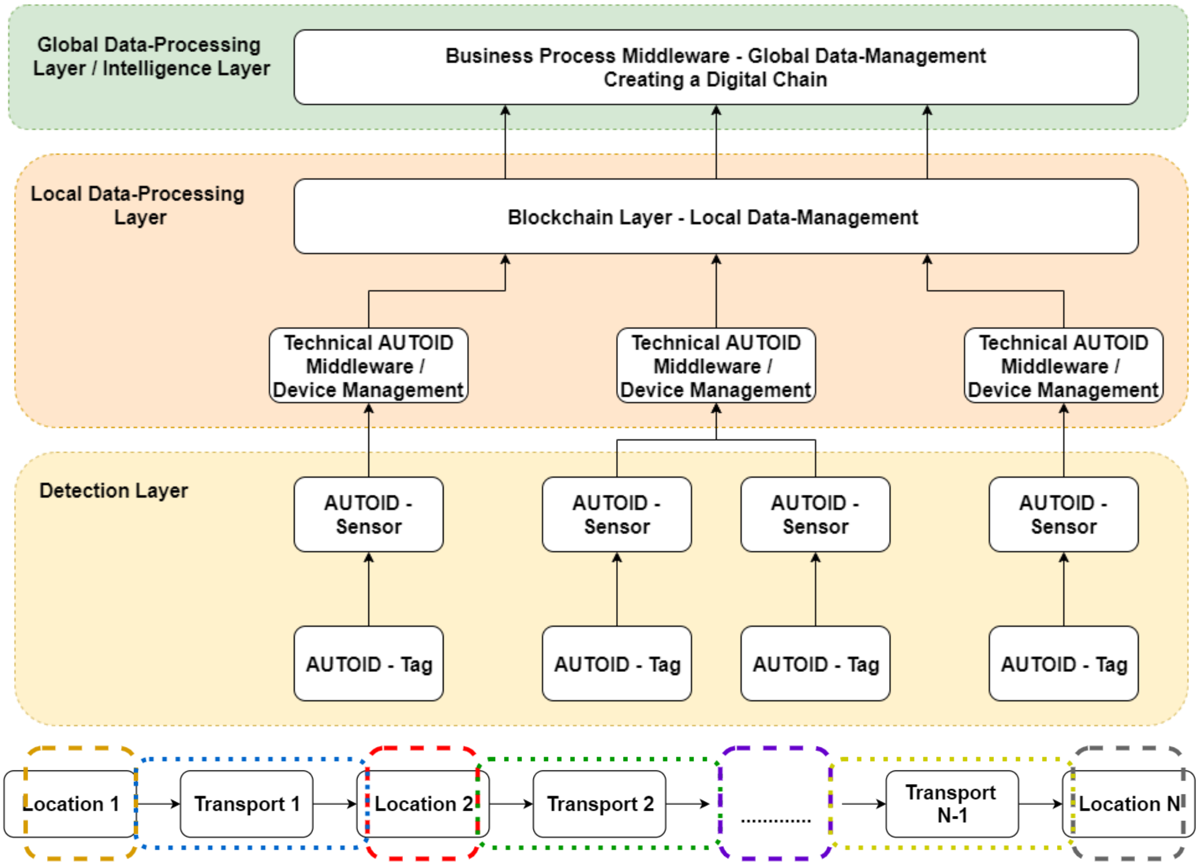


Figure 4.1 Architecture design of a Digital Chain that combines IoT technology with blockchain technology

When products, and therefore tags, pass through the supply chain, they are detected once in range of a AUTOID sensor. Within the design, this detection part is named the ‘Detection Layer’. After a sensor detects a tag and obtains the data from this tag, this data is passed on towards a Technical AUTO-ID middleware application for initial processing. As displayed in Figure 4.1, the connection between the sensor and the local middleware marks the transition between the Detection Layer and the following layer, named the ‘Local Data-Management Layer’. Within this Local Data-Management Layer, in a process that is called ‘Device Management’, the first data-processing steps are executed. During Device Management, incoming, raw data is handled for the first time. Not all data is useful or present in the right format when arriving at Technical AUTOID Middleware application. During Device Management operations, the raw data is filtered and/or events are generated. Transforming the raw data into useful information enables the opportunity for further processing of the data and applying intelligence in later stages. Note that multiple sensors can be connected to a single middleware application during the Device Management processing.

The useful data that remains after the data-management processes of each of the Technical AUTOID Middleware applications needs to be made available/communicated to a global processing application, in order to combine local data together and enable the possibility to apply intelligence covering the complete supply chain. The frequency of communication is determined based on client requirements, however execution of this data-exchange is incorporated within the Device Management.

Connecting the information from the local layer a global data-management layer is accomplished through the use of blockchain technology. Blockchain technology within this design acts as a data-management layer that connects local middleware to the global data-management layer. The Technical AUTOID Middleware application is an IoT device that is connected to the internet; it is capable of constructing an sending transactions on a blockchain. An important benefit of using blockchain technology is its ability to facilitate cross-enterprise data-exchange in real-time.

The next layer in the design, dubbed the 'Global Data-Management Layer', focusses on combining the data of the separate sensors together and converting the data into a model that provides the results of the KPIs as determined during the design requirement phase. This layer of the design is considered as the 'Intelligence Layer' of the design, since it connects all data together to provide visibility and insights with regards to SLOTT performance and bottlenecks of the supply chain. During this stage a Digital Chain is produced based on both the sensor-data of the AUTOID-sensors, as well as specific information that belongs to each of the Technical AUTOID Middleware applications, such as geographic location and sequential position regarding the product flow. Data is retracted from the blockchain and converted into a single Digital Chain. Part of how an intelligence layer of a Digital Chain of a supply chain is constructed from AUTOID sensor-data is displayed during the design of the EPAT in Part 3 'Design Requirements'.

When a Digital Chain of the supply chain is produced, through simulation, analysis and diagnostics of the system, insights are obtained with regards to performance and bottlenecks. The historical data on which the Digital Chain is based provides the opportunity to compare new data to old data, in order to predict when future products will arrive at a certain location. Every time a transaction occurs on the blockchain, the intelligence layer derives this data and compares it to historical values in order to provide predictions. Through continuous updates from the IoT-sensors, the current state of the system is constantly being updated, and alongside it the forecast regarding future arrival times. The continuously updated forecast provides participants of the supply chain with the opportunity to accurately prepare themselves upfront, which leads to diminished dwell-times and results in an increase of supply chain SLOTT performance.

Intelligence Technologies

When the mainframe of a Digital Chain is up and running and all processes and product-flows are well understood, a Digital Chain may be combined with technologies such as ML and AI in order to produce even more accurate predictions. However, the applications of these advanced prediction technologies are outside of the scope of this research. The author recommends to conduct further research towards utilization of these technologies with regards to Digital Chains, as they might enable aspects such as prediction optimization and dynamic asset and resource allocation.

4.2 Module Design

After completion of the architecture design during the previous paragraph, a more in-depth, worked-out module design is constructed that includes the steps required to achieve the desired outcome. As displayed in Figure 4.2, this module design is also divided into the layers as present during the architecture design. More specifically, this module design is already tweaked towards the case-study that was analyzed during this research. This results in a more specific application with regards to the Detection Layer, all other three layers remain more or less generic. The AUTOID technology used in the business-case is RFID technology. The products have RFID tags attached to them and the AUTOID-sensors consist of stationary RFID-antennas.

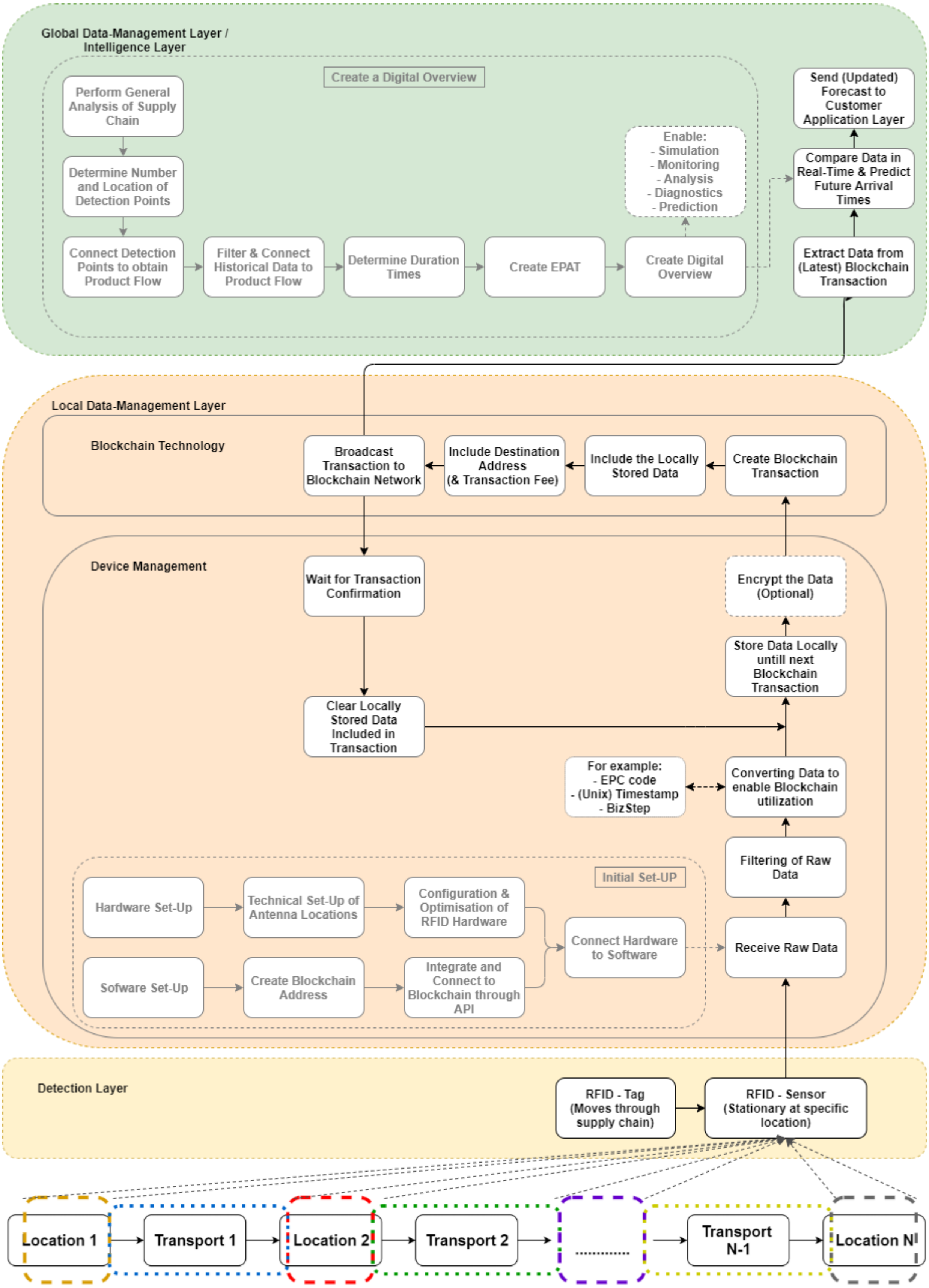


Figure 4.2 Module design of a future-state model of a Digital Chain

Products with RFID tags attached to them move through the supply chain, and in doing so they pass stationary, strategically placed RFID-sensors. When a tag is in detection range of a sensor, the data from this tag is read and send to the Local Data-Management Layer. The device that is part of the Local Data-Management Layer consists of hardware and software, is connected to the internet and possesses processing power/ is able to perform (moderate) operations on its own. During installation of this device two main aspects need to be addressed; the hardware set-up and the software set-up. The hardware set-up consist of the technical set-up with regards to antenna placement and locations, and of configuration and optimization of the RFID hardware. During the technical set-up aspects such as determining the detection range, avoidance of possible signal-jammers and the physical installation are addressed. During configuration and optimization processes the hardware is tuned and tweaked until optimal performance is achieved.

During the software set-up of the system the base for enabling data-management through the use of blockchain technology is provided. The first steps of the software set-up are the creation of a blockchain address, and the integration and connection of the device with a blockchain through use of an API. Note that the middleware device will most likely be a simple node, which means that it is able to send and receive transactions, but it does not store a copy of the blockchain and does not participate in the consensus mechanism of the blockchain. The creation of the blockchain address will most likely occur before the device is physically installed, as the address needs to be known by the Global Data-Management Layer operator in order to connect a blockchain address to a specific RFID detection device. Due to the cryptographic characteristics of blockchain technology, addresses are created pseudonymously, which means that is difficult to obtain the identity behind an address if it is not known beforehand.

The code required to connect and integrate the software from the device itself with the blockchain API is also produced upfront. There are two ways the required code may be integrated on a Device Management Layer; locally on the device itself or through connection with a third party over the internet. Connecting the device with a controlling party over the internet is preferred in this situation, since it provides the opportunity to implement changes and updates without a need for being physically present at the device. As entities within a supply chain may be spread across the world, this may reduce the time needed to update the system drastically. Also new addresses can be created after the passing of a certain period of time, increasing the difficulty of connecting the address to an entity and therefore improving on privacy. When an address is linked to a company, competitors might benefit from this information. In order to avoid this linking of addresses to companies, blockchain addresses should be changed on a regular basis.

Once the initial set-up is completed, raw data can now be processed. During Device Management, the first processing steps with regards to filtering and handling of the data are executed. First, raw data is received from the RFID sensor. After receival, first the data is filtered and/ or events are constructed in order to remove unwanted and unnecessary information. RFID-sensors are able to send and receive multiple signals per second, however not all these signals are useful for further processing. For example, if a tag passes a sensor when passing through a docking-door during inbound operations, it could be detected over a dozen times within a second. In order to reduce the amount of data that needs to be send, the middleware application only keeps the data from the first signal, all other signals belonging to one particular tag are removed. The data that remains is now transformed to ensure that it can be send via a blockchain transaction. The information that is required depends on the specific application, during this research the aspects that were of importance are the Electronic Product Code (EPC), the UNIX timestamp and the BizStep of a tag. The EPC of a RFID tag acts as a identifier for that specific tag, ensuring that each RFID tag has an unique identity and is therefore individually recognizable (Tutorialspoint, 2020). A UNIX timestamp the result of converting the date and time of detection into a single number; the UNIX timestamp of a particular date and time is calculated as the number of seconds that have passed since the UNIX Epoch, which is January 1st 1970 00:00:00 (Unixtimestamp, 2020). The BizStep of a tag, as explained in paragraph 5.4 'Determining detection points', displays whether it is the first time a tag is detected by a certain IoT-sensor (BizStep = Entering), or the last time a tag is detected by a certain IoT-sensor (BizStep = Exiting). It is important that these three aspects are converted consistently, in order to ensure usability in downstream processing steps. The result of the conversion could have a structure that resembles a CSV file. In this design, the data would be structured in the following way:

- EPC code ; UNIX Timestamp ; BizStep= Entering

After conversion of the data, it is stored locally on the device until it is included in the next blockchain transaction. It is likely that more than one tag is detected during the period of time between transactions. So eventually, a list of tag-data is produced that might look like the following:

- EPC code1 ; UNIX Timestamp ; BizStep= Entering
- EPC code2 ; UNIX Timestamp ; BizStep= Entering
- …
- EPC codeN ; UNIX Timestamp ; BizStep= Entering

Optionally this data can be encrypted to ensure no-one except those entitled are able to obtain the original data. When using a permissioned blockchain, access to data could be authorized upfront, while encrypting the data in permissionless blockchains ensures an extra layer of privacy. Once the predetermined time-period has passed a new blockchain transaction is created. The locally stored data is included within the transaction, and after adding the destination address and including the required fee (when making use of permissionless blockchains) the transaction is broadcasted to the network. Within the Local Data-Management Layer, a couple of actions remain to finish the cycle. The device waits until the transaction is confirmed, after which it removes the data that was included in the blockchain transaction from the locally stored data. A new list is produced and the Local Data-Management cycle repeats itself. The data that is included into a confirmed blockchain transaction is now available for use in the Global Data-Management Layer.

During the processes of the Global Data-Management Layer, data from a multitude of Local Data-Management Layers is combined and connected, in order to produce a Digital Chain of the supply chain that is able to increase the level of intelligence to the system. Note that the design of the basics of the intelligence layer of a Digital Chain is similar to the design of the EPAT, as used during the case-study. The construction of the intelligence layer starts with performing a general analysis of the supply chain. During this general analysis, different participants are identified, the processes each entity executes are understood and the flow of goods becomes clear. By determining the number of detection points present in the system, alongside aspects such as obtaining their location and understanding to which sequential process-step they belong, insights are obtained regarding the product flow. Connecting these detection points together enables the possibility to simulate the product flow. Filtering-out data that does not match the product flow, in combination with connecting historical data to the model, enables monitoring and analysis of the performance of the supply chain. Connecting the data together provides the opportunity to determine the duration times of different processes and process-steps. At this point a digital overview of the system is obtaineded, based on historical data, that is able to simulate and monitor the processes within the supply chain. It also enables analysis of the performance of the data, provides the opportunity to identify possible bottlenecks through diagnostics, and is able to make predictions regarding performance based on historical performance.

When data is extracted from the blockchain layer, it consists of just tag information, a timestamp and a BizStep. Through the use of the blockchain address it is send from, this loose data can be connected to a specific readpoint, linking the data to a specific point in the product flow. This data can now be converted and connected to the known product flow of the supply chain. The data from the blockchain transaction can now be compared to the historical results of the Digital Twin, in order to predict the future arrival times of tags at specific locations, producing a forecast of which products are to be expected where and at what time. Since blockchain transactions occur every pre-determined period of time, the forecast is updated with every incoming transaction. These (near) real-time, data-driven communications provide for continuous updating of the state of the system, enabling the possibility to provide iterative forecasting of incoming load, since the latest forecast is updated with every new blockchain transaction. The continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. When entities are prepared, for example providing sufficient capacity at the right time at the right place, transition phases between processes become more fluent and swift. Dwell-time is diminished and therefore the SLOTT performance improves.

4.3 Impact Future-State Design

From the results of the EPAT, regarding the current-state performance of the case-study, it became clear that current handling methods are insufficient with regards to proper and timely handling of incoming load, leading to the presence of dwell-time and therefore a decrease in the SLOTT performance of the supply chain. The design of the EPAT provides insights on the product flow of the supply chain, including identification of bottlenecks and current SLOTT performance. However, the current EPAT is unable to produce an environment that enables for iterative forecasting, since it is unable to provide continuous, real-time updates of the state of the system. This means that the EPAT-tool is only able to provide predictions based on historical performance, and no accurate forecast can be produced regarding future arrival times of products that are passing through the supply chain during that moment.

In order to achieve an environment where continuous, real-time updates are possible, the author produced a design of a Digital Chain based on the combination of IoT-sensor technology, blockchain technology and an intelligence layer. The IoT-sensors enable visibility regarding the whereabouts of goods within a supply chain, while real-time data-exchange is achieved through the use of blockchain technology. The intelligence layer combines the data of numerous sensors together to a single system, in order to produce both an overview of the performance of the supply chain, as well as forecasts regarding the future arrival times of goods.

A future-state, Digital Chain design is constructed in order to provide an environment where iterative forecasting is enabled to diminish dwell-time that occurs in-between processes. The design covers the complete range of steps necessary to achieve accurate forecasting, from the moment of detection of a tag by a sensor, to the production of a forecast regarding future arrival times of incoming load. The design describes how data should be converted and implemented into a blockchain, as well as the forecast that follows from comparing this data to a Digital Chain of the system.

The produced future-state design shows how blockchain technology could be incorporated in supply chains to enable an environment where near real-time, cross-enterprise communication is made possible. The design combines AUTOID technology with IoT-sensor technology, blockchain technology and an EPAT, in order to produce a forecast of future incoming load, to ensure entities are able to prepare in advance with regards to future incoming load. The design allows them to prepare themselves to properly handle and process expected incoming load, in order to avoid dwell-times. Figure 4.3 displays a high level overview of the components of a Digital Chain, the role of blockchain technology, advancements regarding insights due to the specific characteristics of a Digital Chain, and impact a Digital Chain has on supply chains. Note that Figure 4.3 builds upon the preliminary concept design from Chapter 2 'Exploration of Theory'.

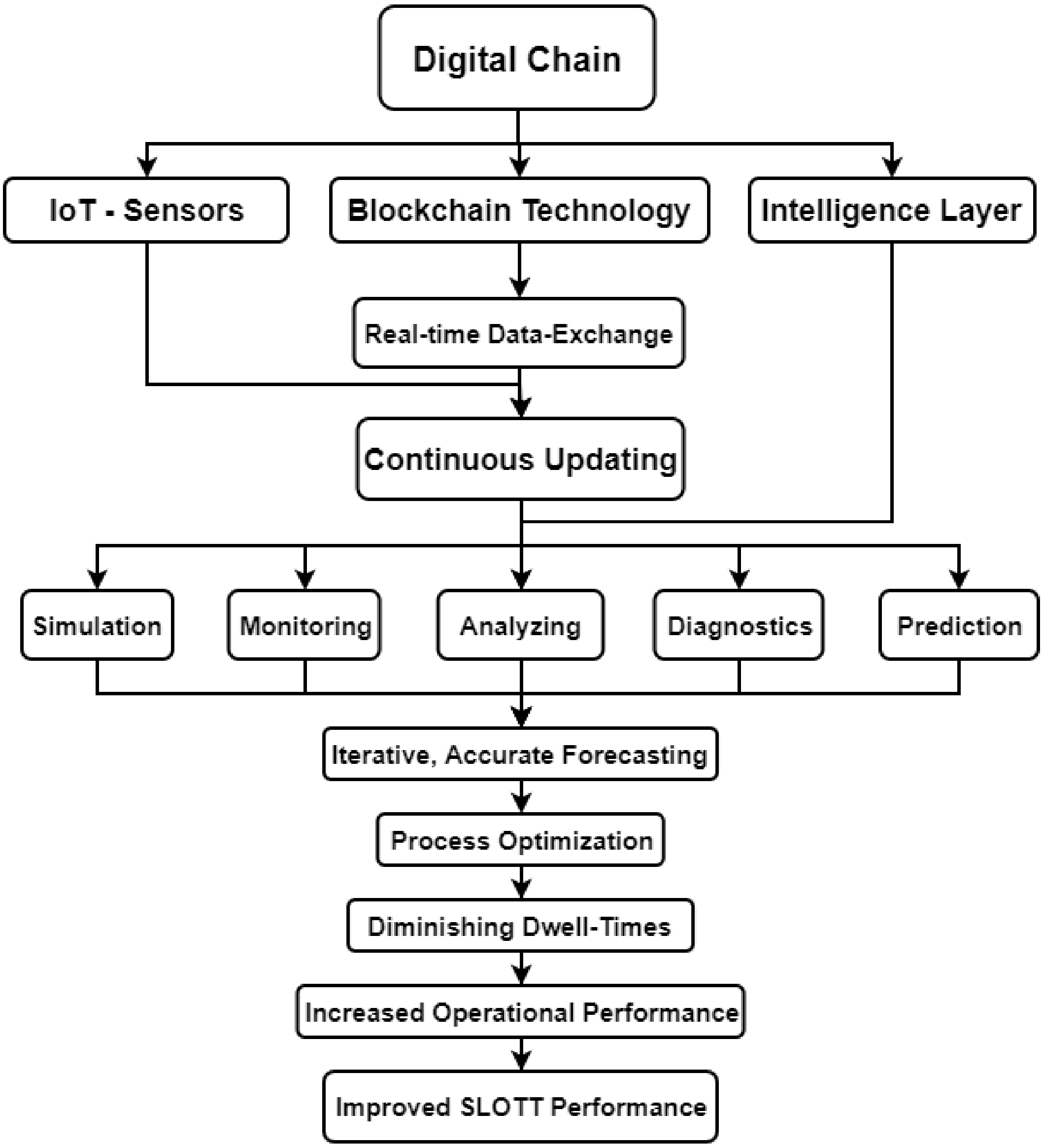


Figure 4.3 Global overview of the characteristics of a Digital Chain and its' impact on supply chains

From Figure 4.3 it becomes clear that three main aspects are present and combined within a Digital Chain; IoT-sensor technology for data-collection, blockchain technology to provide continuous updating of the state of the system and combining this data into a single system through an intelligence layer. The use of sensors provide for a data-driven system, and through continuous updating of state of the system, a Digital Chain is able to accurately mirror its physical counterpart.

Figure 4.3 displays that the use of blockchain technology plays an important role with regards to provision of continuous updating of the state of the system. Blockchain technology is a distributed ledger technology, based on a peer-to-peer network, that act as a data-infrastructure middleware solution to enable data-exchange between the IoT-sensor and the intelligence layer. Blockchain technology consists of multiple specific, distinctive characteristics that redefine how data-management is handled. Key characteristics of blockchain technology are; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions and robustness of the system due to its fault-tolerance. All these characteristics combined establish a technology where trust is embedded into the system. This enables the opportunity to provide trust-free operations between parties and provides an environment in which the current data-management architecture may evolve. Legally binding contracts, such as NDAs, are less important as 'trust' is embedded in blockchain technology through use of mathematical procedures, such as cryptography. As a result of this secure data-exchange through use of blockchain technology, aspects such as data-sharing, data-access and data-transmission can be managed differently. As a result of trustless operations, utilization of blockchain technology provides the opportunity for real-time, cross-enterprise data-exchange.

When a Digital Chain makes use of blockchain technology in a similar way to the provided future-state design, a system is designed where continuous sensor-updates can be communicated in real-time. Real-time data-exchange of sensor-based data ensures that a Digital Chain is able to accurately represent its physical counterpart. In supply chains, this accurate representation provides the ability to improve on business intelligence and advancements with regards to product flows. If the continuous updates from individual sensors are connected and processed swiftly by the intelligence layer, an accurate Digital chain of that supply chain is produced. When this accurate Digital Chain is constructed, aspects such as simulation, monitoring, analysis, diagnostics and prediction are enabled, that are expected by academics to have major impact on both supply chain management and -performance in the future. The increased levels of analysis, diagnostics and prediction achieved through the use of a Digital Chain, enables business intelligence to evolve based on data-driven updates.

Digital Chains are expected to have significant impact regarding the performance of supply chains. The construction of a Digital Chain enables more insights in the performance of individual entities, processes and the complete supply chain. The placement of numerous checkpoints, in the form of IoT-sensors, enable the possibility to divide the supply chain into multiple sectors and evaluate the performance of each of these sectors. The continuous updating of the state of the system, though the use of sensor-based data, together with the insights and predictions that are produced by the intelligence layer, enable for data-driven decision-making. An important result of a continuously updated, data-driven Digital Chain is its ability to generate iterative, accurate forecasts. Since a Digital Chain, when making use of blockchain technology, continuously receives data- updates in real-time, on the state of the supply chain, it is able to produce an accurate forecast on the downstream arrival times of future incoming load. The continuous updates of the system ensure that, when delays occur that were not factored in in the original forecast, the forecast is updated to the most recent state of the system. This iteratively updating of the forecasts leads to accurate representation of reality. As a result of these forecasts, participants of the supply chain are able to prepare themselves with regards to quantity and arrival times of future incoming load. Sufficient handling capacity to accommodate proper handling of goods can be assigned upfront, which leads to fluent and swift transitions between processes, resulting in process optimization across the supply chain. An important aspect of this process optimization are diminished dwell-times of goods passing through the supply chain. Since both the amount of goods and the time of arrival or departure of goods are known upfront, participants next-in-line can ensure sufficient handling capacity is present when requested to prevent the occurrence of dwell-time in-between processes of the supply chain. The result of reducing the dwell-time of goods in supply chains are improvements regarding SLOTT performance in supply chains.

4.4 Evaluation regarding Aspects Covered from Future-State Design

The previous paragraph explains the impact a Digital Chain might have on supply chains in the future, based on both the findings of the author and statements provided by academics. However, a complete Digital Chain was not constructed during this research, as not all aspects from the future-state design have been connected to each other due to time-limitations. This paragraph is intended to provide clarity on what aspects have been addressed during this research, and on those that require further research. Figure 4.4 on the next page shows the module design of a Digital Chain as presented earlier, with the addition of displaying which aspects were addressed during this research. Within Figure 4.4, four different areas are marked, numbered I till IV, that are explained to more extend. When an area is outlined in green, it means that this area has been covered and tested during this reached, while outlines in the color red indicate that that part of the module design remains mostly theoretical.

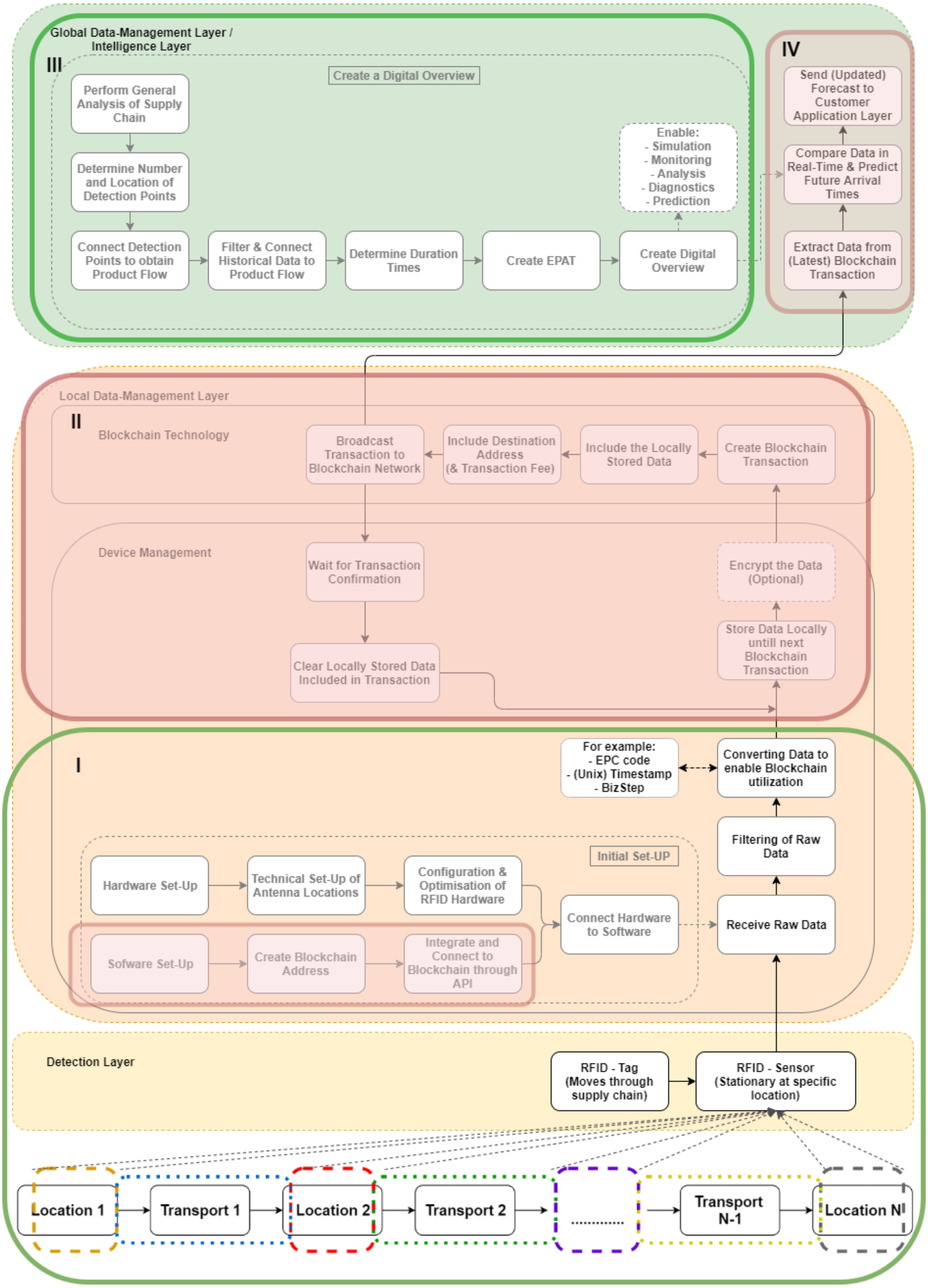


Figure 4.4 Aspects of a future-state Digital Chain design covered during this research; areas outlined with a green rectangle are covered extensively, those outlined in red are not

- Area I - Data-Collection and Device-Management

Area I covers analysis of the supply chain, the Detection Layer and a significant part of the Local Data-Management Layer, in particular concerning Device Management. This area is outlined in green since most of the steps within this area are part of already existing technologies and are widely used in supply chains. For example, setting-up RFID hardware and ensuring RFID tags are detected and their data is filtered and converted into usable information is a large part of the activities within Mieloo & Alexander. However, one aspect within Area I does not exist at the moment of writing; the blockchain software construction and integration to software normally used within device management. First off, the connection of blockchain technology to existing systems through the use of APIs is possible and is already displayed in numerous examples. However, at the moment of writing, the combination and integrating of blockchain technology within RFID-device management is not available to the author's knowledge. Combining and integrating blockchain technology is regarded by the author as an aspect that will be enabled in the near future, as examples in other industries show that this integration is possible.

- Area II - Data-Exchange through Blockchain Technology

Area II covers the remaining area of the Local Data-Management Layer. It consists of both a part of the Device Management aspect and the blockchain technology section that is responsible for executing transactions. Area II is outlined in a red color as these aspects were not combined and tested during this research. Single components of Area II are possible nowadays, however the combination of these components does not exist at the moment. For example, both storing data locally on an IoT-device and encryption of data are often used activities, as well as the occurrence of blockchain transactions. However, the combination of these components for appliance in supply chains has not been constructed. Further research on combining these components is recommended by the author in order to connect the Local Data-Management Layer to the Intelligence Layer and achieve real-time data-exchange.

- Area III - Digital Overview

Area III covers part of the Global Data-Management Layer. The green outline shows that this part of the module design is both covered and tested during this research. Area III covers the implementation-specific information and structure necessary to combine the different sensors together to one Digital Chain. It covers aspects such as determining the flow, order of processes and duration calculations of a particular supply chain. This research designed an EPAT as the intelligence layer for the Digital Chain to enable aspects such as simulation, monitoring, analyzing, diagnosing and prediction, in order to increase supply chain SLOTT performance.

- Area IV - Real-Time Forecasting

Area IV covers the remaining part of the Global Data-Management Layer. The red outline displays that this topic has not been covered and/ or tested during this research. Area IV covers the retrieval of data from a blockchain, comparing this data to historical performance, and providing a forecast of future arrival times. The automated retrieval of data from the blockchain has not been covered during this research since writing of the required code would exceed time-requirements. However, the auditability characteristics of blockchain technology indicate that retrieval of data from a blockchain is currently already possible, as well as feasible, as explained in Appendix III. Once the data is collected from the blockchain layer, comparing the data to historical performance and producing a forecast based on this data is nowadays already common in various industries, therefore the author expects that these aspects are relatively easily implemented. An example of data comparison, followed by forecasting is found in last mile delivery of packages, where a forecast of the arrival time of a delivery is send to customers.

From Figure 4.4 it becomes clear that numerous components of the future-state design need to be addressed before real-time communication is achieved and an accurate Digital Chain can be produced. This research has connected theoretical knowledge from numerous, individual fields together in order to provide a future-state design that is able to improve on supply chain performance in the near future. Besides using knowledge obtained from only literature, this research also covered how certain aspects of the future-state design are already being utilized within industries, for example the hardware set-up, data-receival and data-filtering within the Local Data-Management Layer. This translation towards actual use-cases helps to convert the philosophy of a Digital Chain into real-life applications. The design of the EPAT enabled calculation of the performance of the current-state of the case-study, and is used in the following chapter to display what impact a Digital Chain might have on supply chain SLOTT performance. The implementation of blockchain technology in actual use-cases remains a difficult aspect, therefore the author recommends to conduct more research towards actual utilization of blockchain technology in real-life use-cases.

4.5 Conclusion Future-State Digital Chain Design

From Chapter 3 the design requirements of a Digital Chain became clear, as well as the presence of dwell-time in the analyzed supply chain during the case-study. The EPAT provides insights in the performance of the supply chain, however it is unable to produce an environment that enables for iterative forecasting, as it cannot provide continuous, real-time updates of the state of the system. In order to establish an environment where iterative forecasting is enabled, this chapter answered the following research sub-question: What should a Digital Chain design, that combines IoT-sensors and blockchain technology, look like?

In order to achieve an environment in which continuous, real-time updates are possible, a future-state design of a Digital Chain is constructed that combines blockchain technology, IoT-sensor technology and the EPAT as an intelligence layer. During this chapter the philosophy of Digital Chains is translated into a future-state design that is intended to provide real-time visibility with regards to the whereabouts of goods within a supply chain, in order to enable forecasting of future arrival times of these goods and increase supply chain SLOTT performance.

The future-state Digital Chain design covers the complete range of steps necessary to achieve accurate forecasting, from the moment of detection of a tag by a sensor, to the production of a forecast regarding future arrival times of incoming load. The design describes how data should be converted and implemented into a blockchain, as well as the forecast that follows from comparing this data to a Digital Chain of the system. Three main aspects are combined within the future-state Digital Chain design; IoT-sensor technology for data-collection, blockchain technology to provide continuous, real-time data-exchange regarding the state of the system, and combining this data into a single system through an intelligence layer. The use of sensors provide for a data-driven system, and through continuous updating of state of the system, a Digital Chain is able to accurately mirror its physical counterpart. Since blockchain transactions occur every pre-determined period of time, the forecast is updated with every incoming transaction. This (near) real-time, data-exchange provides for continuous updating of the state of the system, enabling the possibility to produce iterative forecasting of incoming load, since the latest forecast is updated with every new blockchain transaction.

The design displays that once a Digital Chain of a supply chain is constructed, through enhancements in simulation, analysis and diagnostics of the system, insights are obtained with regards to performance and bottlenecks. The increased levels of analysis, diagnostics and prediction achieved through the use of a Digital Chain, enables business intelligence to evolve based on data-driven updates. The Digital Chain design provides the opportunity to compare new data to historical performance data, in order to predict when products will arrive at a certain location. Through continuous updates from the IoT-sensors, the current state of the system is constantly being updated, and therefore the forecast regarding future arrival times as well. Every time a transaction occurs on the blockchain, the intelligence layer derives this data and compares it to historical values in order to provide accurate predictions.

The continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. For example, sufficient handling capacity to accommodate proper handling of goods can be assigned upfront, which leads to fluent and swift transitions between processes, resulting in process optimization across the supply chain. An important aspect of this process optimization are diminished dwell-times of goods passing through the supply chain, which results in improved supply chain SLOTT performance.

Unfortunately, a complete Digital Chain could not be constructed during this research due to time-limitations. Therefore, not all aspects from the future-state design have been connected to each other during this research. Evaluation of the future-state Digital Chain design during this chapter displayed what aspects where covered in-depth, and which aspect require more research. Aspects that are included within the Digital Chain future-state design, but that are not covered to full extend during this research, are either based on knowledge obtained from literature or on current existing implementations of that particular technology.

Since a complete Digital Chain design could not be produced during this research, the actual impact it might have on supply chain SLOTT performance remains mostly theoretical. In order to provide quantification of the impact of Digital Chains on supply chain SLOTT performance, a numerical estimation is produced based on the results case-study. The following chapter covers estimation of the impact of the future-state Digital Chain through scenario-testing of the results of the EPAT of the case-study, comparing current-state with future-state performance.

Chapter 5 Impact of Design through Scenario-Testing

This chapter covers the impact on SLOTT performance of the future-state design as constructed during the previous part. During chapter 4 'Future-State Digital Chain Design, a qualitative future-state design is constructed to display what steps are required to produce a Digital Chain based on IoT-sensors, blockchain technology and an intelligence layer.

During this section, the following research sub-question is answered: 'What is the impact of the design when applied to the case-study?'. As previously explained, during this research a complete Digital Chain was not constructed. Therefore the future-state design remains mostly qualitative and impact remains theoretical. In order to determine the actual impact the design will have on supply chain SLOTT performance, the qualitative design needs quantitative results. During this chapter a numerical estimation of the effect of a Digital Chain, when able to diminish dwell-time, is produced through scenario-testing of the results of the EPAT of the case-study.

5.1 Data-Analysis of EPAT

The first aspect of this chapter covers the method used for the numerical estimation. From the framework design it becomes clear that in order to produce a Digital Chain, multiple different technologies, covering various disciplines, need to be connected to each other. Time-restrictions of this research prohibit generation of the complete design, as too many factors need to be worked out to produce an actual Digital Chain. Therefore the future-state design remains mostly qualitative and impact remains theoretical. However, a numerical estimation of the effect of a Digital Chain that is able to diminish dwell-time is possible through scenario-testing of the results of the EPAT of the case-study. In order to provide a numerical estimation of the impact of the future-state Digital Chan design is based on the combination of the produced EPAT and the case-study. The results of EPAT of the current-state analysis are used to estimate the impact a Digital Chain will have on an actual supply chain SLOTT performance.

Equal to paragraph 3.2 'Current-State Performance', the sub-flow of Flow 1, with final destination Location 3, will be used as an example. The results of all flows will be show during the end of this chapter, in order to enable comparison between the current performance and the future performance. Table 5.1 below show the results of the EPAT for this sub-flow, while Figure 5.1 visualizes the components present within Flow 1.

- Flow 1:

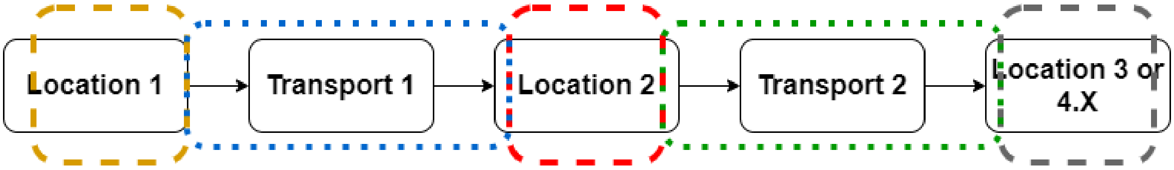


Figure 5.1 Visualization of the components of Flow 1

Table 5.1 Display of the KPIs of Flow 1, Location 1→ Location 2 → Location 3

Percentile #:	Duration (in hours)					Total time [h]	Efficiency* [%]
	Location 1	Location 1 → Location 2	Location 2	Location 2 → Location 3	Location 3		
Median	**16**	**15**	**45**	**21**	**59**	**155**	**155**
Upper Bound	**29**	**17**	**78**	**43**	**87**	**255**	**94**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

In Table 5.1 two percentiles are described; the median and the upper-bound percentile. The median is included because it is closest to an average value that is able to generally describe the throughput times of a sub-flow, while the upper bound percentile represents the upper limit of the EPAT's ability to truthfully represent reality for this sub-flow. By comparing the two, possible differences that influence performance are identified and become visible. Figure 5.2 is a visual representation of the values as present in Table 5.1, plotting the steps of the sub-flow based on time. Not that the green line, indicated with the letter 'A', represents the median, while the orange line, indicated with the letter 'F', represents the upper bound. Figure 5.2 clearly shows which processes are vulnerable for divergence in throughput time as the number of tags increases. When the orange and green line are parallel to each other, it means that the performance of these processes during processing of 50% of the tags takes up as much time as processing 75% of the tags. This is a desirable event since it shows that current handling methods are sufficient to accommodate the load without increasing the throughput time. However, when the two lines diverge from each other it means that the resources are unable to meet the demand at that time. This divergence leads to higher throughput times, which results in a decrease of the SLOTT performance of the system.

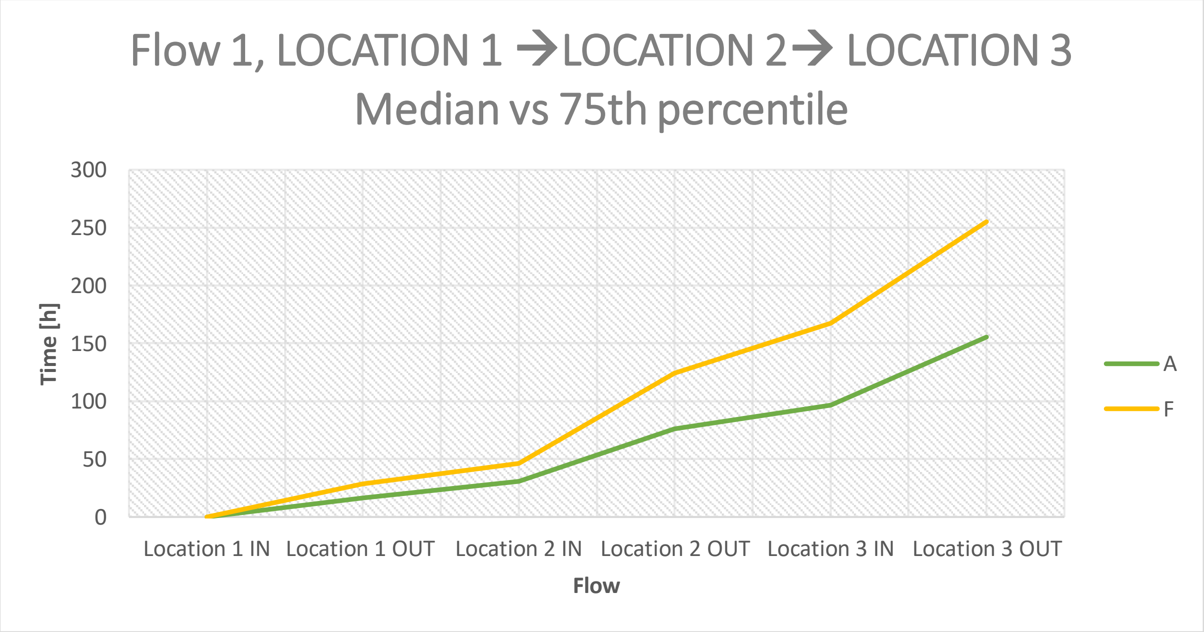


Figure 5.2 Display of the performance of the median and the 75th percentile of Flow 1,Location 1→ Location 2 → Location3

As concluded from the current-state analysis, it becomes clear that the throughput-times of the median and upper-bound differ quite significantly, with a total time of 155 hours and 255 hours, respectively. From Table 5.1 it becomes clear that for the median total time value, the requested service-level is reached. However, looking at the upper-bound performance of this sub-flow paints a different picture; the upper-bound value with regards to the total time is unable to reach the requested service-level. The differences between the value of the median and upper bound of each of the sub-flows show that the throughput time increases alongside an increase in percentage of tags that have passed the system. This means that the allocated assets and resources within a process are incapable of proper handling of the load. When the maximum throughput time of 75% of the tags is higher than that of 50 % of the tags, while passing through the same processes, it becomes clear that the resources are unable to handle the load. Improper handling of the load translates to queueing/ dwell time of products during the processes, which results in longer throughput times and therefore decreases the performance of the system.

5.1.1 Dwell-time

Since the processes are equal for both the median and upper-bound of a sub-flow, but their performance differs significantly, it is concluded that dwell-time is present during the processes that causes a decrease in SLOTT performance of the supply chain. The fact that the data has been collected during a period of a whole year enforces this statement, as it shows a structural difference and cannot be caused by single-events.

In Chapter 5 the assumption is made that the median value is considered as the average throughput time of the supply chain and acts as a baseline during future comparison of performance. Based on this assumption the dwell-time at every location becomes clear. The dwell-time that is present at each entity is the difference between the median value and the upper-bound value of that entity. When translating this towards the impact of utilization of a Digital Chain, if dwell-time is removed from the supply chain, the upper-bound values at each entity are equal to those of the median.

During the numerical estimation of the design on supply chain SLOTT performance, different scenarios are run through the EPAT in order to simulate the impact of a Digital Chain under different conditions.

5.1.2 Safety-level

However, before estimations through use of scenarios may occur, some restrictions are in order. Since estimation of impact of the future-state design is conducted based purely on the EPAT results, reducing the upper-bound value to the median value might give an overly-positive, non-realistic display of the impact of a Digital Chain. In order to move from purely theoretical to a more realistic estimation of the impact of a Digital Chain, a safety-level is introduced to incorporate restrictions that are present in real-life.

Aspects that are taken into account are for example hardware and spatial limitations. If a batch, or a bulk of products arrives at a certain entity that is twice the size of normal incoming load, or in other words peak-load, handling of those goods in reality may take up more time than theory suggests. For example, handling of double the incoming load by a conveyor belt in the same amount of time requires either double the speed of that conveyor belt, or using an additional conveyor belt at regular speed. In theory this might be possible, but in reality you are bound to a maximum speed of equipment, whether or not an additional conveyor belt is present, etc.. Other aspects that are taken into account are the increase in loading/unloading times during peak-load, maximum capacity of spaces such as hallways, indoor travel routes and storage facilities, as well other available assets and resources like number of forklifts present and amount of qualified personnel. Taken all these aspects into account, the author concludes that a safety-level of 1,5 should be taken into account when calculating the impact of a Digital Chain on the supply chain of the case-study.

5.2 Scenarios

Taking the safety-level into account, the calculations regarding the impact of a Digital chain for a particular entity are as follows:

$$\left(\Delta t_{Entity\ i\_UpperBound}\right) - \frac{\left(\Delta t_{Entity\ i_{UpperBound}} - \Delta t_{Entity\ i_{Median}}\right)}{ServiceLevel} \qquad , i \geq 1$$

Different scenarios are tested, where the upper-bound value of one or more entities is replaced by the Digital Chain simulation-value. Table 5.2 displays numerous scenarios and the impact they have on the performance of the supply chain, while Figure 5.3 show the components of Flow 1. Table 5.2 shows the cumulative duration time of goods passing through the sub-flow. If the cell above a number has an orange background color, it means that the upper bound value from the 'old' situation is used. When the design-related value is used at a particular entity, the background color of the cell above is blue and 'Design' is written in that cell. The last column displays the overall efficiency of the supply chain, compared to the service-level. When efficiency is below 100%, the background color of the cell is red, showing that the service-level requirement has not been reached. When efficiency is above 100%, the background color of the cell is green, showing that the service-level requirement is reached. Within Table 5.2, numerous scenarios have been displayed, ranging from the impact of alteration of one entity to alteration of all entities.

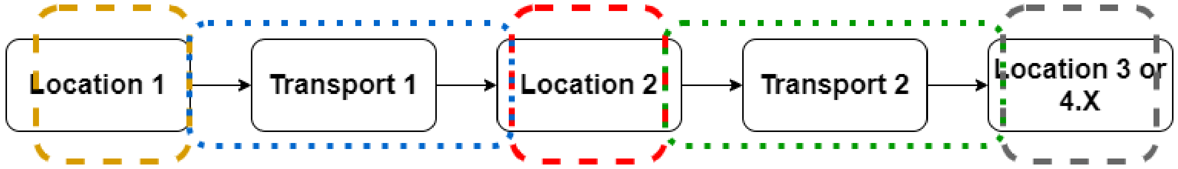


Figure 5.3 Visualization of the components of Flow 1

Table 5.2 Overview of the results of different scenario-tests regarding Flow 1, Location 1 → Location 2 → Location 3

Location 1 IN	Location 1 OUT [h]	Location 2 IN [h]	Location 2 OUT [h]	Location 3 IN [h]	Location 3 OUT [h]	Efficiency* [%]
			Current-State			
0	29	46	124	168	**255**	**94**
	Design					
0	21	38	116	159	**247**	**97**
			Design			
0	29	46	102	145	**233**	**103**
				Design		
0	29	46	124	153	**240**	**100**
					Design	
0	29	46	124	168	**236**	**102**

Table continues on the next page

	Design	🟧	**Design**	🟧	🟧	
0	21	38	94	137	**225**	**107**
	Design	🟧	🟧	**Design**	🟧	
0	21	38	116	144	**232**	**104**
	Design	🟧	🟧	🟧	**Design**	
0	21	38	116	159	**227**	**106**
	🟧	🟧	**Design**		🟧	
0	29	46	102	131	**218**	**110**
	🟧	🟧	**Design**	🟧	**Design**	
0	29	46	102	145	**214**	**112**
	🟧	🟧	🟧	**Design**		
0	29	46	124	153	**221**	**109**
	Design	🟧	**Design**		🟧	
0	21	38	94	122	**210**	**114**
	Design	🟧	**Design**	🟧	**Design**	
0	21	38	94	137	**205**	**117**
	🟧	🟧	**Design**			
0	29	46	102	131	**199**	**121**
	Design	🟧	**Design**			
0	21	38	94	122	**190**	**126**
	Design					
0	21	36	92	120	**189**	**127**

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

The top of Table 5.2 shows the current-situation performance of sub-flow: Flow 1, destination Location 3. It shows the cumulative duration time of goods within the supply chain at the predetermined checkpoints. From the current-situation performance it becomes clear that goods spend a total time of 255 hours within the supply chain, which is similar to an efficiency of 94% when compared to the service-level of 240 hours.

The part below the current-state displays the effect on performance when the design is utilized at only one location. Testing multiple scenarios, where the design-solution is applied to different locations, displays the impact the design has on performance. From Table 5.2 it becomes clear that utilization of the design at only one location already improves upon supply chain performance to some extent. The minimum gain that is achieved by utilization off only one location is 3 % compared to the current-sate efficiency, while the maximum gain is 9%.

After testing scenarios that only apply the design-solution to only one location, numerous scenarios were tested that apply the design to multiple locations. Each scenario shown in Table 5.2 makes clear how often the design is applied, at what location(s) the design is applied, and what impact each scenario has on the performance of the supply chain. From Table 5.2 it becomes clear that utilization of the design in more locations leads to increased SLOTT performance of the supply chain.

In order to provide an overview of the impact the different scenarios have on the supply chain, Table 5.3 shows both the current-state SLOTT performance and efficiency, as the minimum and maximum values that belong to appliance of the design solution to a certain number of locations. An important aspect to note is the increase in efficiency alongside an increase in the number of locations that make use of the design. From Table 5.3 it becomes clear that utilization of the design on all locations is most desirable, as it provides for the highest level of efficiency in the supply chain within the boundaries of the design.

Table 5.3 Overview of minimum and maximum impact appliance of the design on a specific number of locations

Flow 1															
Destination		**Current situation**		**D 1 L****			**D 2 L**			**D 3 L**			**D 4 L**		**D ALL**
				min	**max**		**min**	**max**		**min**	**max**				
Location 3	**[h]**	255		247	233		232	214		210	199		190		189
	[%]*	94		97	103		104	112		114	121		126		127

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%
**Design applied to 1 Location

5.3 Scenario-Testing Results all Sub-Flows

During the previous paragraph, the impact of the design regarding SLOTT performance for only one sub-flow was displayed. However scenario-testing has been performed for all of the sub-flows. The results of appliance of the design to multiple locations for the various sub-flows is found in Appendix IV. From these results it becomes clear that the SLOTT performance of the supply chain improves alongside an increased number of locations that make use of the design. During Chapter 3 'Design Requirements' the current-state performance of supply chain of the case-study was calculated. Since the numerical values of the impact of the design are now also available, the results can be compared to each other to display what impact utilization of a Digital Chain might have on SLOTT performance of supply chains. Figure 5.4 and 5.5 are present to once again show the different flows that were analyzed, while Table 5.4 covers the results of both the current-state performance and the future performance as possible through utilization of a Digital Chain. The upper part of Table 5.4 displays the results as calculated during the current-state performance check, while the lower part shows the results of supply chain when the design is applied to all locations.

- Flow 1

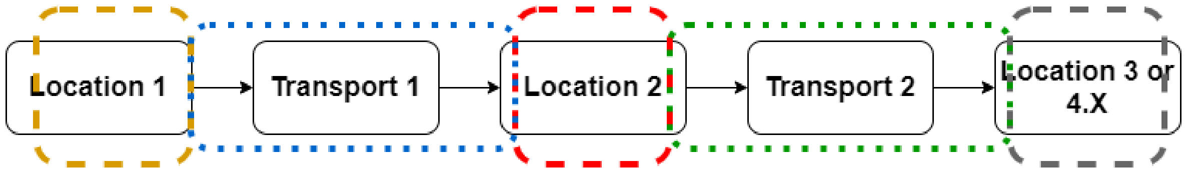


Figure 5.4 Visualization of the components of Flow 1

- Flow 2

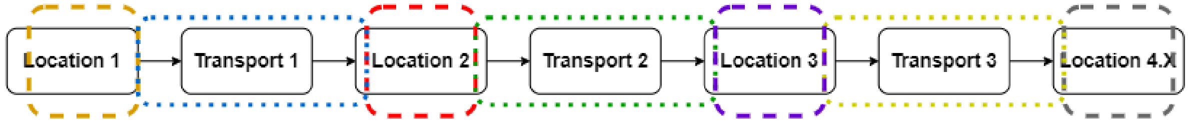


Figure 5.5 Visualization of the components of Flow 2

Table 5.4 Overview of both the current-state and future-state performance of all sub-flows, divided into percentiles, including comparison towards required service-level

Current-State										
		Flow 1					**Flow 2**			
		3	**4.2**	**4.3**	**4.4**		**4.1**	**4.2**	**4.3**	**4.4**
Percentile #:		**Duration [h]**					**Duration [h]**			
Median		155	382	195	202		198	154	218	155
55th		172	512	201	332		217	193	232	167
60th		188	651	212	371		235	215	243	205
65th		202	1006	347	385		258	228	260	232
70th		225	1123	426	417		279	249	274	247
75th		255	1311	449	469			261		
80th			1695	474	642			273		
85th			2124	515	868					
90th										
95th										
100th										

Future-State										
		Flow 1					**Flow 2**			
		3	**4.2**	**4.3**	**4.4**		**4.1**	**4.2**	**4.3**	**4.4**
Percentile #:		**Duration [h]**					**Duration [h]**			
Median		155	382	195	202		198	154	218	155
55th		161	426	197	246		204	167	223	159
60th		166	472	201	259		211	174	226	172
65th		171	590	246	263		218	179	232	181
70th		179	629	272	274		225	186	236	185
75th		189	692	280	291			189		
80th			820	288	349			194		
85th			963	302	424					
90th										
95th										
100th										

From Table 5.4 it becomes clear that utilization of a Digital Chain has a positive effect on the supply chain SLOTT performance. From the current-state performance it becomes clear that none of the eight sub-flows is able to meet its service-level for the upper-bound values. However, from the results of the future-state performance calculations it becomes clear that five out of the eight sub-flows is able to meet the required service-level for the complete range of goods passing through the supply chain. Table 5.5 below displays the improvement each sub-flow is able to achieve when a Digital Chain of that sub-flow is realized that is able to dimmish dwell-time. The percentual improvement is calculated through the following formula:

$$\frac{Improvement\ [h]}{Current\ situation\ [h]} * 100$$

Table 5.5 Overview of the improvements made possible by diminishing dwell-time, specified for the analyzed case-study

Flow 1	**Destination**		**Current situation [h]**		**D ALL***	**Improvement [h]**	**Improvement [%]**
	Location 3	**[h]**	255		189	66	26
	Location 4.2	**[h]**	2124		963	1161	55
	Location 4.3	**[h]**	515		302	213	41
	Location 4.4	**[h]**	868		424	444	51
Flow 2	**Destination**		**Current situation [h]**		**D ALL***	**Improvement [h]**	**Improvement [%]**
	Location 4.1	**[h]**	279		225	54	19
	Location 4.2	**[h]**	273		194	79	29
	Location 4.3	**[h]**	274		236	38	14
	Location 4.4	**[h]**	247		185	62	25

*Design applied to all Locations

5.4 Conclusion Estimation Impact of Design

This chapter answered the following research sub-question: ‘What is the impact of the design when applied to the case-study?’.

Once a numerical estimation on the impact on SLOTT performance through scenario-testing was calculated, the results of the EPAT show that most benefits regarding Digital Chains mentioned in theory are similar to those in practice. The RFID infrastructure as present during the case-study provides sufficient, useful data to produce a digital overview of the supply chain. Before this analysis, only part of the functionality of the RFID infrastructure was used by the participants of the analyzed supply chain. Each entity within the supply chain used, and had access to, only the data that was of concern to them. Little information is shared between entities, and each participant focusses on complying to their own contractual agreements instead of on aspects that cover the complete supply chain, for example performance of the overall supply chain. During analysis of the case-study, access to the data of multiple entities was obtained, and by connecting the data from numerous sensors to each other an EPAT of the supply chain could be constructed, in order to increase visibility of the flow of goods.

The EPAT enables advancements regarding insights in SLOTT performance of the supply chain, and is able to identify if and where possible improvements might be possible within specific parts of the supply chain. Simulation of the supply chain and analysis of the data revealed that internal processes at specific entities take up the most amount of time spend in the supply chain, while the transition/transportation processes are relatively short. The EPAT also shows that the throughput time of products per entity differs significantly between the central tendency and the upper bound values, which results in a decrease of the SLOTT performance of the system.

Based on these insights further diagnostics regarding addressing this decrease in performance were executed in order to propose future improvements. From these diagnostics it became clear that current-state performance provides insufficient capacity to properly handle and process incoming load. This insufficient allocation of handling capacity leads to dwell time of products within the supply chain, for example due to queueing of products. This presence of dwell-time negatively impacts the SLOTT performance of the supply chain.

Once a Digital Chain of a supply chain is produced, dwell-time is diminished. If real-time data-exchange is achieved, the intelligence layer is able to produce an accurate overview of the state of the system at that moment. As a result, the intelligence layer provides the participants of the supply chain with a continuously updated forecast regarding the expected products, for example number of products to be expected at a certain location at a specific moment. This pro-active data-exchange provides participants with the opportunity to prepare for incoming goods, arranging for sufficient handling of products. Proper handling of products along all participants leads to the avoidance of bottlenecks in the system and prevents the occurrence of dwell-time of goods in the supply chain. The prevention of dwell-time of goods results in improved supply chain SLOTT performance.

From the comparison between current-state and future-state SLOTT performance it became clear that utilization of a Digital Chain has a positive effect on supply chain performance. From the current-state performance analysis it became clear that none of the eight sub-flows are able to meet its service-level objective for the upper-bound values. However, from the results of the future-state performance calculations it becomes clear that, due to diminished dwell-time, SLOTT performance of this particular supply chain improves between 14-55%, depending on the sub-flow. As a result, five out of the eight sub-flows of the future-state supply chain are able to meet the required service-level for the complete range of goods, within the boundaries of the EPAT, passing through the supply chain. To compare, during current-state performance none of the sub-flows are able to meet the required service-level for the complete range of goods.

Chapter 6 - Conclusion & Recommendation

6.1 Conclusion

This research focused on obtaining an answer to the following research question; 'What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?'. This research demonstrates that a Digital Chain-solution should be considered as an interesting proposition to improve supply chain Service-Level Objectives regarding Throughput Times (SLOTT) performance in the near future, due to the advancements regarding visibility and business intelligence it accompanies. The combination of IoT-sensors, blockchain technology and an intelligence layer leads to provision of an environment that enables for accurate, iterative forecasting of future incoming load in supply chains. If a Digital Chain is able to receive continuous, data-driven updates on the actual state of the supply chain in real-time, it is able connect the data from individual sensors and produce forecasts regarding future arrival times of incoming load. The continuous updates, facilitated by data-collection through IoT-sensors and real-time data-exchange through utilization of blockchain technology, enable the ability to adjust a forecast if unforeseen delays occur during a process. These iterative forecasts provide participants of the supply chain with visibility on the whereabouts of products and enables the opportunity to prepare themselves upfront with regards to future incoming load, thereby facilitating for proper and swift transitioning and processing of goods. The insights gained in the performance of different entities, together with the ability to prepare upfront, are expected to result in a reduction of dwell-time of products, and therefore improves upon supply chain SLOTT performance. However, more research towards Digital Chain applications is necessary to provide a definitive answer on what the actual impact of Digital Chains on supply chain performance will be. A numerical estimation regarding the increase in performance was obtained during scenario-testing of the future-state Digital Chain design, in which utility of a Digital Chain was simulated trough data-analysis of a case-study. From the data-analysis of eight different sub-flows within the case-study, it became clear that the reduction of undesired dwell-time improved supply chain SLOTT performance by 14-55%, compared to the current-state, depending on which sub-flow is considered. As a result, five out of the eight sub-flows of the future-state supply chain are able to meet the required service-level for the complete range of goods, within the boundaries of the EPAT, passing through the supply chain. To compare, during current-state performance none of the sub-flows are able to meet the required service-level for the complete range of goods.

During this research, first a literature review was conducted in order to understand the components of a Digital Chain, its characteristics, and how it will impact supply chain performance. From this review, it became clear that a Digital Chain enables enhanced simulation, monitoring, analyzing, diagnostics and prediction aspects in supply chains. A Digital Chain allows entities to proactively optimize their operation decisions, enabling aspects such as process optimization, increased operational performance and iterative forecasting.

However, from literature was concluded that current, centralized, legacy solutions are unable to handle, process and exchange data in real-time, limiting the advancements of a Digital Chain. During this research IoT-sensor technology is combined with blockchain technology in order to provide for continuous updates of the state of the system, thereby overcoming the current data-management issues and providing an environment that enables real-time, cross-enterprise data-exchange.

Research was conducted on understanding the characteristics and benefits of utilization of blockchain technology. From this research it became clear that blockchain technology is characterized by four major aspects; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions and robustness of the system due to its fault-tolerance. These characteristics enable the ability to provide trust-free operations. These trust-free operations result in evolvements with regards to data- management and data-accessibility, enabling aspects such as real-time data-exchange.

In order to provide quantitative analysis of SLOTT performance during this research, an Efficiency and Performance Analysis Tool (EPAT) was designed for a specific case-study, which consists of eight different sub-flows. This EPAT acts as an intelligence layer that produces a digital overview of the supply chain and provides insights regarding the presence and impact of dwell-time on performance. Through use of the EPAT, aspects such as identification of bottlenecks, visibility of both individual and supply chain-wide SLOTT performance, and prediction of duration were enabled. Data-analysis based on the results of the EPAT provided a current-state performance analysis which showed that dwell-time is indeed present and negatively impacts SLOTT performance. However, predictions produced by the EPAT, in its current form, are only based on historical performance, as the current situation does not allow for continuous updating and sharing of data in real-time.

A future-state Digital Chain design was constructed, based on the combination of RFID-sensors, blockchain technology and an intelligence layer, in order to provide a system that is able to produce iterative, accurate forecasting of future arrival times, based on the current state of the supply chain. The future-state module design displays all steps required to turn raw data of numerous RFID-sensors into a forecast that predicts future arrival times of goods within a supply chain. The module design shows that utilization of blockchain technology indeed provides for a system where continuous sensor-updates are communicated in real-time, and that the combination of IoT-sensors and blockchain technology lead to an environment where iterative forecasting is enabled. The combination of IoT-sensors, blockchain technology and an intelligence layer provides a data-driven decision-making environment that is able to produce accurate forecasts with regards to future incoming load. If these predictions are frequently updated and shared to other entities within the supply chain, an upfront preparation environment is produced where down-stream entities are able to arrange aspects such as sufficient handling capacity, ensuring proper handling of the incoming load. Proper and adequate handling of incoming load reduce the dwell time of products within a supply chain, resulting in improved supply chain SLOTT performance.

However, a complete, fully functioning Digital Chain was not constructed during this research, as not all individual aspects from the future-state module design have been connected to each other due to time-limitations. Therefore the proposed future-state design remains overall qualitative and more research towards the construction of Digital Chains in actual supply chains is required to provide quantitative insights regarding the impact of Digital Chains on SLOTT performance in supply chains.

However, the design of the EPAT did allow, through scenario-testing, for a numerical estimation on the impact of Digital Chains on SLOTT performance when they are able to diminish dwell-time in supply chains. Through use of the EPAT, a current-state / future-state comparison was performed to highlight the differences in SLOTT performance of the supply chain. From the comparison between current-state and future-state performance it became clear that the reduction of dwell-time is able to improve the SLOTT performance of this particular supply chain between 14-55%, depending on the sub-flow. This performance improvement ensures that five out of eight sub-flows are able to meet the service-level requirements for the complete range of tags, within the boundaries of the EPAT, instead of none of the sub-flows in the current-state.

6.2 Future Research

During this paragraph, future research is proposed on multiple topics covered during this research.

This research covered the combination of two emerging technologies; IoT-sensor technology and blockchain technology, to improve on SLOTT performance. Both of these technologies are still in development currently, and numerous aspects regarding each of these technologies, as well as the combination of these technologies towards applications besides supply chain performance, requests more research.

The first subject on which future research is recommended covers the use of Digital Chain technology in supply chains on a general level. Currently, little research is conducted on the application of Digital Chains in actual supply chains. More research towards implementations of Digital Chain technology in supply chains is requested, to better understand the actual impact of this technology on processes, decision-making, and performance, as well as the issues that present themselves alongside the transition towards utilization of Digital Chains, for example-regarding cost-efficiency. This research indicates that use of a Digital Chain is beneficial with regards to the overall supply chain performance, however more research is recommended towards the impact of Digital Chains with regards to internal processes of entities within a supply chain, for example on aspects such as warehouse lay-outs, manufacturing sequences and process optimization.

Another aspect that requires more research covers the combination of blockchain technology with data-driven ‘intelligence’ technologies such as Artificial Intelligence, Big-Data, Machine Learning. This research showed that blockchain technology as a middleware solution is able to overcome some of the current data-management issues and therefore enables real-time communication, however prediction optimization is not possible through the use of blockchain technology. Further research should be conducted on combining IoT-sensors and blockchain technology with other intelligence technologies to achieve forecast optimization and aspects focused on providing an additional level of control, such as the enablement of dynamic asset and resource allocation based on the provided forecast.

The author recommends conducting research towards optimization of anticipatory planning and dynamic asset and resource allocation, as those aspects are presumed to have significant influence on the presence of undesired dwell-time. First of all, the author recommends to conduct further research into the current resource allocations of the internal processes at each location, in order to identify and address the specific bottlenecks of these processes. Through analysis of the allocations at specific locations more insight is gained in the capacity of the allocations and decision-making regarding the distribution of these assets and allocation may be improved. Also further research should be conducted that focusses on optimizing the anticipatory planning and dynamic allocation of assets and resources. As previously mentioned, the designed Digital Chain could be combined with technologies such as AI and ML, in order to predict incoming load more accurately and produce a more detailed forecast. More research is recommended towards matching Digital Chain technology with models that are able to compare predicted forecasts with available resources, in order to optimize the distribution of these assets and resources. Optimization of these distributions ensure that the highest level of SLOTT performance is reached with the available capacity.

Data-management is another important topic that would benefit from further research. The construction of Digital Chains lead to an increase of data that needs to be transmitted, stored and processed. As identified by academics, this increase leads to exceeding capacity of current legacy systems in the near future. Through the use of blockchain technology some aspects of data-management are overcome, however more research on data-management is necessary in order to meet the increasing demand of data and to provide future-proof data-management solutions. Aspects such as data-storage, data-access, data-processing, data-sharing, data-transmission and data-authenticity need to be further researched. For example, data-architecture patterns need to be researched further to enable accurate data-processing and further research is requested on these data-capture mechanisms in order to validate the benefits of application of these mechanisms for specific Digital Chain use cases.

Blockchain technology itself is also an important topic that needs to be researched to more extend, in order to accurately determine what impact it will have on supply chains and supply chain management. Many of the technical challenges lay within the development of blockchain technology, such as consensus mechanisms, chain structures, data-storage management, interoperability and governance. Also regulations concerning blockchain technology are still to be decided. In the near future, issues regarding privacy, security, scalability, efficiency, latency, transaction throughput and block size need to be addressed before the technology becomes mature. For example, new types of consensus protocols are still being developed at the moment of writing, all with different properties. More research needs to be conducted on consensus protocols such as Proof-of-Work, Proof-of-Stake, DAGs, Avalanche and others, in order to understand their benefits, limitations and suitability for specific use-cases. Further research is also requested on scalability techniques that increase throughput and/ or lower latency, such as sidechains, state channels and sharding solutions. With regards to privacy of data, more research is requested on techniques such as Zero-Knowledge Proof technology, Ring signatures and mixing techniques. Also research is required with regards to data-storage on blockchains. Further research should be conducted regarding storage of data in blockchains, for example on how on-chain data should be combined with off-chain data systems, in order to prevent clogging of the blockchain. Gaining knowledge on what data should be included in- and exclude from a blockchain transaction enables further evolvement with regards to application of blockchain technology in reality.

The last topic of recommendations regarding future research covers the results of the case-study. From the results of the case-study, it became clear that two types of improvements are present that would positively influence SLOTT performance of the supply chain; performance of internal processes of individual entities, and overall performance of the complete supply chain. This research has focused on the overall performance of the supply chain, however the design of the EPAT also provides the ability to focus of the performance of individual processes and/or entities. Conducting specific research on the internal processes of entities, such as in-depth analysis of the process-steps as present within each entity, should be conducted. Conducting specific research generally leads to identification and resolving of bottlenecks during the internal processes, which generally leads to a higher level of SLOTT performance of the supply chain.

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Appendices

Appendix I & II

Both Appendix I and II are excluded from this document as they contain sensitive information that cannot be made public. Appendix I and II are present in separate files, accessible only to authorized entities.

Appendix III - Blockchain Technology Explained

III.2 How does blockchain technology work?

As mentioned above, academic research has identified that utilization of blockchain technology may impact industries and societies to great extend (Gaehtgens & Allan, 2017). However, since blockchain is an emerging technology, in general there is a lack of knowledge on the subject. To see the potential of new technologies, it is important to understand how these technologies work, what it is able to do and what limitations it has. Therefore, this paragraph focusses on understanding blockchain technology, by breaking down the technology into multiple components and explaining each component.

III.2.1 Elements of a blockchain

Traditional databases provide adding, deleting, changing and querying of data. In blockchain systems, only adding and querying data is possible, therefore transactions stored on the blockchain become permanent and undeletable. This immutability and auditability are the result of combining multiple elements of a blockchain.

Three elements make up the core of a blockchain, as displayed in Figure III.1. These elements are a distributed storage mechanism based on a peer-to-peer network, a time-stamp based chain-block structure, and a consensus mechanism based on decentralized nodes (Yuan & Wang, 2018). These three elements together produce the characteristics of a blockchain, which are cryptographically secured, append-only, immutability, auditability, transaction authentication and integrity, fault tolerance and trust-free operations (Bashir, 2017) (Makhdoom, 2019). These three elements will be explained in more depth. Before doing so, other important aspect such as nodes, transactions and blocks are explained briefly.

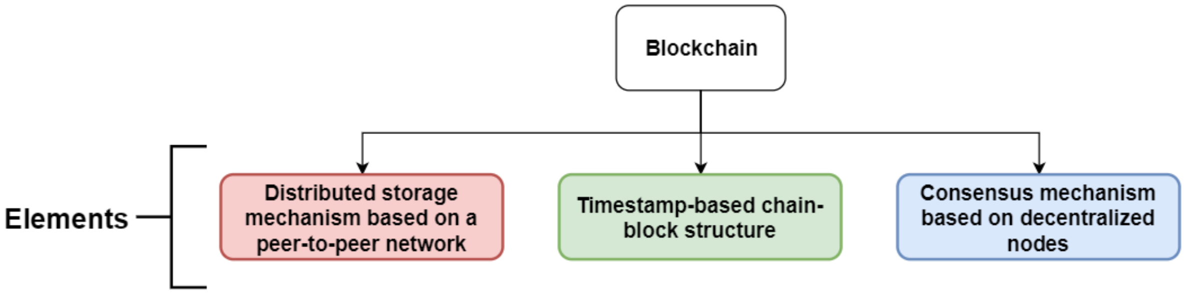


Figure III.1 Elements of a blockchain

III.2.2 Distributed storage mechanism on a P2P network

The first key element of blockchain technology that is explained is a distributed storage mechanism based on a peer-to-peer (P2P) network. Figure III.2 displays how a distributed P2P system works (left), compared to a centralized system (right). In the centralized system, five entities are present;

four entities that conduct transactions and one central authority that is in control of the transaction ledger. The central authority, in this example represented by a clearing house, maintains and updates the ledger of all participants. All transactions go through this clearing house and it is not possible for entities to send transactions directly between them.

Blockchain technology does not make use of such a centralized structure. The communication and storage mechanism of blockchain technology is based on a distributed network, where all nodes are able to send and receive transactions directly. In a distributed network, there is no need for a central authority who is in control of maintaining the ledger. Instead, all entities have a copy of the ledger. After each transaction, an entity updates the ledger and broadcasts it to all nodes, ensuring that every node has the most recent version.

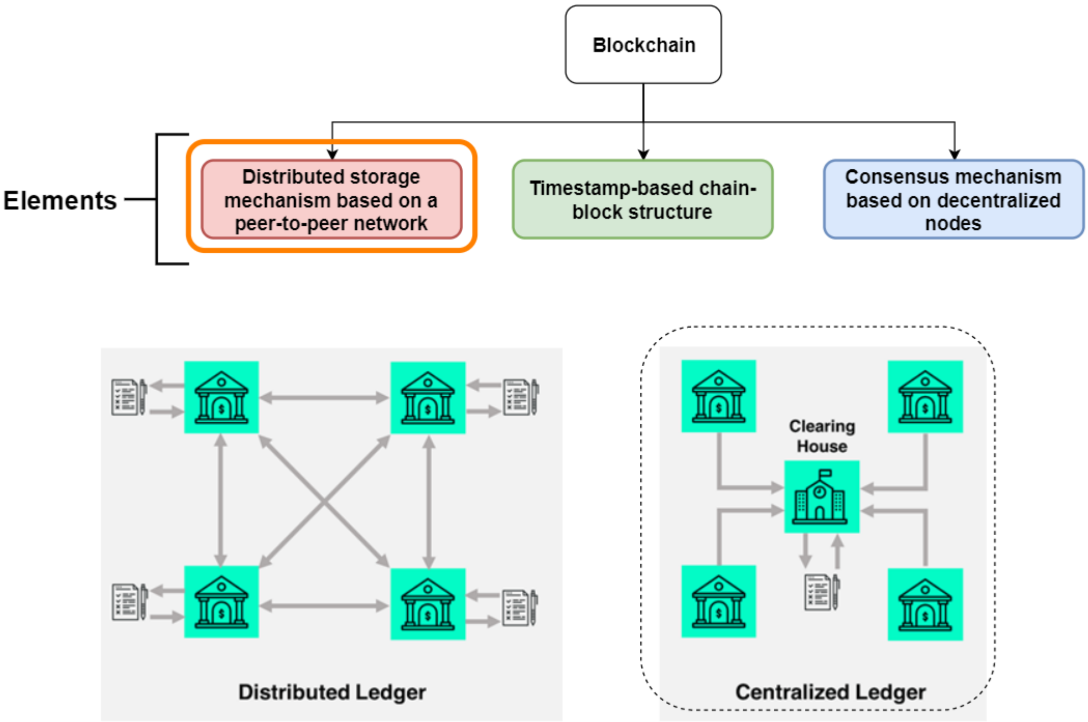


Figure III.2 Elements of a blockchain - Distributed storage mechanism based on a (P2P) network (TradeIX Ltd, 2018)

In the centralized system, all nodes are dependent on the central authority. This dependency on a single entity leads to some undesirable vulnerabilities. First of all, it creates a single point-of-failure for the system. If for some reason (technical issues, software bugs, hardware problems, hacks, bankruptcy, etc.) the central authority is unable to maintain and update the ledger, or data is lost, the whole system is affected and may be unable to continue performing its activities. Second, the dependency on a central authority also empowers the central authority to a certain extend. Since the central authority controls the ledger, data- access is controlled by this authority; it is able to decide which transactions are approved, which transactions are denied, and may even restrict access to information or accounts. Another important aspect is the possibility for data-manipulation. Since the central authority is in control of the ledger, vulnerability is present regarding malicious actions of this entity such as data-alteration for personal benefit.

Blockchain technology is able to address these issues. In a distributed network, all nodes have a copy of the ledger and are able to directly communicate to each other. This removes the need for a centralized authority, and therefore vulnerability with regards to a single point-of-failure is eliminated.

However, the distributed storage mechanism on its own is not capable to address the issues regarding data-access management, validation and verification of transactions, and data-manipulation. Explanation of the time-stamped, chain-block structure and the consensus mechanism will provide understanding of how these aspects are managed.

Other important aspects

Before further explanation of the remaining key elements of blockchain technology, it is regarded beneficial by the author to first get a general overview of other important aspects besides the three key elements. These aspects consist of nodes, transaction validation and transaction cycles; what happens when a transaction occurs in the network.

Transaction Cycle

A transaction (TX) can be described as the transfer of goods, services, funds, information etc. between multiple parties (Merrian, 2020). Transactions are a core aspect in blockchain technology and proceed in a particular way before being finalized, also displayed in Figure III.3. When a node in the network sends a transaction to another node within the network, it actually sends a proposal for that transaction. This transaction proposal is timestamped and broadcasted to all other full and validation nodes present in the network. Each transaction that enters the blockchain system must first be validated and approved by the majority of the network nodes before it may be included in a timestamped block. The full and validator nodes will validate and verify the transaction by means of a consensus mechanism; a set of predetermined rules to ensure agreement between nodes in a distributed system (Investopedia, 2020). When a new block is suggested to be added to the existing chain, the nodes in the network must first verify that the suggested block only contains valid transactions and refers to the correct previous block by means of cryptography, also known as reaching consensus. Consensus is an agreement between the nodes in a decentralized network that helps validating and authenticating transactions and values, ensuring that all nodes share the same data and data manipulation from malicious actors is prevented (LFS171x, 2019). Consensus mechanisms are defined by parameters such as authentication, decentralized governance, integrity, non-repudiation and performance (Seibold & Samman, 2016).

After approval, the transaction is no longer a proposal and it is added to a Mempool. This Mempool can be seen as a queue of approved transactions where block creators pick transactions from. When a block is produced, numerous transactions are pulled from the Mempool and are incorporated within this block, until the limit of a block’s capacity is reached. The block is closed after certain conditions, provided by the consensus mechanism, are met, and a new block is produced. Each block is connected cryptographically to the previous block, creating a block-chain. A transaction is completed after closure of multiple concurrent blocks after closure of the block the transaction is incorporated in. The number of blocks required to finalize a transaction is dependent on the consensus mechanism.

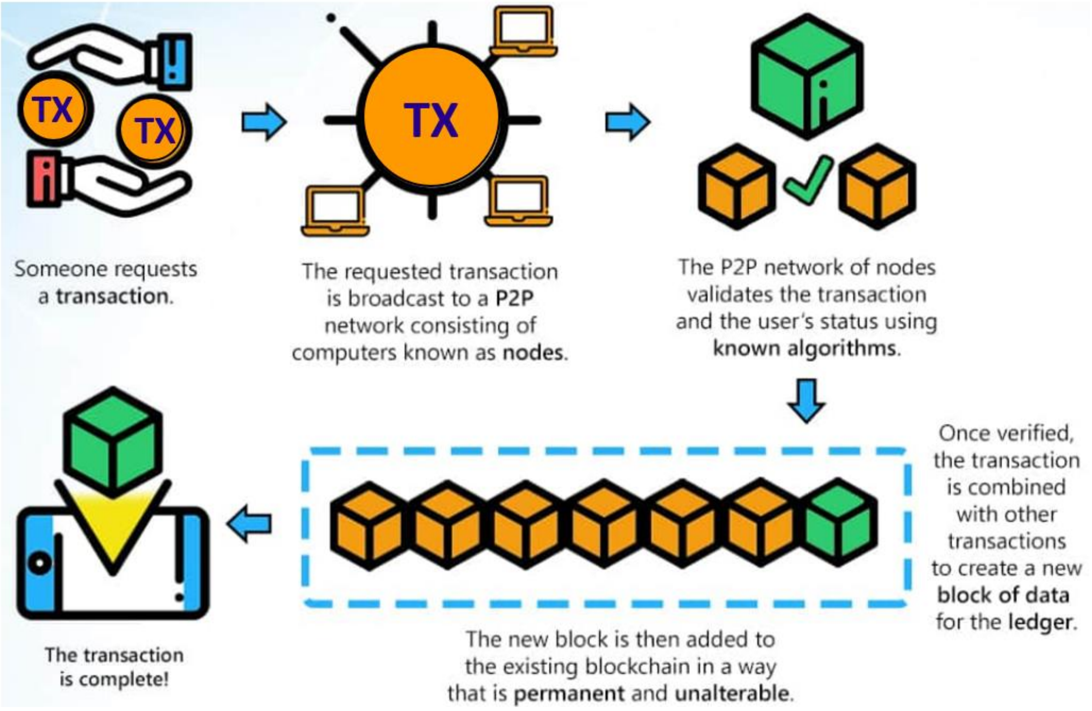


Figure III.3 An example of a blockchain transaction cycle (Blockgeeks, 2020)

Nodes

Within a blockchain, different types of nodes may exist. These differences in nodes are based on capabilities and resources, such as computation power and memory. The different types of nodes are; validator/ miner nodes, full nodes and simple/ normal nodes. A simple node is able to participate in the network by sending and receiving transactions. A simple node does not store a copy of the entire network and does not participate in the consensus mechanism. A full node does store a copy of the entire blockchain, however they also do not participate it validating and producing blocks. However, full nodes do validate transactions by means of the consensus protocol, making them essential in securing the blockchain. Validator nodes are full nodes that do participate in the consensus mechanism, validating and/ or producing new blocks and therefore extending the blockchain. Validator nodes are selected based on consensus protocol specific criteria.

Transaction Validation & Verification

In the paragraph ‘Transaction Cycle’, transaction validation and verification was first mentioned. This paragraph goes into more depth about how validation and verification is achieved.

In blockchain technology, each transaction is signed with a digital signature (Bashir, 2017). This digital signature validates the identity of the sender, by proving that the transaction originates from the sender cryptographically (Narayanan et al., 2016). The digital signature is derived by means of asymmetric encryption techniques. Blockchain technology makes use of asymmetric encryption, generating a key pair for each address. This key pair consists of a private key and a public key, which are connected through a mathematical relationship (Buldas, Laanoja & Truu, 2017). From the private key, through hashing algorithms, a public key is derived. In the same fashion, from this public key a public address is derived. However, vice versa it is impossible; It is not possible to derive a private key when a public key is known. The public key and public address are available for insight to other nodes, while the private key is personal and needs to remain secret. During a transaction, a unique digital signature is produced through the private key. Only a private key is able to produce the signature, however its corresponding public key is able to verify that the signature originated from the private key, therefore validating the identity of the sender. During a transaction, data, the digital signature, and the public key are included in the transaction. The combination of these three aspects enable verification of the transaction and its sender. The digital signature also validates the authenticity of the transaction. A digital signature is dependent on the data included in the transaction, and if data is modified during the process the signature becomes invalid. Figure III.4 visualizes the aspects as explained above.

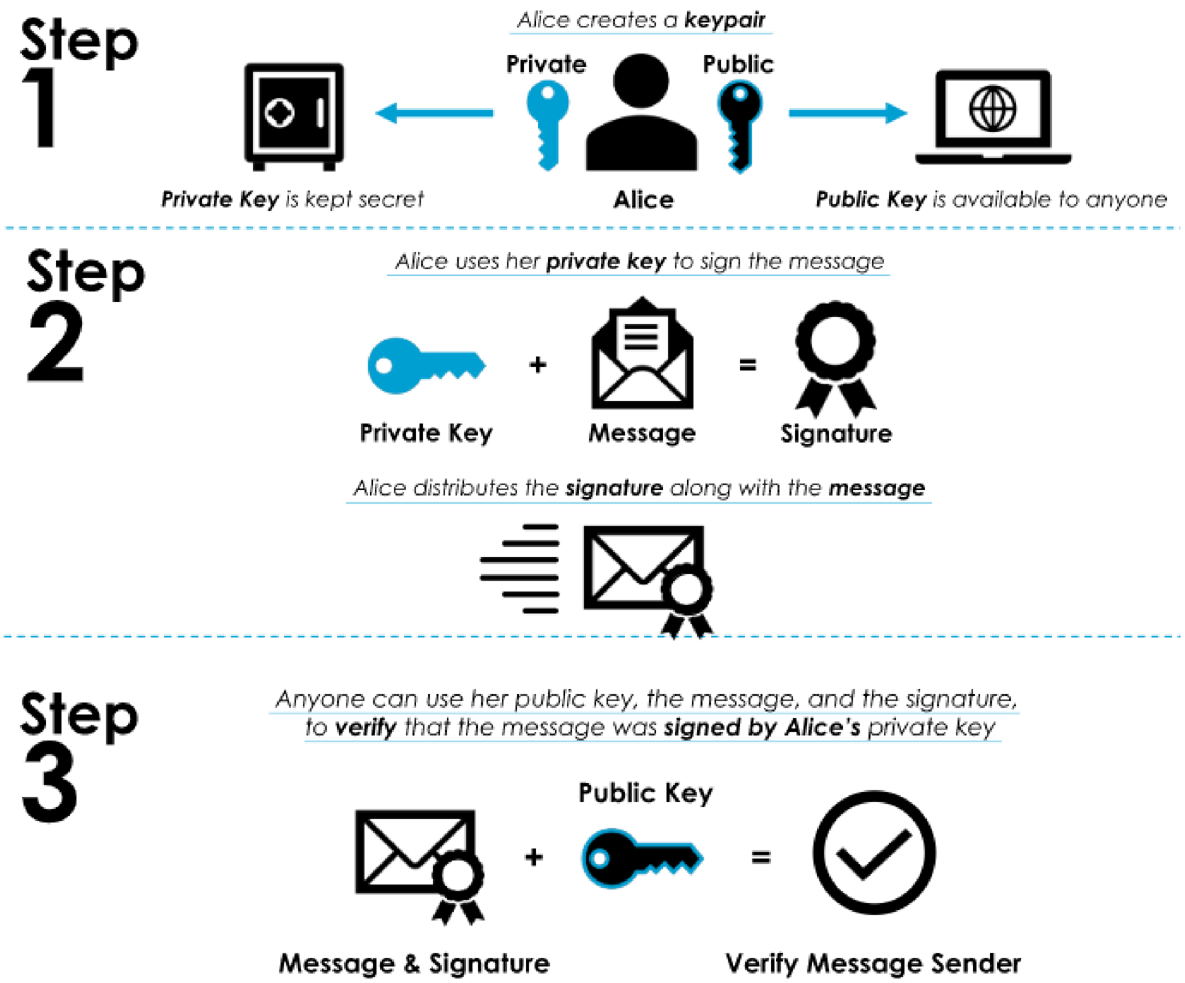


Figure III.4 Visualization of ensuring authentication of transactions through key pair encryption (Isara, 2020)

III.2.3 Timestamp-based chain-block structure

The second key element of a blockchain is a timestamp-based chain-block structure, see Figure III.5. This paragraph focuses on explaining how blocks are formed and linked to each other, as well as how transactions are incorporated in these blocks.

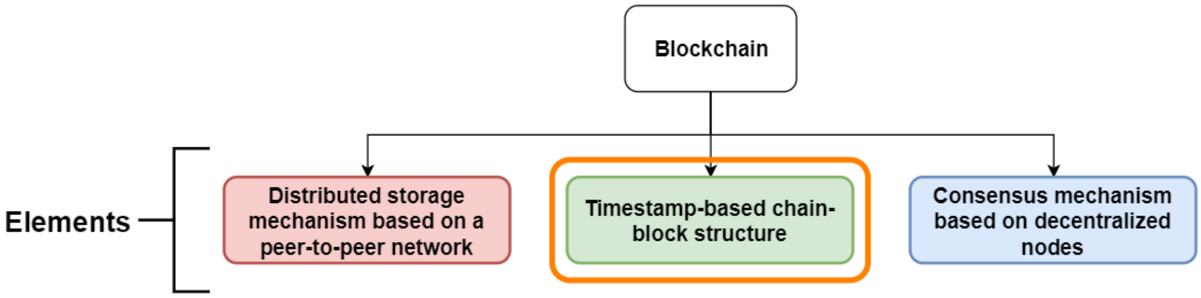


Figure III.5 Elements of a blockchain - timestamp-based chain-block structure

Blocks

A block consists of a collection of transactions that are included during the time between creation and closure of a block. The creation of a new block takes up a certain amount of time due to requirements of the consensus mechanism. Besides transactions, a block also contains information regarding the blockchain framework itself, enabling linking of blocks in a correct and unique way. Examples of this blockchain framework information are the blockchain version number, the timestamp, hash of the previous block, the Merkle Root Hash, and a random nonce (Azzi, Kilany & Sokhn, 2019). These aspects are explained in the upcoming paragraphs.

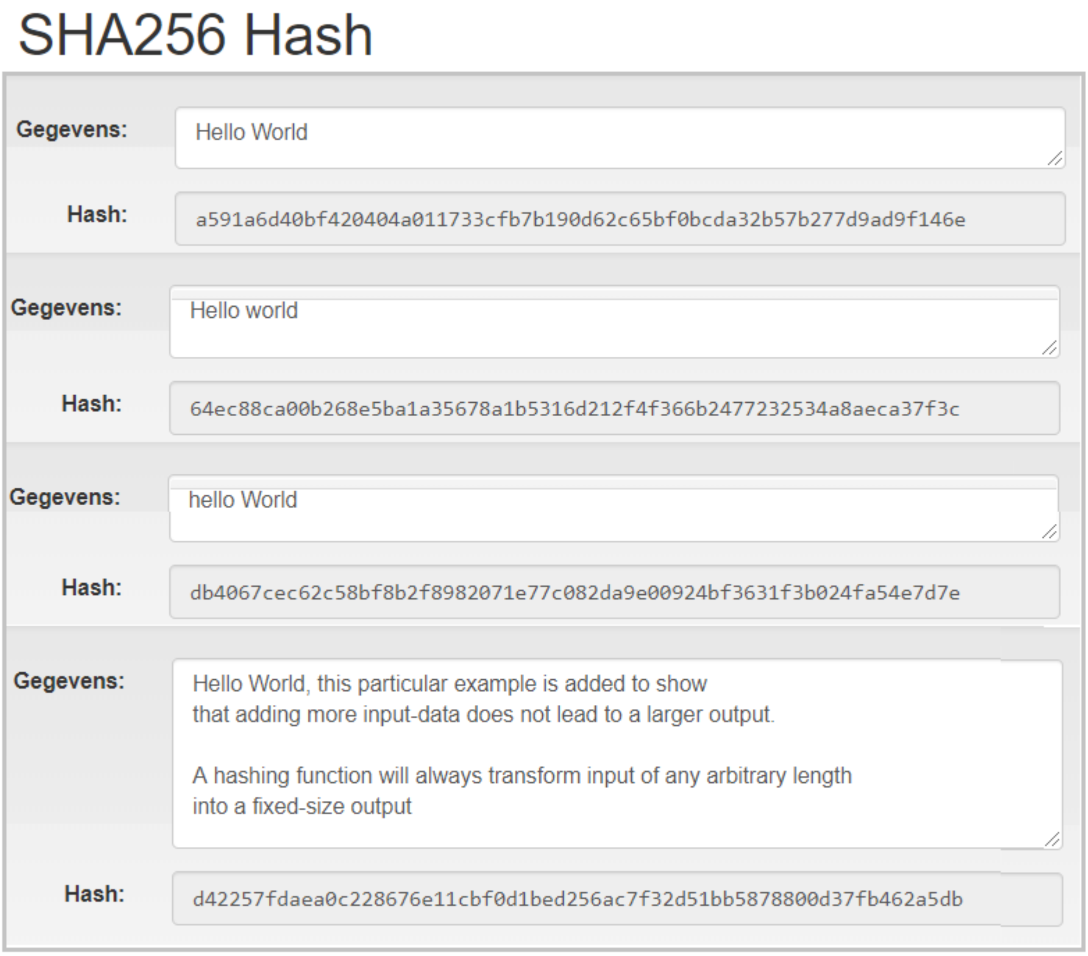
Hashing algorithms

Hashing algorithms play an important role in blockchain technology, especially regarding data-management and linking of blocks in a chain-like structure. Hash functions are essential components in both blockchain technology and information security (Drescher, 2017). Hash functions are mathematical processes that transform arbitrary sizes of data to fixed-size data outputs. Hash functions guarantee the security of information, since alterations of the input data lead to a completely different output hash. Figure III.6 provides some examples of how input data is converted to a SHA-256 hashed output.

Cryptographic hash functions have some unique characteristics that provide suitability for use in blockchain technology. For example, the data that is being hashed fully determines the hash value. This means that no other data besides the input data is able to result in a particular hash. Because every hash is unique and directly related to specific information, as found within a transaction, hashes are excellent cryptographic tools for providing identification of a transaction. Different input data cannot lead to the same output-hash, therefore authenticity of a transaction is also guaranteed. It is not possible for two different transactions to have the same hash.

Another important feature of hashing functions is the fact that equal input always leads to exactly the same hash as output. This provides a degree of auditability and authenticity of a transaction. During an audit that researches authenticity of a transaction, there is only need for accessibility of the input-data of the original transaction. When the transaction is reproduced with the available data, the hashes of both transaction can be compared. If they are equal, the input of both transactions were the same and authenticity of the transaction is ensured. When the hashes differ it means that the input was not equal and data was altered.

Other important aspects of hashing algorithms are the degree of randomness that is present during execution of the mathematical processes and resilience against reverse operations. A hash function generates a new, completely different, unpredictable hash if differences are present within the input data, no matter how small the variation or modification is. Any variation or modification in the input data leads to a different hash, and it is impossible to predict how a hash will look like after alteration of the input data (Sparknotes, 2020). Hashing functions are one-way functions, therefore they are resilient against reverse operations; it is not possible to derive the input data from a hash.



SHA256 Hash

Gegevens: Hello World

Hash: a591a6d40bf420404a011733cfb7b190d62c65bf0bcda32b57b277d9ad9f146e

Gegevens: Hello world

Hash: 64ec88ca00b268e5ba1a35678a1b5316d212f4f366b2477232534a8aeca37f3c

Gegevens: hello World

Hash: db4067cec62c58bf8b2f8982071e77c082da9e00924bf3631f3b024fa54e7d7e

Gegevens:

Hello World, this particular example is added to show
that adding more input-data does not lead to a larger output.

A hashing function will always transform input of any arbitrary length
into a fixed-size output

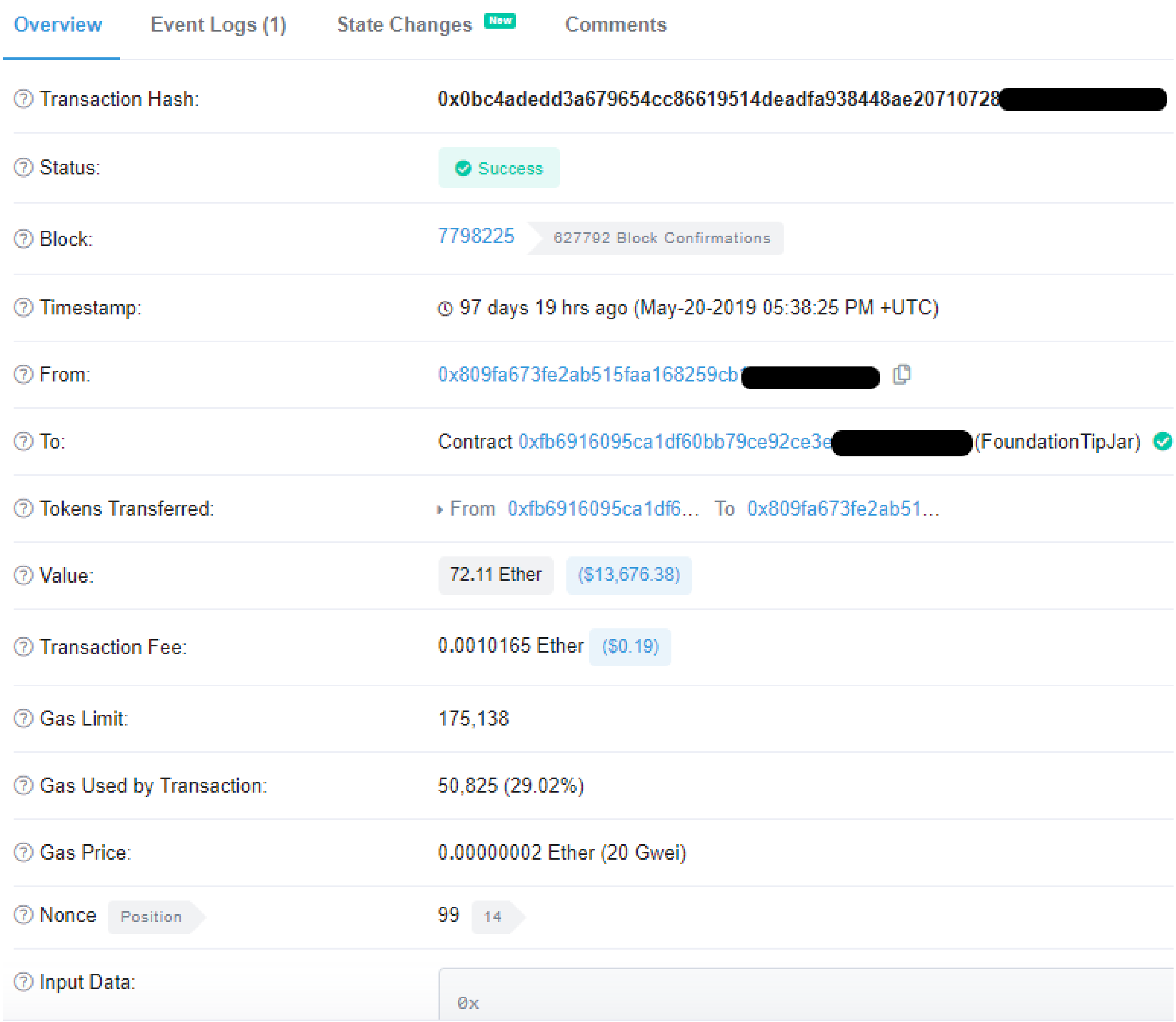
Hash: d42257fdaea0c228676e11cbf0d1bed256ac7f32d51bb5878800d37fb462a5db

Figure III.6 Visual display of a SHA-256 hashing algorithm input-output conversion (Brownworth, 2020)

From Figure III.6 a few things should become clear. When looking at the input, found after ‘Gegevens’, for the top 3 examples there are only minor alterations in the input. The only differences are found in using capital or lowercase letters for a single letter. However, when comparing the corresponding hashed outputs, it becomes clear that these are completely different. The only aspect that these outputs have in common is the fact that they are of equal length. The bottom example emphasizes on this conclusion since its input is significantly larger compared to the other examples while remaining an equal length output. So two aspects become clear; 1) It is not possible to predict an output based on the input, 2) The output of a SHA-256 hashing function is always of equal length.

Transaction structure

Hashing functions are an important aspect regarding the structure of a transaction. When a transaction is proposed, basic information is converted into a hashed transaction proposal, enabling the data to be stored on the blockchain. This basic information consists of for example asset type, quantity, sender address, receiver address, time and date. To ensure authenticity and integrity, as explained in the paragraph 'Transaction Validation & Verification', the proposed transaction is provided with a cryptographic signature, making the transaction unique. An example of basic transaction information on the permissionless Ethereum blockchain is displayed in Figure III.7. It should be noted that the transaction hash is the result of all information within the transaction, and acts as identification of the transaction when incorporated in a block.



Transaction Hash: 0x0bc4adedd3a679654cc86619514deadfa938448ae20710728[redacted]

Status: ✓ Success

Block: 7798225 627792 Block Confirmations

Timestamp: 97 days 19 hrs ago (May-20-2019 05:38:25 PM +UTC)

From: 0x809fa673fe2ab515faa168259cb[redacted]

To: Contract 0xfb6916095ca1df60bb79ce92ce3e[redacted](FoundationTipJar) ✓

Tokens Transferred: From 0xfb6916095ca1df6... To 0x809fa673fe2ab51...

Value: 72.11 Ether ($13,676.38)

Transaction Fee: 0.0010165 Ether ($0.19)

Gas Limit: 175,138

Gas Used by Transaction: 50,825 (29.02%)

Gas Price: 0.00000002 Ether (20 Gwei)

Nonce Position: 99 14

Input Data: 0x

Figure III.7 Basic transaction information on the Ethereum blockchain, partly concealed (Etherscan, 2020)

Block Structure

Hashing functions also play a large role in the way blocks are compiled and structured. This section will focus on how hash functions are incorporated in blocks. Let's start with explaining how blocks are constructed.

The framework of a block consist of a block body and a block header, as displayed in Figure III.8. The block body contains of a list of all transactions that were validated during the processing of that block (Pierro, 2017). The total number of transactions within a particular block depend on both the size of the transactions and the block itself.

The block header contains more diversified information. One of the aspects a block header contains is the block version, which indicates the set of rules that should be followed to validate the system. Another aspect of the header is a hash of the previous block header, connecting the two together. Implementing a reference to the previous block enables the ability of linking multiple consecutive blocks to form a chain-like structure. A hash is a uniquely generated number and could be considered as a digital fingerprint of data to lock it within a blockchain (Laurence, 2017). Other information the header contains are the timestamp and the Merkle Tree Root Hash. In blockchain technology, all transactions are timestamped to ensure verification and recording. The timestamp ensures the originality of the data, makes transactions more traceable, and reinforces irreversible modifications (Yang, 2019). The Merkle Tree Root Hash represents the hash value of all the transactions within that block, as displayed in figure 1.2. The purpose of the Merkle Tree Root Hash is to validate the transaction efficiently and to detect data tampering (Ramamurthy, 2015). Merkle Trees allow efficient and secure verification of data sets (Blockonomi, 2020). The Merkle Tree allows for the detection of any changes to data within the transactions of a block, by simply rerunning through the process for each transaction and comparing the results to the original Root hash. The tree-like structure ensure efficient identification of where changes in the data have occurred.

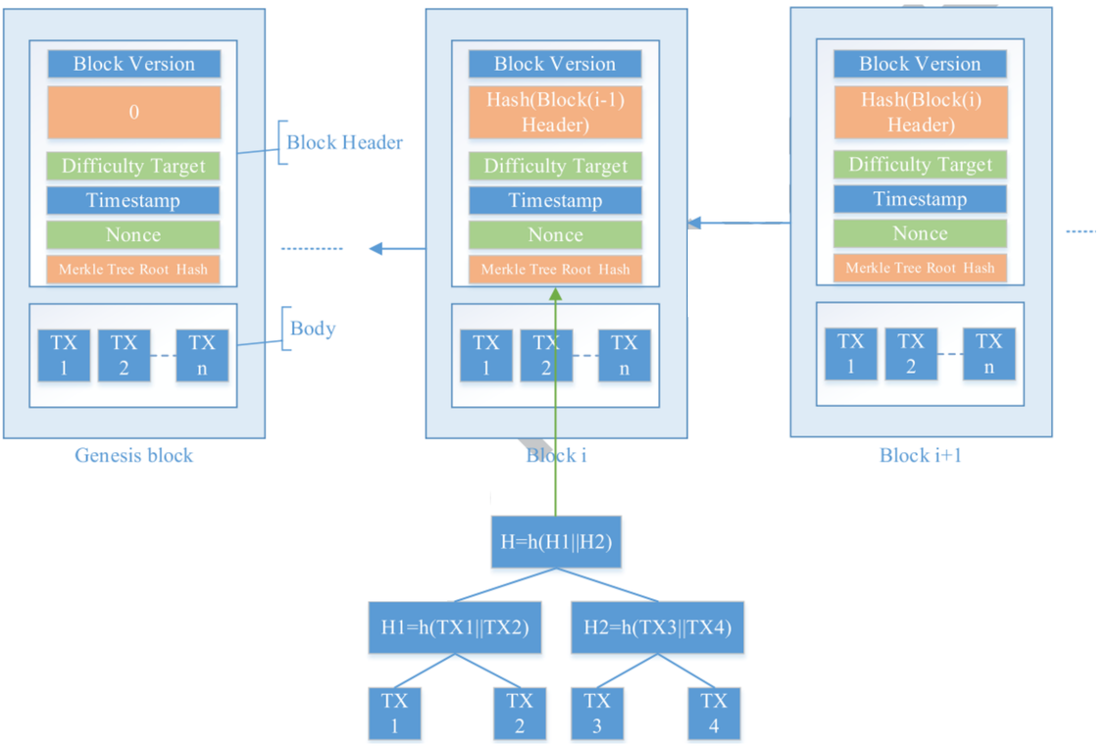


Figure III.8 Blockchain structure (Azzi, Kilany & Sokhn, 2019)

The block header also contains the nonce and the difficulty target. The nonce is a one-time code in the form of a completely random number and is used to meet certain requirements provided by the consensus protocol. The difficulty target is an algorithm that can adjust the difficulty level of the production of the block. In case the time it takes to produce a block differs too much from the pre-specified time it should take, the algorithm can adjust its difficulty to a level that production of the block takes as much time as was pre-specified. It is important to note that the difficulty can be adjusted only gradually and therefore it takes multiple blocks before an adjustment can be made.

To produce a block in a blockchain, The Merkle Tree Root Hash, Timestamp, Hash of the previous block header and the nonce need to be combined to a hash that is lower than a value set by the Difficulty Target for that block. To accomplish such a hash the nonce needs to be guessed repeatedly, since there are very few possibilities to achieve the requirements. The other aspects in this cryptographic 'puzzle', such as block number, hash of the previous block etc., have a defined meaning and may not be changed. When a hash is found that fits the requirements, consensus is reached and a new block with that particular hash is produced (Zheng et al., 2017).

All aspects of the block header and the block body are necessary to provide the network with enough cryptographic techniques to secure the network and ensure immutability, authenticity, integrity and non-repudiation of the blockchain's ledger (Christidis & Devetsikiotis, 2016). For example, combining The Merkle Tree Root Hash and the hash pointers enables security and trackability of all historical changes made to the global state. To verify any transaction, the Merkle Tree Root Hash path related to the requested transaction must be checked. Verifying transactions this way ensures instant detection if modifications in an specific transaction have occurred. The block header hash verifies the integrity of the block and its transactions, and by embedding the previous block hash in its own block header it links the blocks together, creating a chain- like structure. Once a block is added to the blockchain, the transactions cannot be modified or deleted afterwards (Tien Tuan Anh et al., 2017).

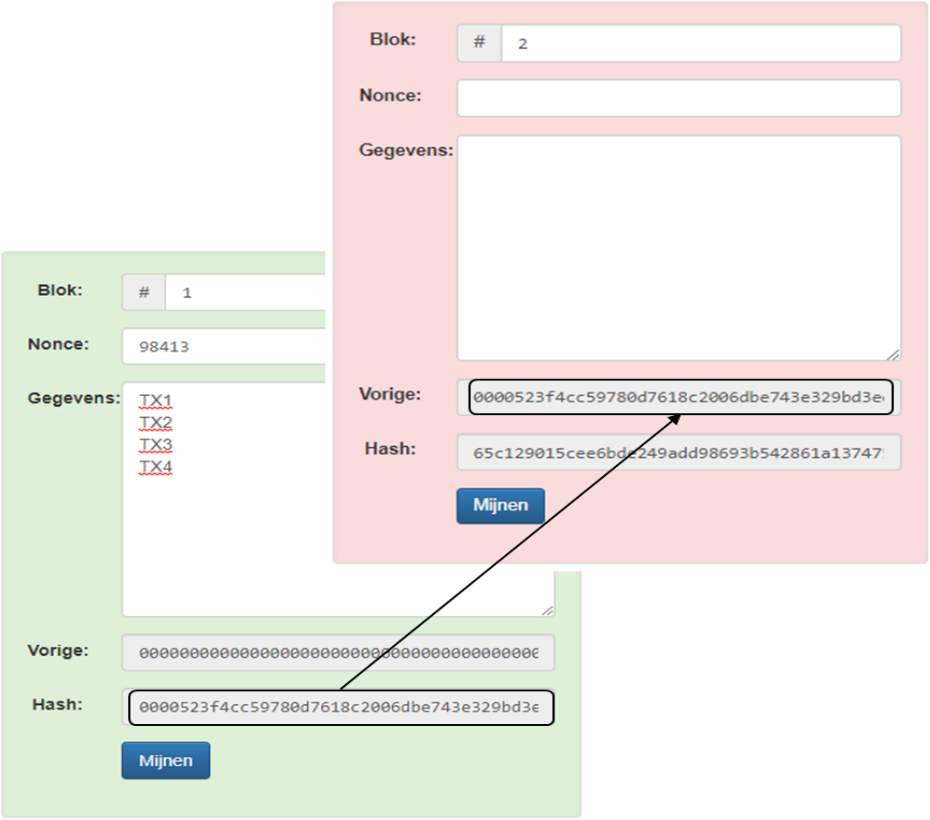
The evaluation and verification process required when adding data to the blockchain, combined with modern encryption methods, ensures security of the data within the blockchain ledger against unauthorized access and/ or manipulation. This results in a system where users always have access to a comprehensive audit trail of activities (Miles, 2017).

Immutability

This paragraph demonstrates how immutability is achieved in blockchain technology. This demonstration is done through examples of a simplified blockchain. In these examples, every block consists of a few key components; A block number, a nonce, a data input field (in this example the data input field is called 'Gegevens'), the hash of the block and the hash of the previous block.

Figure III.9 displays the beginning of a blockchain. The bottom left, green block is the first block of the blockchain. This block is called the 'Genesis' block and differs from other blocks since it does not have a previous block. In this example, block #1 is completed and block #2 has been produced. A block is only closed when it is deemed valid by the consensus protocol. In this example, a block becomes valid if the hash of the block satisfies the requirement set by the difficulty rate. The difficulty rate determines how specific a hash needs to be. The difficulty rate has a direct relation to the nonce; the higher the difficulty rate, the lesser options there are for a nonce to comply with the requirements. To recall, a nonce is a one-time code in the form of a completely random number that are repeatedly guessed in order to solve a cryptographic puzzle. The function of the difficulty rate is to maintain the pre-determined time-period it takes between the production of blocks. When computing power of nodes increases, also known as hash-power, the number of nonces that can be guessed in a particular time-period increases. If this number increases, a nonce that meets the requirements is found in a shorter period of time, and the time between creation and closure of a block becomes less. Shorter block times lead to a decrease in the security of the system, therefore they are considered undesirable. In general, block times are balanced between transaction throughput and security of the system. By decreasing the block time, the chance of orphan blocks increases, which leads to vulnerability regarding malicious actions and increases both energy consumption and the chance of blockchain-forks. Shorter block times do increase the transaction throughput, however both the decrease in security and possibility for using more intelligent scaling solutions emphasize that reducing the block size has more downsides than upsides. To counteract fluctuations in the block time due to in-/ decreased hash-power, the difficulty rate can be adjusted up- or downwards. However, due to the centralized nature of the consensus protocol, the adjustment lags time-wise and the production of numerous blocks passes before the adjustment is incorporated.

In the example used in this paragraph, the difficulty target is set on finding a hash that starts with a least four zeros. Only when a hash is found that meets the difficulty target, then a block is deemed valid. As can be derived from Figure III.9, after inclusion of transaction 1 till 4 in block #1, a nonce of value 98413 leads to a hash that meets the difficulty requirements. The block is deemed valid by the consensus protocol, also indicated by the green background color, and therefore closure of block #1 and creation of block #2 may occur. The top right picture of Figure III.9 shows the structure of block #2 directly after production. At first, only the block number and hash of the previous block are present. Embedding the hash of the previous block in the current block is essential for linking the blocks together. The chain-block structure is obtained by linking blocks through incorporation of the block hash of the previous block. After creation of the block, transactions are added, the proper nonce is guessed, the block is validated and closed afterwards, and a new block is created.

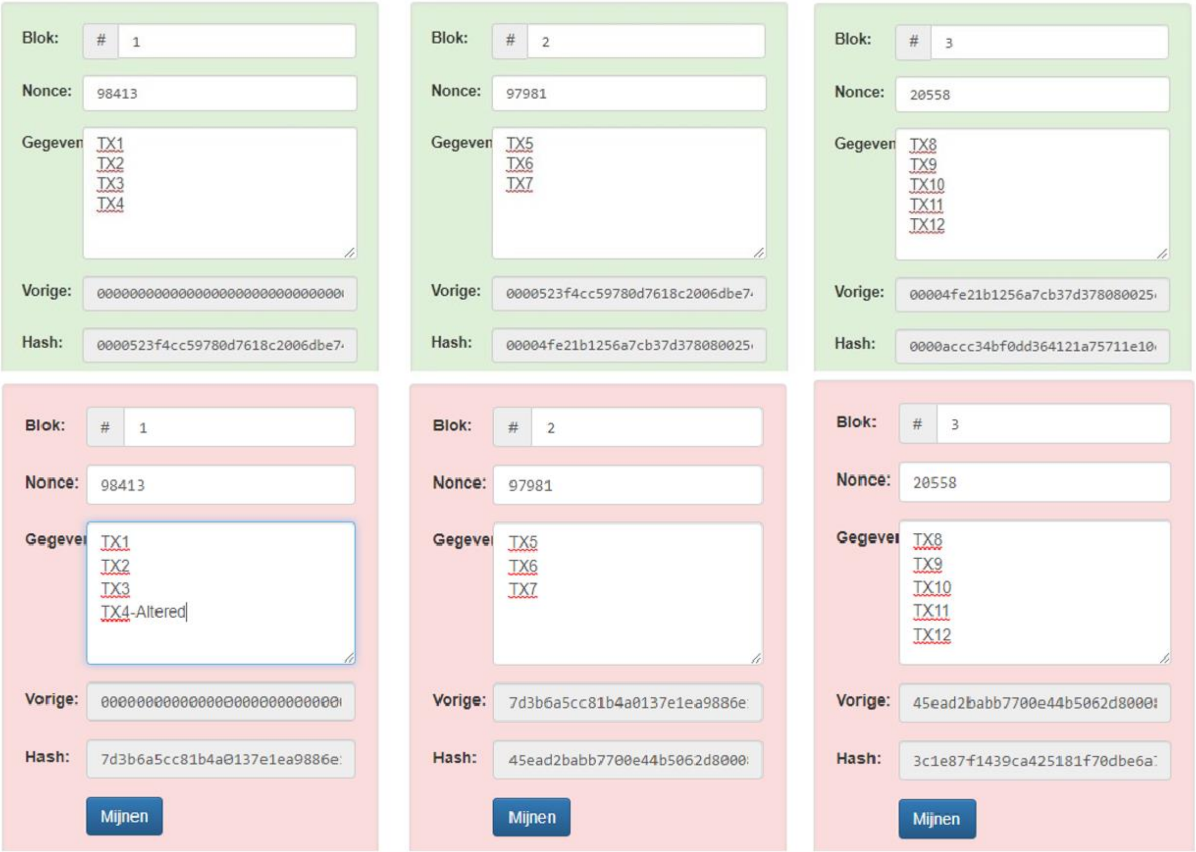

Blok: # 2
Nonce:
Gegevens:
Vorige: 0000523f4cc59780d7618c2006dbe743e329bd3e
Hash: 65c129015cee6bde249add98693b542861a13747

Blok: # 1
Nonce: 98413
Gegevens: TX1
TX2
TX3
TX4
Vorige: 000000000000000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe743e329bd3

Figure III.9 Visualization of how blockchain- blocks are compiled (Brownworth, 2020)

Now that the basics are clear, an explanation of how immutability is achieved in blockchain technology may occur. The explanation builds upon the previous example, as can be derived from Figure III.10. The top row of Figure III.10 displays the blockchain after completion of three blocks. All three blocks are considered valid and have transaction included in them.

In the bottom row of Figure III.10, transaction 4, which is included in block #1, has been altered. An alteration of the transaction leads to a difference in input-data. And from the characteristics of hash functions it became clear that a different input leads to a completely different output hash. So, an alteration of a transaction leads to a different block-hash. As seen on the bottom left picture, this new block-hash does not meet the requirements of the difficulty target and therefore the consensus mechanism. Therefore this block becomes invalid. But the hash of block-hash of block #1 is also embedded in block #2. This means that the input-data of block #2 also differs from the original situation. Again, the alterations result in a different block-hash of the block, therefore it fails to meet the difficulty requirements, leading to invalidation of the block. And this process continues itself throughout all the blocks that are produced after the block which incorporates the alteration of a transaction.


Blok: # 1
Nonce: 98413
Gegeven TX1
TX2
TX3
TX4
Vorige: 00000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe7

Blok: # 2
Nonce: 97981
Gegeven TX5
TX6
TX7
Vorige: 0000523f4cc59780d7618c2006dbe7
Hash: 00004fe21b1256a7cb37d378080025

Blok: # 3
Nonce: 20558
Gegeven TX8
TX9
TX10
TX11
TX12
Vorige: 00004fe21b1256a7cb37d378080025
Hash: 0000accc34bf0dd364121a75711e10

Blok: # 1
Nonce: 98413
Gegeve TX1
TX2
TX3
TX4-Altered
Vorige: 00000000000000000000000000000
Hash: 7d3b6a5cc81b4a0137e1ea9886e

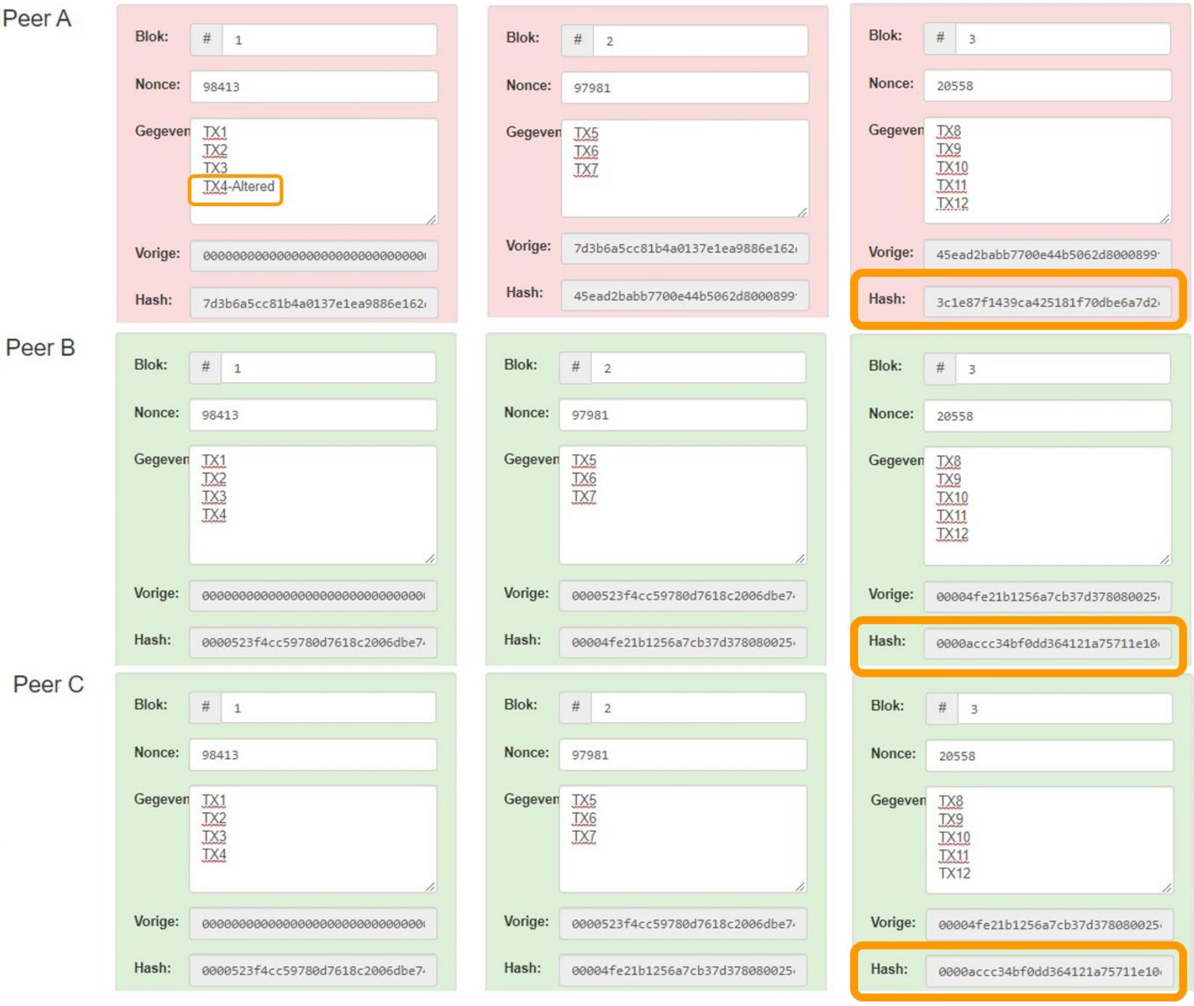
Blok: # 2
Nonce: 97981
Gegeve TX5
TX6
TX7
Vorige: 7d3b6a5cc81b4a0137e1ea9886e
Hash: 45ead2babb7700e44b5062d8000

Blok: # 3
Nonce: 20558
Gegeve TX8
TX9
TX10
TX11
TX12
Vorige: 45ead2babb7700e44b5062d8000
Hash: 3c1e87f1439ca425181f70dbe6a

Figure III.10 Display of the impact of altering one transaction in a blockchain (Brownworth, 2020)

When there is only an single node present in the system that is able to close and create blocks, the situation after alteration might be corrected. It is possible to re-solve the cryptographic puzzle of block #1 by changing the nonce, ensuring validation of that particular block. However, this leads again to a different block-hash of block #1 compared to the original hash. And since the hash of block #1 is linked to block #2, is also affects this block. The new hash of block #1 invalidates block #2. So block #2 needs to be re-mined in order to validate the block, affecting block #3, etc. So all blocks after the altered block need to be re-mined in order to cover up the alteration of a single transaction.

However, it becomes increasingly difficult to alter data when the number of peers in the network increases. Figure III.11 displays the blockchain when there are three peers present. In this example, peer A has made an alteration to transaction III in block #1. This alteration has occurred after three blocks were completed, broadcasted to the network and approved by other nodes. As became clear from earlier examples, the alteration leads to invalidation of all consecutive blocks of Peer A. Since the latest block of the blockchain of Peer A is deemed invalid by the consensus mechanism, future blocks cannot be built on top of this blockchain, since the rest of the network will not accept them.



Peer A

Blok: # 1
Nonce: 98413
Gegeven: TX1 TX2 TX3 TX4-Altered
Vorige: 00000000000000000000000000000
Hash: 7d3b6a5cc81b4a0137e1ea9886e162

Blok: # 2
Nonce: 97981
Gegeven: TX5 TX6 TX7
Vorige: 7d3b6a5cc81b4a0137e1ea9886e162
Hash: 45ead2babb7700e44b5062d8000899

Blok: # 3
Nonce: 20558
Gegeven: TX8 TX9 TX10 TX11 TX12
Vorige: 45ead2babb7700e44b5062d8000899
Hash: 3c1e87f1439ca425181f70dbe6a7d2

Peer B

Blok: # 1
Nonce: 98413
Gegeven: TX1 TX2 TX3 TX4
Vorige: 00000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe7

Blok: # 2
Nonce: 97981
Gegeven: TX5 TX6 TX7
Vorige: 0000523f4cc59780d7618c2006dbe7
Hash: 00004fe21b1256a7cb37d378080025

Blok: # 3
Nonce: 20558
Gegeven: TX8 TX9 TX10 TX11 TX12
Vorige: 00004fe21b1256a7cb37d378080025
Hash: 0000accc34bf0dd364121a75711e10

Peer C

Blok: # 1
Nonce: 98413
Gegeven: TX1 TX2 TX3 TX4
Vorige: 00000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe7

Blok: # 2
Nonce: 97981
Gegeven: TX5 TX6 TX7
Vorige: 0000523f4cc59780d7618c2006dbe7
Hash: 00004fe21b1256a7cb37d378080025

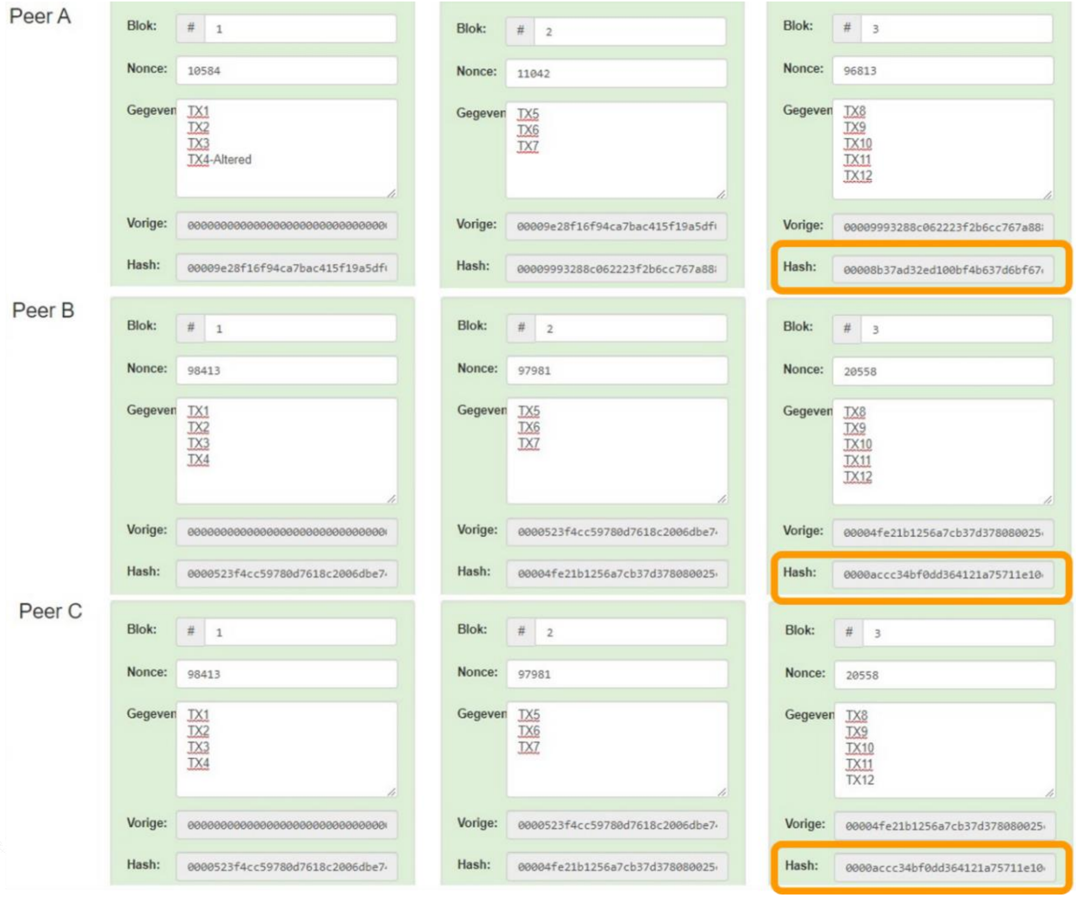
Blok: # 3
Nonce: 20558
Gegeven: TX8 TX9 TX10 TX11 TX12
Vorige: 00004fe21b1256a7cb37d378080025
Hash: 0000accc34bf0dd364121a75711e10

Figure III.11 Display of the impact of altering one transaction in a blockchain consisting of multiple peers (Brownworth, 2020)

As in the previous example, Peer A could try to cover up the alteration by re-mining all blocks up until the most recent one. However, re-solving the cryptographic puzzles costs both energy and time. Especially the time restrictions are very hard to overcome. The first issue regarding time is based on the difficulty target. The difficulty target for that block was set to a specific value in order to ensure that solving the puzzle required a certain amount of time. The second issue regarding time is the continuous addition of new blocks to the blockchain. The system is not dependent on a single node, therefore new blocks will be produced continuously, expanding the blockchain more and more. So in order for Peer A to cover up the alteration of a transaction, it needs to be able to produce and validate blocks faster than all other nodes in the network, in order to eliminate the backlog and catch up until the most recent block. In practice it is impossible to do so.

However, there is another factor in play that ensures immutability of data. Because Peer A has different input-data somewhere in the blockchain, all consecutive block-hashes are different compared to the original chain. This means that even if Peer A is able to catch up to the most current block, validating all blocks along the way, the block-hash of the most current block will differ from other nodes, as displayed in Figure III.12. Since there are multiple, different chains present that have been deemed valid by the consensus mechanism up until the most recent block, the network has to decide which blockchain is considered genuine. This decision is based on the number of nodes that agree on a particular chain. The majority of the network, 2/3 of the nodes in this example, agrees on the exact same block-hash of the latest block, as displayed in Figure III.12. Since the majority of the network reached consensus on the latest state of the network, only blocks can be produced on top of the blocks that have the specific block-hash that was agreed upon. Therefore, no new blocks that are produced on top of the blockchain of Peer A will be accepted by the rest of the network.

This example emphasizes the importance of the 'network effect' in blockchain technology; an increase of independent peers in the network leads to higher resilience against malicious actions, increasing the security of the network. Because of the incorporation of hashing functions, a distributed consensus mechanism, and other cryptographic techniques, blockchain technology is able to establish a tamper-proof network, ensuring immutability and auditability of transactions and the network itself.



Blok: # 1
Nonce: 10584
Gegeven
TX1
TX2
TX3
TX4-Altered
Vorige: 000000000000000000000000000000
Hash: 00009e28f16f94ca7bac415f19a5df

Blok: # 2
Nonce: 11042
Gegeven
TX5
TX6
TX7
Vorige: 00009e28f16f94ca7bac415f19a5df
Hash: 00009993288c062223f2b6cc767a88

Blok: # 3
Nonce: 96813
Gegeven
TX8
TX9
TX10
TX11
TX12
Vorige: 00009993288c062223f2b6cc767a88
Hash: 00008b37ad32ed100bf4b637d6bf67

Blok: # 1
Nonce: 98413
Gegeven
TX1
TX2
TX3
TX4
Vorige: 000000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe7

Blok: # 2
Nonce: 97981
Gegeven
TX5
TX6
TX7
Vorige: 0000523f4cc59780d7618c2006dbe7
Hash: 00004fe21b1256a7cb37d378080025

Blok: # 3
Nonce: 20558
Gegeven
TX8
TX9
TX10
TX11
TX12
Vorige: 00004fe21b1256a7cb37d378080025
Hash: 0000accc34bf0dd364121a75711e10

Blok: # 1
Nonce: 98413
Gegeven
TX1
TX2
TX3
TX4
Vorige: 000000000000000000000000000000
Hash: 0000523f4cc59780d7618c2006dbe7

Blok: # 2
Nonce: 97981
Gegeven
TX5
TX6
TX7
Vorige: 0000523f4cc59780d7618c2006dbe7
Hash: 00004fe21b1256a7cb37d378080025

Blok: # 3
Nonce: 20558
Gegeven
TX8
TX9
TX10
TX11
TX12
Vorige: 00004fe21b1256a7cb37d378080025
Hash: 0000accc34bf0dd364121a75711e10

Figure III.12 Display of the differences of altering & covering up one transaction in a blockchain consisting of multiple peers (Brownworth, 2020)

III.2.4 Consensus mechanism based on decentralized nodes

The third key component of blockchain technology is a consensus mechanism based on decentralized nodes, as displayed in Figure III.13.

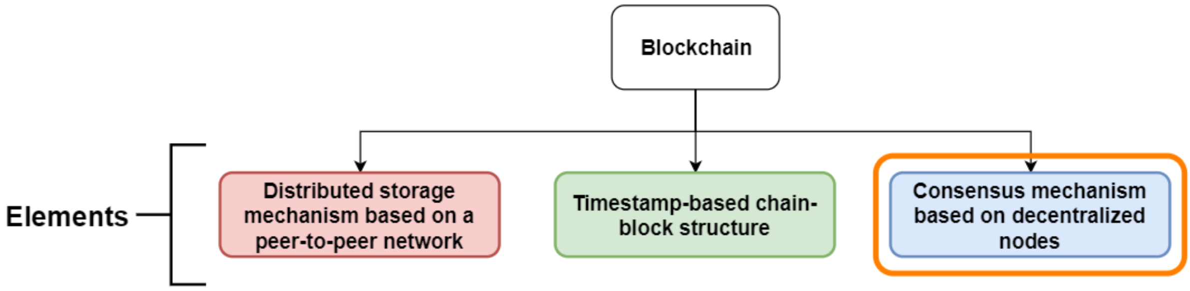


Figure III.13 Elements of a blockchain - consensus mechanism based on decentralized nodes

The consensus protocol of a blockchain is of great importance, since it is the core of the blockchain system. It forms the working entity, and both the security and the robustness of the system are provided by the consensus protocol. Implementing a correct and efficient consensus protocol ensures proper functionality of the blockchain and lays the foundation on which the system can grow. If there are flaws in the consensus protocol, malicious actions may occur. An example of malicious actions would be compromising of data recorded on the blockchain. Even worse, if the consensus protocol fails it could lead to cheating of malicious actors, or even a blockchain- fork (Baliga, 2017).

Blockchain consensus is considered the agreement of common value among a group of a multitude of nodes within a blockchain system. The consensus protocol of a blockchain is its core element, since it determines the rules for broadcasting transactions, information sharing and replicating states (Viriyasitavat, 2019). The applicability and efficacy of any blockchain depends on how its consensus mechanism addresses the following three key properties; safety, liveness and fault tolerance, see Figure III.14 (Hammerschmidt, 2017). Safety refers to the guarantee that something bad will never happen. Safety is related to the properties validity, agreement and termination. Validity states that when a correct process proposes a particular value, then any correct process should result to that particular value. Agreement ensures that no two correct processes decide differently. Termination ensures that all correct processes eventually decide on a value. In general, a consensus protocol is considered safe when at least one honest node produces a valid output to a particular process. Other nodes produce or receive this exact outcome, making them identical for all nodes, resulting in consistency of the shared state (Baliga, 2017). Liveness guarantees that eventually something good will happen. Liveness in distributed systems, similar to termination in traditional consensus, state that a correct process will decide on one particular value. Both termination and liveness have some overlap, therefore they have an equal explanation in Figure III.14. Later on in this paragraph it will become clear why termination is placed under the property safety. Liveness is ensured by a consensus protocol if all honest nodes participating produce a value eventually, where after all correct values are being processed. The time it takes to come to a value to a particular process is unbounded, therefore not every node is required to have an identical state of the system at any given point in time (Viriyasitavat, 2019). A consensus protocol is considered fault tolerant if it is resilient at any point to failures within reaching consensus from numerous of the participating nodes within a network. As long as the number of faulty nodes is limited, correct consensus is reached and the system will operate correctly. Failure of participating nodes can be divided into two categories; fail-stop-/ crash-failure and Byzantine failures. Faulty nodes due to fail-stop/ crash-failure, temporarily or permanently stop participating in the consensus mechanism and stop sending and receiving messages. Byzantine failures are caused by malicious nodes that try to attack the consensus protocol with the intend to alter its properties (Lamport, Shostak & Pease, 1982).

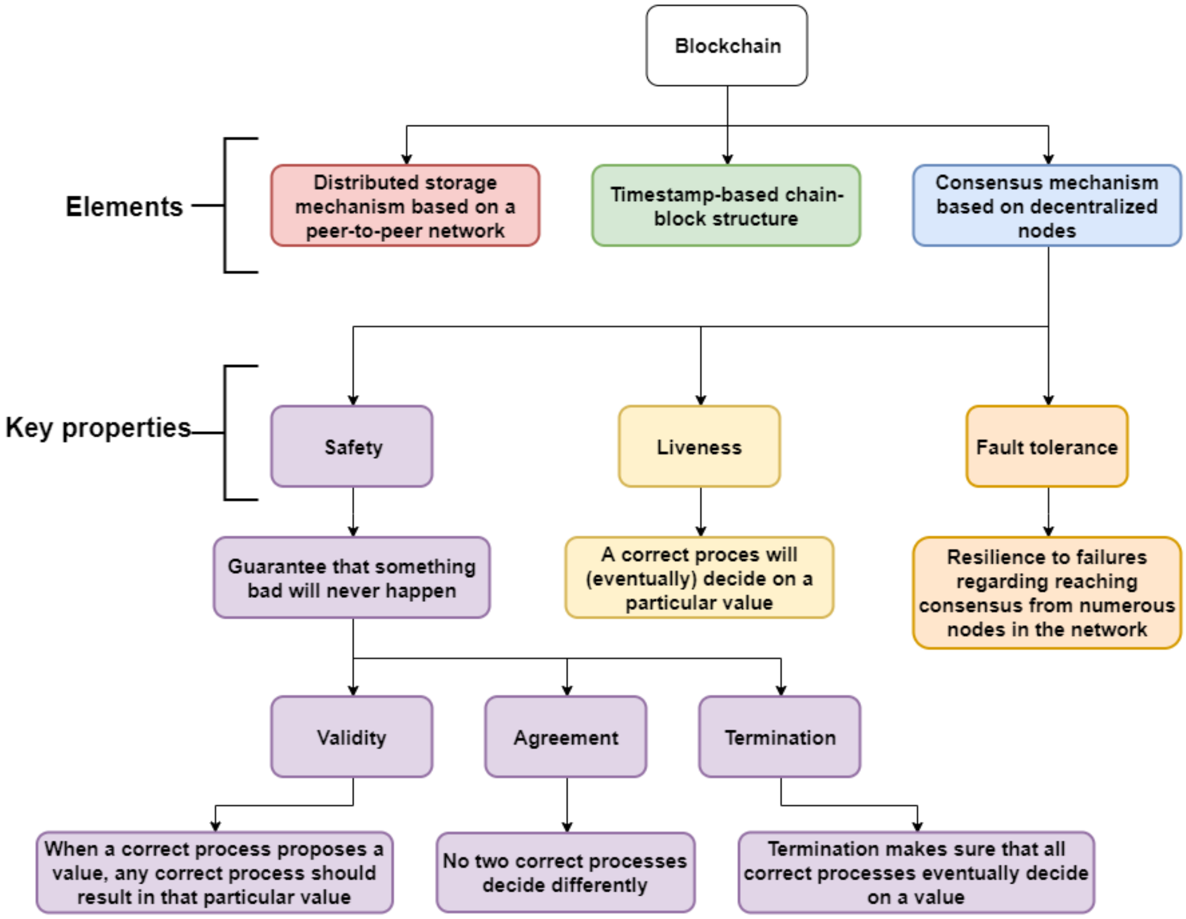


Figure III.14 Explanation of important aspects regarding the consensus mechanism and their connection to each other

Unfortunately, it is proven to be impossible for any deterministic asynchronous consensus protocol to fully optimize safety, liveness and fault tolerance at the same time. At best a protocol can optimize two out of three. So distributed consensus protocols, as can be found in blockchains, need to sacrifice one of these properties. Which property is sacrificed depends on the blockchains' requirements and assumptions (Lynch, Fischer & Fowler, 1982). One of the factors that needs to be taken into account regarding the choice for a particular consensus mechanism is transaction finality, or the timespan before transactions can be confirmed. Finality is the time between broadcasting a transaction to the network and the time it takes till the final confirmation. Finality is an important factor since it is related to the throughput of a system.

Consensus mechanisms in blockchains, for example Proof-of Work, guarantee fault tolerance and liveness. Since any deterministic asynchronous consensus protocol can only optimize two out of three properties, safety cannot be guaranteed, as displayed in Figure III.15. Therefore, due to latency of propagation, finality cannot be guaranteed, which could lead to different nodes having different views of the ledger. To address the issue of safety within blockchain consensus protocols, adjustments are made to classic consensus mechanisms to address issues such as Byzantine failures.

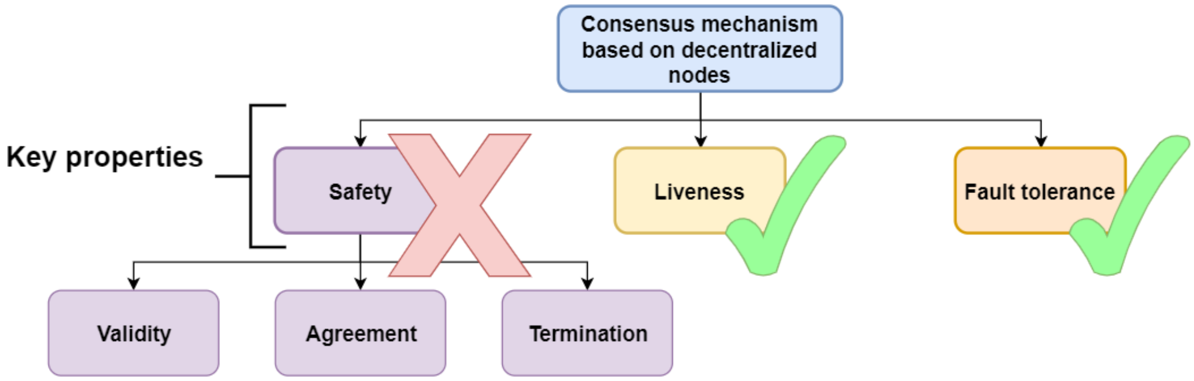


Figure III.15 Trade-off between the key properties of a consensus mechanism. A distributed, deterministic, consensus protocol is limited to the optimization of a maximum of two key properties. Most blockchain consensus protocols guarantee liveness and fault-tolerance.

Byzantine fault tolerance & blockchain consensus mechanisms

Blockchain systems operate on a distributed network. Distributed networks, compared to centralized networks, have a disadvantage regarding communication synchrony, since the possibility exists that not every message is delivered to all participants within a known time-span. Therefore classic consensus is unsolvable in asynchronous networks (Fischer, Lynch & Paterson, 1985). To bypass this impossibility in blockchains, multiple solutions regarding the consensus problem are proposed, based on probabilistic guarantees by enhancing randomization. Randomization bypasses the classic deterministic consensus problem by using probabilistic properties instead (Aspnes, 2003), (Miller et al., 2016).

The Byzantine failure model is derived from the Byzantine Generals Problem, which attempts to reach agreement on a mutual attack between differently located generals in the presence of traitors. Byzantine failures occur due to malicious participants behaving arbitrarily compared to other participants (Lamport, Shostak & Pease, 1982). An example of malicious behavior in value transfer blockchains, such as Bitcoin, is a double-spend attack, where the exact same digital asset/ token/ coin is spend in multiple different transactions. Byzantine Fault tolerance consensus mechanisms are related to state machine replication protocols that protect the system against arbitrary faults by distributing replicas of the services on multiple nodes (Schneider, 1990). A Byzantine fault-tolerant consensus mechanism guarantees security of the blockchain, since the consensus mechanism solves the consensus problem. Solving the consensus problem, otherwise known as reaching consensus, ensures that the produced blocks are ordered in a particular way, preventing appended blocks in the future from containing conflicting transactions. It guarantees that for a given index, all correct processes agree on a unique block of transactions (Gramoli, 2017). Safety and liveness properties of a Byzantine fault-tolerant consensus protocol are able to execute properly if there are no more than (n-1)/3 faulty replicas in the system, with n being the total number of replicas (Castro & Liskov, 2002).

Three properties related to safety form the core of a Byzantine consensus mechanism; Agreement, validity and termination. Agreement is reached when no two correct processes decide on a different outcome of blocks. Validity covers that the outcome on a decided block is proposed by a single process, making the block unique. Termination makes sure that all correct processes eventually decide on a block. Only when all three of these properties are achieved by the consensus algorithm the Byzantine consensus problem is solved. But since asynchronous systems cannot fulfill these properties, some adjustments to this classic consensus protocol need to be made to ensure reaching consensus. Also, Byzantine fault-tolerance based consensus protocols are considered to have poor scalability because of the exponentially increasing number of communication required when scaling up. When using only a few validator nodes, Byzantine fault-tolerance consensus protocols are able to achieve throughputs of tens of thousands transactions per second, with latencies as fast as the internet speed (Bessani, Sousa & Alchieri, 2014). However, adding only a few more validation nodes to the network reduces the throughput sharply (Hardjono & Smith, 2016), (Castro & Liskov, 2002).

Most permissionless blockchain consensus protocols, as displayed in Figure III.16, adjust the agreement property within Byzantine consensus mechanisms, creating a trade-off between termination and agreement. The agreement property becomes probabilistic agreement; no two correct processes decide on different blocks with a probability of at least δ. This adjustment violates safety properties by enabling non-null probability, but it guarantees termination(Aspnes, 2012). Implementing this property into the consensus mechanism ensures responsiveness of the system. Participants receive a result on their transaction, stating whether the transaction is valid or invalid. However, it might take some time before the result is acquired. Predetermined periods of time, calculated in number of blocks, are required to acknowledge and validate a transaction. If within this period of time no invalidation of the processed transaction is detected, the transaction is considered valid.

The main benefits of using this consensus mechanism are the improvement of scalability of a distributed system and the security of the network. Proof-of-Work consensus mechanisms, as present in the Bitcoin network, are computationally intensive and therefore it is difficult for a single attacker to outperform all other validation nodes with regards of the production of multiple consecutive blocks. This feature makes Proof-of-Work blockchains more resilient to double-spending attacks (Nakamoto, 2008).

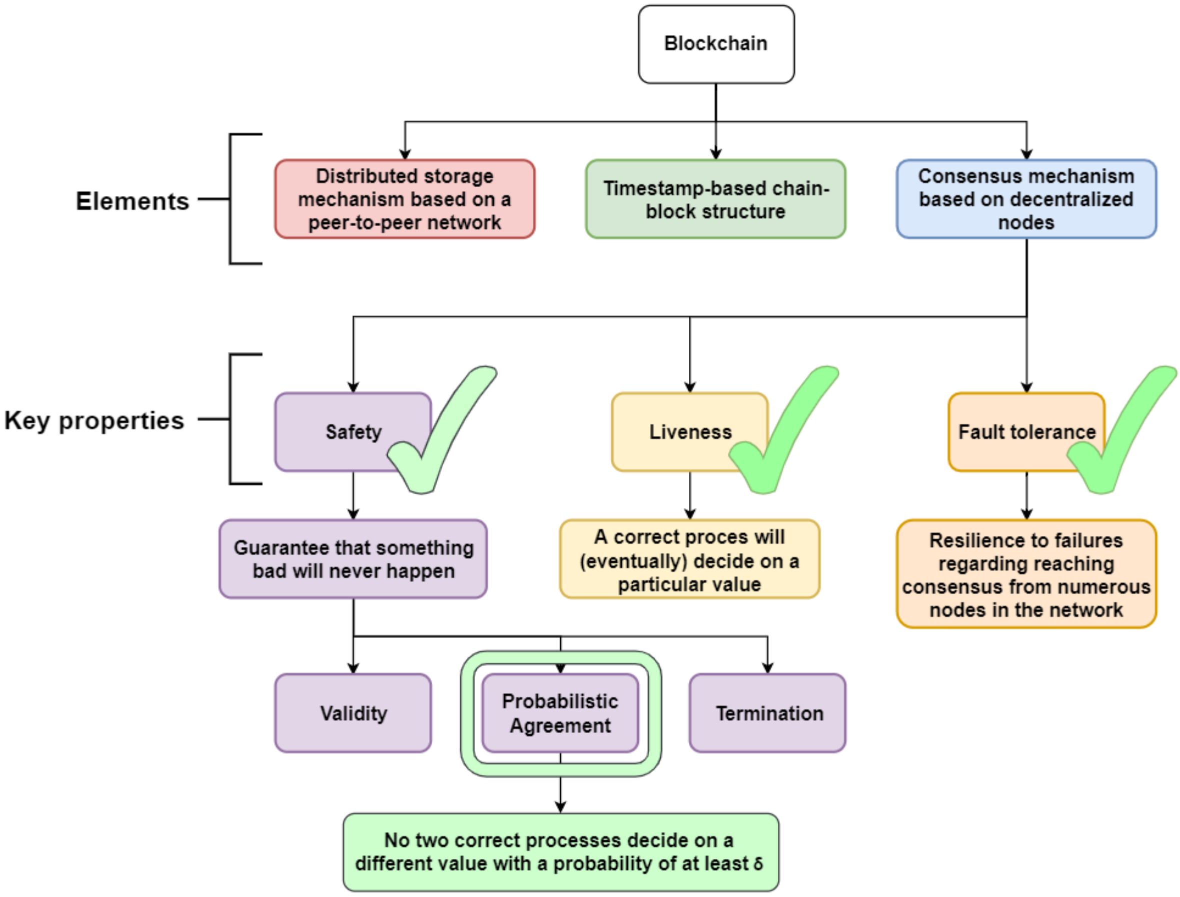


Figure III.16 Replacing of agreement with probabilistic agreement ensures a high level of safety in blockchain consensus protocols

Disadvantages blockchain consensus protocols

Because of the trade-off between agreement and termination within a probabilistic blockchain consensus protocol, there remains a chance that the safety properties of a blockchain might be violated as a drawback of randomized consensus. This means that network delays and the distribution of hashing power will have a more profound impact on the stability of the system, increasing the vulnerability for malicious actions such as double-spending and 51% attacks (Finney, 2011), (Eyal & Sirer, 2014).

Another disadvantage of Proof-of-Work consensus protocols has to do with price-discrimination. Proof-of-Work is an incentive based consensus protocol, making it vulnerable to greed of the validation nodes. Along with every transaction, a transaction fee is send to assure the transaction will be processed. The value of a transaction fee can be chosen by the sender. Validator nodes will process the transactions with the highest fee first, since it generates more income. Therefore, the possibility exist that a transaction accompanied with a low fee is not included into the next block after broadcasting, resulting in a long duration before finality of a transaction is reached.

Since blockchain technology is still in development, alternative consensus protocols are being designed/ invented/ adjusted during the time of writing. Examples of alternative consensus protocols are Proof-of-Stake (PoS), Proof-of-Authority (PoA) and Delegated Byzantine Fault Tolerant (DBFT). These consensus protocols are relatively young and need to be researched and tested more before they can be deployed on a mass scale. The Proof-of-Stake consensus is gaining attention lately and will therefore be discussed shortly, all others will be disregarded in this research.

Proof-of-Stake is a consensus mechanism which is designed to improve upon Proof-of-Work's computational requirements and high costs. Proof-of-Stake does not require validation nodes to solve a puzzle, but they are assigned by the consensus protocol by means of the stake they have in the network. Proof-of-Stake is based on the implication that people with high stakes in the network are unlikely to act malicious, since accepting faulty transactions will result in losing their stake. The incentive within a Proof-of-Stake consensus mechanism are the transaction fees rewarded for producing a new block. The coinage of a validation node is important within deciding which validation node is allowed to produce a new block. Coinage is the staking value multiplied by the time it is held. The validation node with the highest coinage is eligible to produce a new block. After claiming the reward for producing a new block, the coinage of the validating node is reset, meaning both the transaction fees and prior stake are considered to be new, adjusting the time the stake is held to zero. Resetting the coinage decreases the chance for a single validation node to produce consecutive blocks, ensuring the consensus protocol to be distributed among stakeholders (Szabo, 2004). The probability of a 51% attack by a malicious actor on a Proof-of-Stake blockchain is considered more difficult compared to a Proof-of-Work blockchain, since it must own enough stake to ensure it has the highest coinage for the upcoming block, while its coinage has been reset due to production of the last block (Gao & Nobuhara, 2017). Proof-of-Stake consensus mechanisms reduce the computationally intensiveness and corresponding costs of Proof-of-Work consensus mechanisms, while also improving the throughput. Finality however remains an issue for both of these consensus protocols (EconoTimes, 2017).

III.3 Smart contracts

A smart contract is a piece of code deployed on the blockchain, which provides the ability to self-execute when a state change occurs within the blockchain. Smart contracts are series of commitments defined in digital form, who contain both execution conditions and execution logic. When the execution conditions are met, execution logic is carried out immediately and corresponding data is transmitted or released (Christidis & Devetsikiotis, 2016). From a technical standpoint, a smart contract is a web server that is built on top of a blockchain instead of on the internet. This means that smart contracts can host specific contract programs, which ensures a certain degree of automation (Yu et al., 2017). In smart contracts, the rights and obligations of participants, as well as the trigger conditions for execution of the smart contract and corresponding results are specified. Once appended to the blockchain, a smart contract will execute objectively and accurate. Before a smart contract is deployed on the blockchain, other nodes must first verify and validate on the inputs, outputs and states affected by this contract, to ensure that no errors will occur (Tien Tuan Anh et al., 2017). Smart contracts are able to communicate with each other through their individual addresses and application programmable interfaces (APIs) (Ethereum, 2017).

A smart contract will only execute when the change of state complies with the set of conditions that are predefined, via a programming logic, within the smart contract. The rules and consequences within a smart contract are defined similar to those of a traditional legal document, including obligations, benefits and penalties (Gupta, 2017). But since these contracts are written in programming code languages, they are able to auto-execute when triggered, leading to higher levels of automation and more streamlined processes (Barnard, 2017). Because a smart contract has the ability to self-execute, it is considered one of the most important and disrupting parts of blockchain technology (Swan, 2015), (Szabo, 1997a), (Szabo, 1997b).

When combining both blockchain technology and smart contracts, the result is an improvement of synchronization and automation of business operations and processes, which leads to the automation of transferring various types of ownership of assets, property and value (Luu et al., 2016). Applications of industries where smart contracts can be applied in consist of for example auto pay, digital rights management, financial services including loan mortgage and inheritances, supply chain management and smart grids (Huckle, Bhattacharya, White & Beloff, 2016), (Christidis & Devetsikiotis, 2016).

Benefits of self-executing smart contracts are a reduction in the need for trusted intermediaries, since contractual conditions such as payment terms and confidentiality can be executed automatically when pre- defined conditions are met. Smart contracts provide users the freedom to ensure only authorized entities have access to their data, without having to trust third parties such as cloud service providers (Khan, Minhaj Ahmad, Salah & Khaled, 2018).

III.4 Permissionless vs Permissioned Blockchains

Blockchain networks can be classified in two main categories. These categories are permissionless blockchains and permissioned blockchains. The distinction between permissioned and permissionless blockchains lies in the scheme of ledger sharing, the number of validation nodes regarding the consensus protocol and the allowance to participate in the system (Buterin, 2014). Within the category permissioned blockchains there are also two options, private blockchains and consortium blockchains.

III.4.1 Permissionless blockchains

A permissionless blockchain, also known as a public blockchain, is an open distributed ledger where any node can join, add or append to the network freely (Garzik, 2015). Any two peers are able to conduct a transaction on the network without authentication of a central authority and are allowed to participate in the consensus protocol (Sankar, Sindhu & Sethumadhavan, 2017). Each node within a blockchain has equal permissions and obligations to all other nodes regarding access to data from other nodes and the allowance of other nodes to access your data (Lin et al., 2017). Bitcoin and Ethereum are examples of permissionless blockchains. These permissionless blockchains have all the benefits as described before. To recall, some of the main benefits of blockchain technology are cryptographically security, append-only, immutability, auditability, transaction authentication and integrity, fault tolerance and trust-free operations (Bashir, 2017).

However, permissionless blockchains also have some downsides. Some of these downsides are a lack of privacy regarding data and the identity of nodes, and transaction finality. Permissionless blockchains have little privacy regarding transactions, all transactions can be seen by other participants, including the data within a transaction. To ensure a certain degree of identity privacy, two-key cryptography is implemented. When a node enters the network, a key pair is generated. This key pair consists of a private key and a public key. Before broadcasting a transaction to the network, a node must sign the transaction to prove authenticity. The public key of a node is used to verify this authenticity, and the private key is used to encrypt the hash derived from that particular transaction (Tien Tuan Anh et al., 2017). The usage of a key pair enables the possibility of separating the identities of the nodes within a public blockchain from a real-world identity. The identity between two parties becomes either pseudonymous or even anonymous (Vaughn, 2015). Identity is often regarded pseudonymous since transactions to entities who also require a real world identity will lead to connecting a public address of a node to a real world identity. Purchasing an item on a website including delivery to your address for example enables the linkage of identities. Because of the pseudonymity of a permissionless blockchain, connectivity is also relatively low, this results in a longer period of time to reach finality in transactions and therefore relatively low throughput (Pilkington, 2016), (Lukas, 2018).

As mentioned above, another issue permissionless blockchains undergo is the transaction finality. Because distributed ledgers do not have one single entity that controls the system, incentives have to be forged to make sure that participants maintain and secure the network, which leads to an increase in finality time. The incentives used in Proof-of-Work blockchains are transaction fees and block rewards. Because permissionless blockchains are incentive- based, the transaction costs are relatively high compared to permissioned blockchains (Buterin, 2015). Also a substantial amount of computational power is required during the consensus mechanism to maintain a permissionless blockchain on a large scale (Jayachandran, 2017).

III.4.2 Permissioned blockchains

A permissioned blockchain is a controlled distributed ledger, where nodes have to be granted access by a central authority. The decision making and the validation process are executed by this central authority. All nodes within the network are authenticated, their identities are known by the other participating nodes of the network. This level of control is achieved by adding an access control layer on top of the public/ private keypair, as used in a permissionless blockchain (Sankar, Sindhu & Sethumadhavan, 2017). Since access to data is restricted to only authorized nodes, a permissioned blockchain offers more transaction privacy compared to a permissionless blockchain.

When implementing blockchain in business-to-business (B2B) applications, a choice has to be made regarding the use of a permissioned or permissionless blockchain. Since businesses have to deal with privacy concerns such as competition and identity anonymity, permissioned blockchains are considered more favorable at the moment (Chang, 2019). Another aspect, the accessibility of data, is in some industries also of importance. Access to certain data can be determined by the role a participant plays within a supply chain (Gupta, 2017). In some environments privacy and data accessibility are critical since transactions may contain sensitive data. An example of an industry where privacy is critical is the medical industry, where data about patients must remain confident.

Other advantages of a permissioned blockchain compared to a permissionless blockchain are lower costs and a higher transactional throughput. Since all participating nodes are verified, security of the network becomes less computationally intensive. Therefore consensus is reached in a shorter amount of time, resulting in a higher capacity, enabling a higher throughput. High throughput enables a reduction in cost, since there is less incentive to pay a higher transaction fee to get processed faster. Costly incentive mechanisms or mining activities as required in permissionless blockchains are unnecessary, since all nodes are authorized and are therefore considered trustworthy (Coburn, 2018), (Buterin, 2015). Because trust is gained through authorization, permissioned blockchains could make use of Byzantine fault-tolerance consensus protocols. (Makhdoom, 2019) Also, when granting a node permission to participate in the blockchain, during authorization high capabilities of machinery can be ensured by demanding for example high computation capacity and a high bandwidth internet connection (Preethi, 2017).

Within permissioned blockchains, a distinction can be made between two types; a private blockchain and a consortium blockchain. Within a private blockchain, one single entity is responsible for executing and maintaining the consensus mechanism, authorizing nodes to participate in the network and grand access to particular data. In a consortium blockchain, multiple entities are responsible for these actions. The generation of each block is determined jointly by pre-authorized nodes. Consortium blockchains are shared and validated by a predefined group of nodes, only authorized nodes are responsible for maintaining the consensus protocol. Other nodes within the network are able to add transactions, but do not participate in the consensus protocol. Both of these permissioned blockchains have their own advantages and disadvantages.

In general, due to a limited number of validation nodes, permissioned blockchains can reach finality almost immediately after broadcasting a transaction, therefore they achieve a relative high transaction throughput (Lukas, 2018). Increasing the number of involved nodes in the consensus mechanism usually leads to a reduction of throughput. However, less nodes involved in the consensus protocol leads to more centralization, with increases the vulnerability of the system to malicious actions such as DoS attacks. The number of nodes involved in the consensus mechanism also determine the scalability of the system. Permissioned blockchains are considered to be not very scalable since there are only a few validator nodes present, which causes problems when the number of transactions increases.

III.4.3 Consortium blockchains

Consortium blockchains can be considered a semi-permissioned blockchain and have a higher degree of openness when compared to a private blockchain. The main nodes, who are pre-authorized and selected initially, operate in a trusted environment and are responsible for providing consensus to the system. However, multiple participants can be incorporated into the system afterwards. The degree of openness however varies by means of access control based on the consortium policies. Information stored on a consortium blockchain is regulated by the policies of this consortium. Nodes that are added later on by one of the authorized nodes can be restricted in viewing data by only granting access to data relevant for that node/ entity. Consortium blockchains are therefore suited for semi-closed systems consisting of multiple enterprises. Consortium blockchains benefit from the advantages of decentralization, while data remains private if necessary.

Since membership is pre-determined, participants are aware of the number of nodes within that consortium. When a participant does not have the most up to date version of the blockchain, it can contact a majority of the participants, who can make sure that participant catches up to the latest version. Because all identities of participants are known, it also prevents Sybil attacks, in which multiple identities are forged by an attacker (Gramoli, 2017). New participants of a consortium blockchain are first checked and authenticated before permission is granted to enter the consortium, therefore it is considered that a malicious actor is not able to convince the majority of a consortium to allow access to fake identities in large numbers compared to the consortium size.

III.4.4 Similarities

While different in approach regarding decentralization and privacy, both types of blockchain have multiple similar benefits compared to centralized systems. Both operate on a decentralized peer-to-peer network, where a multitude of nodes maintains the integrity of the system through a consensus protocol, establishing an immutable and append-only ledger even in the presence of some faulty or malicious nodes. Both blockchains also synchronize and verify transactions through a consensus protocol, therefore single points of failure are eliminated and data integrity is achieved (Coburn, 2018).

Despite the permissioned nature of a consortium blockchain, it bears multiple similarities to permissionless blockchains. The failure model of a consortium blockchain is equal to that of a permissionless blockchain. A consortium blockchain also undergoes Byzantine failures, since different participants often have conflicting interests, and the consensus mechanism should protect the system from possible misbehavior.

Another similarity is found within the communication model. Participants of a consortium might be located in different areas of the world, therefore communication and transactions often take place over the internet. Since the internet connection relies on a multitude of machines and mechanisms outside of the consortium, it is impossible to control or anticipate on traffic disruptions, congestions and delays, making the connection unpredictable, which results in possible issues regarding synchronization.

III.5 Blockchain Usefulness Questionnaire – Generic

From paragraph 2.4 ‘Analysis of Blockchain Technology’ multiple limitations and challenges that currently exist are presented. Before designing a system that utilizes blockchain technology, a check should be executed to ensure use of blockchain technology is possible and/ or useful. This check consists of answering a questionnaire about the requirements of the system, where answers need to meet certain prerequisites.

Blockchain technology is a distributed ledger technology. It is designed to produce a database-layer that functions as a data-management infrastructure for ecosystems that consist of multiple participants. In order to ensure that use of blockchain technology is useful, meaningful and/ or beneficial regarding an application, different questions should be asked upfront. From numerous sources questions are derived that assist in discovering whether or not the use of blockchain technology is possible and/or useful (Chowdhury et al., 2018), (Fernandez-Carames & Fraga-Lamas, 2018), (Yaga et al., 2018), (Arvindpdmn, 2020), (Graham, 2018), (Sebastien Meunier, 2019), (World Economic Forum, 2018), (World Economic Forum, 2018b), (Iannarone, 2018), (Anwar, 2019), (Spinaci, 2018).

This questionnaire acts as an indicator for usability of blockchain technology and is displayed in Table III.1. From Table III.1 it becomes clear that three answers are possible; Yes, Maybe, and No. In some cases the circumstances or conditions of a system are well-known, and therefore the answer can be a clear ‘Yes’ or ‘No’. However, due to a variety of reasons, often such a clear answer is not possible and ‘Maybe’ is best possible answer at that time. In order to overcome the uncertainty that is present when a question is answered with ‘Maybe’, numerous questions are incorporated within the questionnaire.

Table III.1 Blockchain usefulness questionnaire - Generic

Blockchain usefulness questionnaire	**Yes**	**Maybe**	**No**
Are multiple parties present/ involved?	▨	▨	
Do multiple entities need to contribute data?	▨	▨	
Is use of a database required/ beneficial?	▨	▨	
Is there need for a shared database?	▨	▨	
Do multiple parties require shared read/ write access?	▨	▨	
Is there trust deficit present among parties	▨	▨	
Do these parties have conflicting interests?	▨	▨	
Is difficulty found in deciding who should be in control of data- management?	▨	▨	
Can a traditional database easily/ simply meet the needs of all participants?		▨	▨
Is there need for historical transaction records?	▨	▨	

Is high-throughput requested (1000+ TPS)?			▨
Is high performance required (millisecond transaction finality)?			▨
Do large amounts of data need to be stored?			▨

The grey shaded cells in Table III.1 display the answers that indicate that the use of blockchain technology might be suitable and/or beneficial. In general, if the majority of answers matches the light-grey shaded cells that accompany that particular question, and the answer to all bottom three questions are 'No', utilization of blockchain technology is considered useful. As derived from Table III.1, the cells in the bottom three rows, belonging to the answer 'No', are shaded in a distinctive dark-grey color. This distinction is present since the answer to each of these questions determines whether utilization of blockchain technology is nowadays possible at all. Currently, the characteristics of blockchain technology, in particular regarding permissionless blockchains, have limitations with regards to throughput, finality of transactions and data-storage capacity. So, in order to make use of blockchain technology at the moment of writing, the answers to these three bottom questions need to be 'No'.

III.6 Blockchain Usefulness Questionnaire – Case-Study

In order to ensure that utilization of blockchain technology is possible and beneficial to the analyzed business-case, the Blockchain usefulness questionnaire is filled in for this case-study. Table III.2 below displays the filled in questionnaire, and below Table III.2 more explanation with regards to the provided answers is present. The results of the questionnaire are verified with supply chain experts from the business-case.

Table III.2 Blockchain Usefulness Questionnaire – Business Case specific

Blockchain usefulness questionnaire	Yes	Maybe	No
Are multiple parties present/ involved?	X		
Do multiple entities need to contribute and read data?	X		
Is use of a database required/ beneficial?	X		
Is there need for a shared database?	X		
Do these parties have conflicting interests?	X		
Is there trust deficit present among parties?	X		
Is difficulty found in deciding who should be in control of data- management?	X		
Can a traditional database easily/ simply meet the needs of all participants?		X	
Is there need for historical (transaction) records?	X		
Is high-throughput requested (1000+ TPS)?			X
Is high performance required (millisecond transaction finality)?			X
Do large amounts of data need to be stored?			X

From the analysis of the business-case two different main flows were identified. Each of the identified flows consisted of five or more participants. So multiple participants are present in the system. During the analysis, data was obtained from different locations spread across the numerous entities, which means that multiple entities do indeed contribute data. Currently, the data from all entities is collected by a third party and combined within a database. The collection of data from different sources shows that a shared database is required/ beneficial. Although all parties within the supply chain are part of an overarching organization, they all have their own contractual agreements and interests. These parties try to produce an environment that is most beneficial to themselves. This means that interests of different participants often misaligns, resulting in conflicting interests. These conflicting interests also lead to trust deficits between the participants. For example, data-sharing regarding performance between different entities within the supply chain is often a difficult topic. Usually data-sharing is enabled only after signing legal documents that penalize parties if certain agreements are violated. An example of such a document is a non-disclosure agreement, or NDA. Due to the presence of all these legal obligations and individual interests, among other reasons, difficulty is found in deciding who is in control of data-management within the supply chain. Nowadays third party IT providers are often hired to manage the data, again under strict contractual agreements. Utilization of blockchain technology is able to overcome some of this trust-deficit and need for legal documents. The characteristics of blockchain technology ensure ‘trust’ is embedded in the system by means of math and cryptography. Therefore less of these legal documents may be required in the future. However, the legal side of utilization of blockchain technology is out of scope during this research and will therefore not be researched and explained to more extend. However, as legal obligations are an important aspect in numerous industries, the author does recommend further research towards this aspect in the future.

One of the major advantages of a well-performing Digital Chain is the ability to accurately represent a physical system. This digital representation leads to the possibility to analyze its performance and identify/execute modifications that may lead to improvements of the system. However, in order to ensure a modification actually improves the system, it should be compared to past performance. And in order to enable comparison to past performance, historical data and/ or records are required. From the results of the analysis it becomes clear that the answer to the bottom three questions is ‘No’. The duration of time spend in the supply chain is in the order of hours, meaning that both high throughput and high performance is not necessary. Also, the Digital Chain is based on the electronic product code of a RFID tag, which consists of a string of text of only a small amount of characters long. This means that only a little amount of data needs to be send per tag during a transaction.

Appendix IV - Scenario-Testing Results Impact Diminished Dwell-Time

Different scenarios are tested, where the upper-bound value of one or more entities is replaced by the Digital Chain simulation-value. The tables below display numerous scenarios and the impact they have on the performance of the supply chain. These tables shows the cumulative duration time of goods passing through the sub-flow. If the cell above a number has an orange background color, it means that the upper bound value from the 'old' situation is used. When the design-related value is used at a particular entity, the background color of the cell above is blue and 'Design' is written in that cell. The last column displays the overall efficiency of the supply chain, compared to the service-level. When efficiency is below 100%, the background color of the cell is red, showing that the service-level requirement has not been reached. When efficiency is above 100%, the background color of the cell is green, showing that the service-level requirement is reached. Within Table 5.2, numerous scenarios have been displayed, ranging from the impact of alteration of one entity to alteration of all entities.

Location 1 IN	Location 1 OUT	Location 2 IN	Location 2 OUT	Location 3 IN	Location 3 OUT	Performance SL* [%]
	Current-State [h]					
0	29	46	124	168	**255**	**94**
	Design					
0	21	38	116	159	**247**	**97**
			Design			
0	29	46	102	145	**233**	**103**
				Design		
0	29	46	124	153	**240**	**100**
					Design	
0	29	46	124	168	**236**	**102**
	Design		**Design**			
0	21	38	94	137	**225**	**107**
	Design			**Design**		
0	21	38	116	144	**232**	**104**
	Design				**Design**	
0	21	38	116	159	**227**	**106**
			Design	**Design**		
0	29	46	102	131	**218**	**110**
			Design		**Design**	
0	29	46	102	145	**214**	**112**
				Design	**Design**	
0	29	46	124	153	**221**	**109**
	Design		**Design**	**Design**		
0	21	38	94	122	**210**	**114**
	Design		**Design**		**Design**	
0	21	38	94	137	**205**	**117**
			Design	**Design**	**Design**	
0	29	46	102	131	**199**	**121**

Table continues on the next page

	Design		**Design**	**Design**	**Design**	
0	21	38	94	122	**190**	**126**
	Design					
0	21	36	92	120	**189**	**127**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 1 - Location 4.2

Location 1 IN	**Location 1 OUT**	**Location 2 IN**	**Location 2 OUT**	**Location 4.2 IN**	**Location 4.2 OUT**	**Performance SL* [%]**
	Current-State [h]					
0	102	123	260	1405	**2124**	**11**
	Design					
0	45	65	203	1348	**2066**	**12**
			Design			
0	102	123	217	1362	**2081**	**12**
				Design		
0	102	123	260	712	**1430**	**17**
					Design	
0	102	123	260	1405	**1761**	**14**
	Design		**Design**			
0	45	65	160	1304	**2023**	**12**
	Design			**Design**		
0	45	65	203	654	**1373**	**17**
	Design				**Design**	
0	45	65	203	1348	**1703**	**14**
			Design	**Design**		
0	102	123	217	668	**1387**	**17**
			Design		**Design**	
0	102	123	217	1362	**1718**	**14**
				Design	**Design**	
0	102	123	260	712	**1067**	**22**
	Solution		**Design**	**Design**		
0	45	65	160	611	**1329**	**18**
	Design		**Design**		**Design**	
0	45	65	160	1304	**1660**	**14**
			Design	**Design**	**Design**	
0	102	123	217	668	**1024**	**23**
	Design		**Design**	**Design**	**Design**	
0	45	65	160	611	**966**	**25**
	Design					
0	45	62	156	607	**963**	**25**

Flow 1 - Location 4.3

Location 1 IN	**Location 1 OUT**	**Location 2 IN**	**Location 2 OUT**	**Location 4.3 IN**	**Location 4.3 OUT**	**Performance SL* [%]**
	Current-State [h]					
0	30	48	154	183	515	**47**
	Design					
0	19	37	144	172	505	**48**
			Design			
0	30	48	122	151	483	**50**
				Design		
0	30	48	154	177	509	**47**
					Design	
0	30	48	154	183	353	**68**
	Design		**Design**			
0	19	37	111	140	472	**51**
	Design			**Design**		
0	19	37	144	166	498	**48**
	Design				**Design**	
0	19	37	144	172	343	**70**
			Design	**Design**		
0	30	48	122	144	476	**50**
			Design		**Design**	
0	30	48	122	151	321	**75**
				Design	**Design**	
0	30	48	154	177	347	**69**
	Solution		**Design**	**Design**		
0	19	37	111	133	466	**52**
	Design		**Design**		**Design**	
0	19	37	111	140	310	**77**
			Solution	**Design**	**Design**	
0	30	48	122	144	314	**76**
	Design		**Design**	**Design**	**Design**	
0	19	37	111	133	304	**79**
	Design [h]					
0	19	35	109	131	302	**80**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 1 - Location 4.4

Location 1 IN	**Location 1 OUT**	**Location 2 IN**	**Location 2 OUT**	**Location 4.4 IN**	**Location 4.4 OUT**	**Performance SL* [%]**
	Current-State [h]					
0	24	42	274	312	868	**28**
	Design					
0	16	34	265	303	859	**28**
			Design			
0	24	42	163	201	758	**32**
				Design		
0	24	42	274	306	862	**28**
					Design	
0	24	42	274	312	552	**43**
	Design		**Design**			
0	16	34	155	192	749	**32**
	Design			**Design**		
0	16	34	265	297	853	**28**
	Design				**Design**	
0	16	34	265	303	543	**44**
			Design	**Design**		
0	24	42	163	195	752	**32**
			Design		**Design**	
0	24	42	163	201	442	**54**
				Design	**Design**	
0	24	42	274	306	546	**44**
	Solution		**Design**	**Design**		
0	16	34	155	187	743	**32**
	Design		**Design**		**Design**	
0	16	34	155	192	433	**55**
			Design	**Design**	**Design**	
0	24	42	163	195	436	**55**
	Design		**Design**	**Design**	**Design**	
0	16	34	155	187	427	**56**
	Design [h]					
0	16	31	152	184	424	**57**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 2 - Location 4.1

Location 1 IN	Location 1 OUT	Location 2 IN	Location 2 OUT	Location 3 IN	Location 3 OUT	Location 4.1 IN	Location 4.1 OUT	Performance SL* [%]
	Current-State [h]							
0	0	42	99	120	173	194	279	**86**
	Design							
0	20	36	94	114	168	188	273	**88**
			Design					
0	0	42	81	102	156	176	261	**92**
				Design				
0	0	42	99	118	171	192	277	**87**
					Design			
0	0	42	99	120	159	179	264	**91**
						Design		
0	0	42	99	120	173	191	276	**87**
							Design	
0	0	42	99	120	173	194	268	**89**
To save space, results below this point only display the least and most effective combination of application of the design on a specific number of locations								
				Design		**Design**		
0	25	42	99	118	171	189	274	**87**
			Design		**Design**			
0	25	42	81	102	141	161	246	**98**
	Design			**Design**		**Design**		
0	20	36	94	112	166	184	269	**89**
			Design		**Design**		**Design**	
0	25	42	81	102	141	161	236	**102**
	Design			**Design**		**Design**	**Design**	
0	20	36	94	112	166	184	259	**93**
	Design		**Design**		**Design**		**Design**	
0	20	36	76	97	136	156	230	**104**
	Design			**Design**	**Design**	**Design**	**Design**	
0	20	36	94	112	151	169	244	**98**
	Design		**Design**		**Design**	**Design**	**Design**	
0	20	36	76	97	136	154	228	**105**
	Design		**Design**	**Design**	**Design**	**Design**	**Design**	
0	20	36	76	95	134	151	226	**106**
	Design [h]							
0	20	35	75	94	132	150	225	**107**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 2 - Location 4.2

Location 1 IN	Location 1 OUT	Location 2 IN	Location 2 OUT	Location 3 IN	Location 3 OUT	Location 4.2 IN	Location 4.2 OUT	Performance SL* [%]
	Current-State [h]							
0	28	46	100	126	179	199	273	**88**
	Design							
0	18	36	90	116	169	189	263	**91**
			Design					
0	28	46	85	110	163	183	257	**93**
				Design				
0	28	46	100	120	173	193	267	**90**
					Design			
0	28	46	100	126	162	182	256	**94**
						Design		
0	28	46	100	126	179	197	271	**89**
							Design	
0	28	46	100	126	179	199	247	**97**
To save space, results below this point only display the least and most effective combination of application of the design on a specific number of locations								
				Design		**Design**		
0	28	46	100	120	173	191	264	**91**
					Design		**Design**	
0	28	46	100	126	162	182	230	**104**
	Design			**Design**		**Design**		
0	18	36	90	110	163	181	254	**94**
			Design		**Design**		**Design**	
0	28	46	85	110	147	167	215	**112**
	Design		**Design**	**Design**		**Design**		
0	18	36	75	94	147	165	239	**101**
	Design		**Design**		**Design**		**Design**	
0	18	36	75	100	136	157	205	**117**
	Design		**Design**	**Design**	**Design**	**Design**		
0	18	36	75	94	130	148	222	**108**
	Design		**Design**	**Design**	**Design**		**Design**	
0	18	36	75	94	130	150	198	**121**
	Design		**Design**	**Design**	**Design**	**Design**	**Design**	
0	18	36	75	94	130	148	196	**122**
	Design [h]							
0	18	33	72	91	128	146	194	**124**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 2 - Location 4.3

Location 1 IN	**Location 1 OUT**	**Location 2 IN**	**Location 2 OUT**	**Location 3 IN**	**Location 3 OUT**	**Location 4.3 IN**	**Location 4.3 OUT**	**Performance SL* [%]**
	Current-State [h]							
0	26	43	92	114	169	183	274	**88**
	Design							
0	21	38	87	108	164	178	268	**89**
			Design					
0	26	43	79	100	155	169	260	**92**
				Design				
0	26	43	92	111	167	181	271	**88**
					Design			
0	26	43	92	114	159	174	264	**91**
						Design		
0	26	43	92	114	169	182	273	**88**
							Design	
0	26	43	92	114	169	183	270	**89**
To save space, results below this point only display the least and most effective combination of application of the design on a specific number of locations								
				Design		**Design**		
0	26	43	92	111	167	180	270	**89**
			Design		**Design**			
0	26	43	79	100	145	160	250	**96**
				Design		**Design**	**Design**	
0	26	43	92	111	167	180	266	**90**
	Design		**Design**		**Design**			
0	21	38	73	94	140	154	245	**98**
	Design			**Design**		**Design**	**Design**	
0	21	38	87	106	161	174	261	**92**
	Design		**Design**		**Design**		**Design**	
0	21	38	73	94	140	154	241	**100**
	Design			**Design**	**Design**	**Design**	**Design**	
0	21	38	87	106	152	165	251	**95**
	Design		**Design**	**Design**	**Design**		**Design**	
0	21	38	73	92	138	152	238	**101**
	Design		**Design**	**Design**	**Design**	**Design**	**Design**	
0	21	38	73	92	138	151	237	**101**
	Design [h]							
0	21	37	72	91	137	150	236	**101**

* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

Flow 2 - Location 4.4

Location 1 IN	Location 1 OUT	Location 2 IN	Location 2 OUT	Location 3 IN	Location 3 OUT	Location 4.4 IN	Location 4.4 OUT	Performance SL* [%]
	Current-State [h]							
0	29	46	94	118	166	194	247	**97**
	Design							
0	23	39	88	112	160	188	240	**100**
			Design					
0	29	46	79	103	151	179	231	**104**
				Design				
0	29	46	94	114	161	189	242	**99**
					Design			
0	29	46	94	118	154	182	234	**103**
						Design		
0	29	46	94	118	166	192	245	**98**
							Design	
0	29	46	94	118	166	194	228	**105**
To save space, results below this point only display the least and most effective combination of application of the design on a specific number of locations								
				Design		**Design**		
0	29	46	94	114	161	187	240	**100**
			Design				**Design**	
0	29	46	79	103	151	179	212	**113**
	Design			**Design**		**Design**		
0	23	39	88	107	155	181	233	**103**
			Design		**Design**		**Design**	
0	29	46	79	103	138	166	200	**120**
	Design			**Design**	**Design**	**Design**		
0	23	39	88	107	143	169	221	**109**
	Design		**Design**		**Design**		**Design**	
0	23	39	73	97	132	160	193	**124**
	Design		**Design**	**Design**	**Design**	**Design**		
0	23	39	73	92	127	153	205	**117**
	Design		**Design**	**Design**	**Design**		**Design**	
0	23	39	73	92	127	155	189	**127**
	Design		**Design**	**Design**	**Design**	**Design**	**Design**	
0	23	39	73	92	127	153	187	**129**
	Design [h]							
0	23	38	71	91	126	152	185	**129**

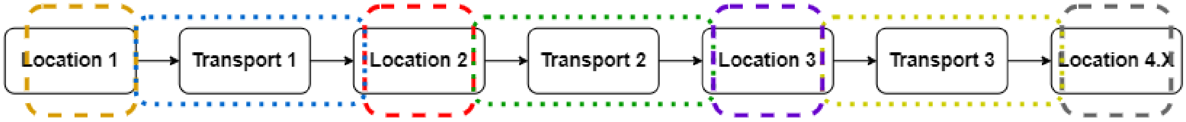
* Performance is relative to the current Service-Level Objective of 240 [h], which is 100%

The tables below provide an overview of the minimum and maximum effect of appliance of the design on a different number of locations, for different sub-flows.

Flow 1															
Destination		**Current situation**		**D 1 L****			**D 2 L**			**D 3 L**			**D 4 L**		**D ALL**
				min	**max**		**min**	**max**		**min**	**max**				
Location 3	**[h]**	255		247	233		232	214		210	199		190		189
	[%]*	94		97	103		104	112		114	121		126		127
Location 4.2	**[h]**	2124		2081	1430		2023	1067		1660	1024		966		963
	[%]*	11		12	17		12	22		14	23		25		25
Location 4.3	**[h]**	515		509	353		498	321		466	310		304		302
	[%]*	47		47	68		48	75		52	77		79		80
Location 4.4	**[h]**	868		758	552		853	442		743	436		427		424
	[%]*	28		28	43		28	54		32	55		56		57

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

**Design applied to 1 Location



Flow 2												
Destination		**Current situation**		**D 1 L****			**D 2 L**			**D 3 L**		
				min	**max**		**min**	**max**		**min**	**max**	
Location 3	**[h]**	279		277	261		274	246		269	236	
	[%]*	86		87	92		87	98		89	102	
Location 4.2	**[h]**	273		271	247		264	230		254	215	
	[%]*	88		89	97		91	104		94	112	…
Location 4.3	**[h]**	274		273	260		270	250		266	245	
	[%]*	88		88	92		89	96		90	98	
Location 4.4	**[h]**	247		245	228		240	212		233	200	
	[%]*	97		98	105		100	113		103	120	

Flow 2											
Destination			**D 4 L**			**D 5 L**			**D 6 L**		**D ALL**
			min	**max**		**min**	**max**				
Location 3	**[h]**		259	230		244	228		226		225
	[%]*		93	104		98	105		106		107
Location 4.2	**[h]**		239	205		222	198		196		194
	[%]*	…	101	117		108	121		122		124
Location 4.3	**[h]**		261	241		251	238		237		236
	[%]*		92	100		95	101		101		101
Location 4.4	**[h]**		221	193		205	189		187		185
	[%]*		109	124		117	127		129		129

* Efficiency is relative to the current Service-Level Objective of 240 [h], which is 100%

**Design applied to 1 Location

Flow 1	**Destination**		**Current situation**		**D ALL***	**Improvement [h]**	**Improvement [%]**
	Location 3	**[h]**	255		189	66	26
		[%]	94		127		
	Location 4.2	**[h]**	2124		963	1161	55
		[%]	11		25		
	Location 4.3	**[h]**	515		302	213	41
		[%]	47		80		
	Location 4.4	**[h]**	868		424	444	51
		[%]	28		57		
Flow 2	**Destination**		**Current situation**		**D ALL***	**Improvement [h]**	**Improvement [%]**
	Location 4.1	**[h]**	279		225	54	19
		[%]	86		107		
	Location 4.2	**[h]**	273		194	79	29
		[%]	88		124		
	Location 4.3	**[h]**	274		236	38	14
		[%]	88		101		
	Location 4.4	**[h]**	247		185	62	25
		[%]	97		129		

*Design applied to all Locations

Appendix V - Scientific Paper

Abstract

In recent years market expansion and globalization have led to new market requirements, which resulted in more complex supply chains. Within these complex supply chains, the lack of visibility and cross-enterprise data-exchange on the whereabouts of goods has led to the occurrence of undesired dwell-time of products between processes, resulting in a decrease in supply chain performance with regards to throughput times. This paper addresses the current lack of visibility and cross-enterprise data-exchange in supply chains by designing a Digital Chain that is based on Internet of Things (IoT)-sensor technology and blockchain technology. Through use of a Digital Chain, undesired dwell-time of goods is diminished and therefore supply chain performance is improved concerning Service-Level Objectives regarding Throughput Times (SLOTT). A Digital Chain is defined as a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. Digital Chains are expected to improve supply chain SLOTT performance as they provide for upfront, iterative forecasting of arrival times of goods. In this paper the following research question is answered: 'What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?'

1 Introduction

Supply chains are considered as one of the major cornerstones of both industries and society as present nowadays. A supply chain is a system that is designed to transport products or services between different participants (Azzi, Kilany & Sokhn, 2019). Parties involved within a supply chain might consist of numerous organizations, enterprises, knowledge, information, activities, and resources, among others. In recent years market expansion and globalization have led to new market requirements, which resulted in an increase of intermediaries and therefore more complex supply chains (Astill et al., 2019). An important aspect regarding the cause of increased complexity in supply chains is the presence of the digitalization trend, which lead to drastic producer and consumer behavior changes in recent years (Botkina et al., 2018). An example of this would be the transition to next day delivery, or even same-day delivery, from items purchased on the internet. The requirements accompanying these behavioral changes have impacted supply chains and supply chain management, resulting in a continuous strive for further increasing efficiency and performance of supply chains (Kshetri, 2018).

Due to an increased number of intermediaries between producers and customers, the collaboration between parties in the supply chain becomes more difficult, resulting in little knowledge and overview of the processes that occur within the supply chain. The lack of visibility and data-exchange lead to the occurrence of dwell-time, as the transition between processes of different entities are not synchronized and stagnation of the progress occurs. Dwell-time of goods in supply chains is considered an undesired phenomenon, as it produces inefficiencies in supply chains and therefore diminishes performance (IBM, 2017), (Kuo & Liang, 2016).

To enable further evolvement of performance and efficiency within supply chains, the lack of cross-enterprise data-exchange should be addressed (Badia-Melis et al., 2015), (Aung & Chang, 2014). Before addressing data-exchange related issues is enabled, an entity first needs to have visibility with regards to internal processes and the whereabouts of goods. With the rise of IoT-sensor technology, detection of products throughout a supply chain is made possible and visibility may be automated. However, current enterprise systems are generally of a centralized nature, and this type of structure is regarded by academics to cause limitations to the applicability of IoT technology in the near future, as their data-management abilities will become insufficient (Boschi, Borin, Cesar Raimundo, & Batocchio, 2018), (Dorri, Kanhere & Jurdak, 2016). Without cross-enterprise visibility and data-exchange, it is not possible to diminish dwell-time and take the next steps with regards to improving supply chain performance.

New, emerging technologies such as blockchain technology, 5G, AI, edge & fog computing, Distributed File Storage systems, NoSQL- & NewSQL databases, and cloud storage systems have been identified by academics that might improve on real-time data-exchange (Qi et al., 2019). However, most of these technologies need to be explored further to provide insight on future impact on supply chain performance. At the time of writing, no clear solutions to real-time data-exchange issues are present that can be deployed on a large scale. To improve supply chain performance, more research is requested towards distributed data-exchange mechanisms, as Industry 4.0 requires decentralized decision-making (Zheng et al., 2018), (Hermann, Pentek & Otto, 2016), (Schmidt & Wagner, 2019).

2 Methodology

2.1 Research Gap & Question

Currently, a research gap is present with regards to combining new, emerging data-management technologies with IoT-sensors to improve supply chain performance. This paper covers the research on combining IoT-sensors with blockchain technology to overcome the lack of visibility and real-time data-exchange in supply chains. Blockchain technology has been identified by academics as a technology that could potentially overcome the issues regarding the lack of real-time data-exchange due to its specific characteristics, and should therefore be explored to more extend (Laaper et al., 2017), (Zyskind, Nathan & Pentland, 2015), (Ramamurthy, 2016). However, currently knowledge is lacking on combining blockchain technology with RFID-sensor technology to improve supply chain SLOTT performance.

This paper aims to add value to the academic world by providing knowledge on combining and connecting blockchain technology with Radio Frequency Identification (RFID) sensor technology to improve supply chain performance. This paper provides the design requirements of a Digital Chain that enables enhanced visibility and real-time data-exchange in supply chains with regards to the whereabouts of goods at a specific time, to diminish dwell-times and improving on performance with concerning Service-Level Objectives regarding Throughput Times (SLOTT).

This paper answers the following research question: ‘What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?’ A Digital Chain is a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. Utilization of IoT-sensor technology is regarded to overcome the current visibility issues, while using blockchain technology as the main driver for real-time data-exchange is expected to solve communication-related issues.

2.2 Approach

This research is structured alongside the theory-oriented case-study methodology as proposed by Dul & Hak (Dul & Hak, 2007). It follows the consecutive steps as displayed in Figure 2.1. During the introduction of the paper and the previous paragraph, the background of the research, current research gap, and this paper’s research question were presented. After completion of this ‘Problem Definition’ section, a deeper understanding of the fundamentals of Digital Chains and blockchain technology is obtained through literature reviews in order to get a grasp on the impact Digital Chains will have on supply chain performance. During this ‘Exploration of Theory’ phase, the following research sub-questions are answered; ‘What is a ‘Digital Chain’ and how will it impact supply chains?’, as well as ‘Is blockchain technology able to provide real-time data-exchange in supply chains?’ During this phase the characteristics of both of these technologies are addressed, as well as how they complement each other and their potential impact on supply chain SLOTT performance.

The obtained knowledge is then transformed into 'Design Requirements' by answering the research sub-question; What are the design requirements for a Digital Chain? During this phase also the goal of the design is made clear, as well as identification of the KPIs. 'Design Requirements' also provides a translation towards an actual use-case of a Digital Chain in the form of a case-study. The following sub-question is answered; 'Wat is the current-state performance, through use of a case-study?' During the current-state performance analysis, data from multiple already installed RFID-sensors is combined and transformed into a digital overview of the complete supply chain that is able to display the supply chains' SLOTT performance.

After obtaining the design requirements, the concurrent step is to produce an actual 'Design'. From both theory and design requirements a future-state Digital Chain module design is created that combines RFID technology and blockchain technology by means of an intelligence layer. The goal of this Digital Chain is to enable iterative forecasting, which is able to reduce dwell-time that is caused by the lack of visibility and data-exchange in supply chains and therefore improves upon SLOTT performance. During the 'Design' phase the following research sub-question is answered; 'What should a Digital Chain design, that combines IoT-sensors and blockchain technology, look like?'.

After designing a future-state Digital Chain, the design is applied to the previously mentioned use-case in order to determine its actual impact on SLOTT performance in supply chains. During the 'Impact of Design' phase, the following research sub-question is answered; 'What is the impact of the design when applied to the case-study?. During this phase a numerical estimation of the effect of a Digital Chain is provided through scenario-testing of the results of the previously used case-study. Data-analysis of the current-state performance and future-sate performance enables comparison of the two and displays the impact of the design. The last phase of this paper is the 'Conclusion & Recommendation' phase, in which the research question is answered and future research is recommended.

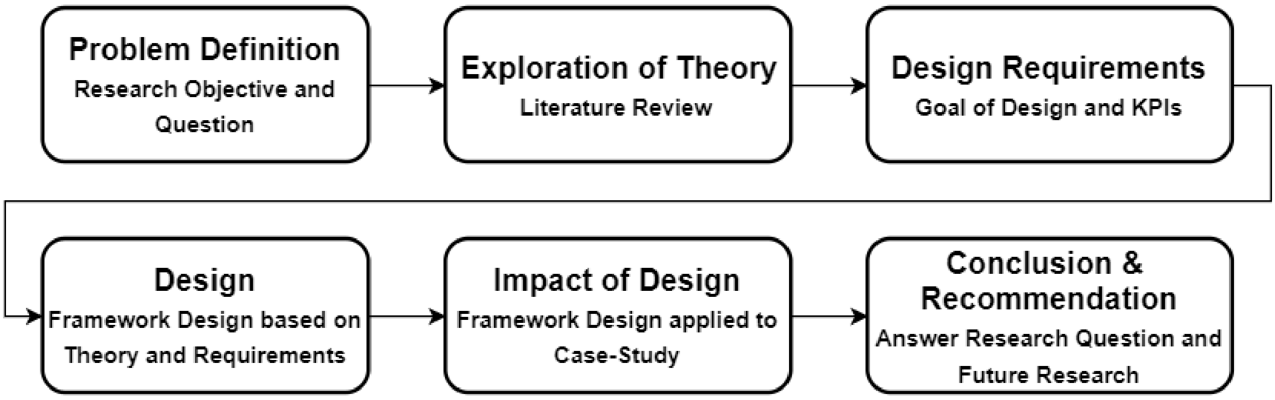


Figure 2.1 Overview of the approach of the research

2.3 Literature Review - What is a 'Digital Chain' and how will it impact supply chains?

The digitalization trend in industrial systems as present in recent years can be divided into four stages; digital enablement, digitalization assistance, digital control and link, and cyber-physical integration (Qi et al., 2019). During these phases, industry networks have shifted from digital conversion of paper documents towards the aim of creating cyber-physical systems (CPS) that are able to merge the physical and digital world together. Through technologies such as Fieldbus, Ethernet, CAD, and the current advancements regarding IoT, big data and AI, supply chains are progressing more and more towards these cyber-physical systems (Lu, Liu, Wang, Huang, & Xu, 2020). A CPS possesses the ability to transform industries and business processes regarding simulation, monitoring and prediction (Rosen, von Wichert, Lo, & Bettenhausen, 2015), (Schleich, Anwer, Mathieu, & Wartzack, 2017), (Tao & Qi, 2019).

An example of the evolvement towards CPSs in manufacturing environments is present in the form of 'Digital Twin' (DT) technology, where the use of sensors and continuous updating is applied to hardware solutions such as analyzing an airplanes' structural behavior digitally, with the intention of prediction its behavior (Tuegel, Ingraffea, Eason & Spottswood, 2011). However, DT technology is aimed at hardware applications, such as airplane engines and manufacturing machinery, and in its current form it is not suited for application in supply chains. Therefore the concept of a 'Digital Chain' is introduced, which builds upon both CPS and DT technology, and is focused purely on supply chain applications. A Digital Chain is therefore defined as; a digital representation of a physical supply chain that mimics its counterpart in great detail through continuous updating of state changes of the physical counterpart via sensor-based data. Figure 2.2 displays the three main aspects that together form a Digital Chain; these aspects are now explained to more extend.

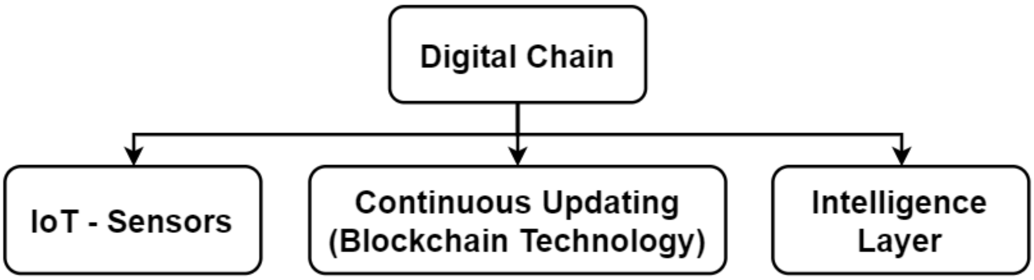


Figure 2.2 Main components of a Digital Chain

2.3.1 Data- collection through IoT-sensors

Sensor technology is a key aspect regarding the effectiveness of a Digital Chain; a Digital Chain is able to reflect the performance of its physical counterpart through continuous updates from sensor-based data. Without these continuous sensor-data updates, a Digital Chain is incapable to provide a proper representation of the physical world. The collection of data through IoT- sensors has the advantage that the data becomes evidence-based; all data originates from factual occurrences as sensors are only able to detect its actual surroundings. IoT-sensor technology is considered a major driver of a Digital Chain since it is both able to collect and store data from individual sensors, as well as the transmittance of this data to processing entities via the internet. All data collected by sensors needs to be transmitted to processing entities in order to enable analysis of the data.

When designing a Digital Chain of a supply chain to determine the performance of the flow of goods, it is important that the products are detected throughout the supply chain. In order to achieve detection of goods, each product needs to be individually identifiable by a sensor. This research is focused on SLOTT performance of supply chains with regards to the flow of goods, so it is of importance that both detection and identification of (individual) products is made possible, as well as the time and location of detection. During the paper visibility of goods throughout complete supply chains is achieved through the use of automatic identification and data capture (AIDC or Auto-ID) technologies such as barcodes, QR-codes, and RFID tags. Sensors that are able to detect these hardware Auto-ID components consist of cameras, scanners and antennas, among others.

2.3.2 Continuous updating of the collected data in real-time

A major driving feature of a Digital Chain is the need for frequent and continuous data-exchange between the physical and digital world. An important criterion is the processing architecture regarding latency of data. The performance of aspects such as real-time locating, analyzing and controlling of processes are all dependent on latency; the higher the latency, the less accurate a system is. Without an adequate, time-sensitive data-synchronization mechanism, the connection between reality and its digital representation is lost. Successful deployment of a Digital Chain is therefore dependent on its high-performance data-transmission and data-processing abilities of time-series data (Lu, Liu, Wang, Huang, & Xu, 2020). An accurate Digital Chain requires high-performance, low-latency data-transmission that enables real-time communication between the physical and digital world. Due to is specific characteristics, blockchain technology is identified as a solution that provides for real-time communication of sensor-based data (Yli-Huumo et al., 2016), (Huang, Wang, Yan, & Fang, 2020). However, in order to understand blockchain technology and its' implied benefits regarding data-exchange, the following question is answered in the upcoming paragraph: Is blockchain technology able to provide real-time data-exchange in supply chains?

Is blockchain technology able to provide real-time data-exchange in supply chains?

Blockchain technology emerged in 2008 after the Bitcoin whitepaper was published (Nakamoto, 2008). Benos et al. defined blockchain technology as: "a database architecture which enables the keeping and sharing of records in a distributed and decentralized way, while ensuring its integrity through the use of consensus-based validation protocols and cryptographic signatures" (Benos et al., 2017). Blockchain technology is a distributed ledger technology in which all transactions are encrypted, shared and recorded in a chronological order. A blockchain network consists of multiple participants, or nodes, that maintain a set of a shared state and modify that state by performing and validating transactions in a peer-to-peer system (Tien Tuan Anh et al., 2017). A transaction is regarded as a process that changes the state of the blockchain. Traditional databases provide adding, deleting, changing and querying of data. In blockchain systems, only adding and querying data is possible, therefore transactions stored on the blockchain become permanent and undeletable.

Three elements make up the core of a blockchain, as displayed in Figure 2.3. These elements are a distributed storage mechanism based on a peer-to-peer network, a time-stamp based chain-block structure, and a consensus mechanism based on decentralized nodes (Yuan & Wang, 2018). These three elements together lead to multiple specific, distinctive characteristics of blockchain technology that redefine how data-management is handled.

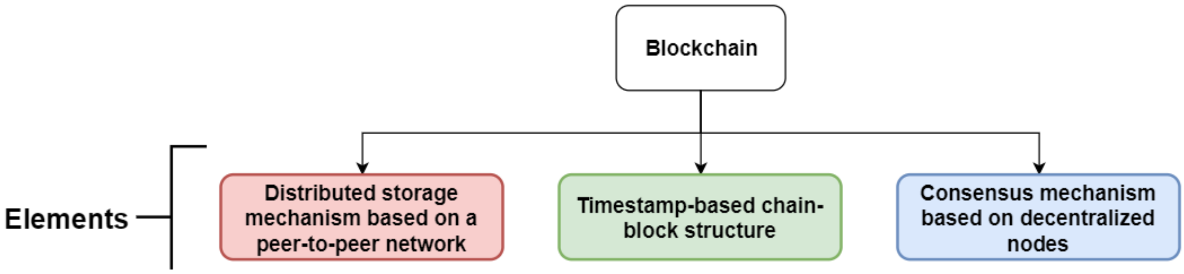


Figure 2.3 Elements of a blockchain

Key characteristics of blockchain technology are; security of the system through cryptographic techniques, immutability of the data once transacted, auditability of transactions and robustness of the system due to its fault-tolerance (Bashir, 2017), (Makhdoom, 2019). All these characteristics combined produces a technology where trust is embedded into the system through use of cryptographical procedures. This enables the opportunity to provide trust-free operations between parties and produces an environment in which the current data-management architecture may evolve. As a result of this secure data-exchange and trustless operations, utilization of blockchain technology provides the opportunity for real-time, cross-enterprise data-exchange.

The use of blockchain technology as a data-infrastructure middleware layer enables real-time communication of sensor-data between an IoT-sensor and an intelligence layer, ensuring the possibility for accurate representation of the current state of the system.

2.3.3 Digital Overview through an Intelligence Layer

In order to produce a Digital Chain, entities within the supply chain need to be connected to each other. If these connections are not present, visibility throughout the supply chain cannot be obtained and further evolvement regarding collaboration becomes difficult.

Data is obtained from individual sensors in the physical space and communicated through blockchain technology in real-time. The data that is obtained by individual, independent sensors can now be retrieved from the blockchain layer and connected to each other. Connecting the data together by an intelligence layer establishes a digital model that represents the physical supply chain. Within this model aspects such as relations, patterns, and flows between different sensors can be derived, and insights regarding SLOTT performance and efficiency of a supply chain become clear. The recognition and understanding of patterns leads to more intelligent and accurate decision-making, resulting in system optimization and a higher level of performance (Tao & Zhang, 2017), (Kuehn, 2019). Note: Utilization of a specific technology or program that acts as the intelligence layer as discussed above is out of scope during this research due to time-restrictions. The combination of a Digital Chain with emerging intelligence technologies such as AI, ML and Big Data is therefore identified as interesting future research, but no further research is conducted during this research.

2.4 Literature Review - Preliminary Concept Design

In general, Digital Chain applications in supply chains are considered as value-adding, decision-making support applications that enable evolvement of supply chain management regarding performance and efficiency (Qiu, Zhou, Liu, Gao, & Tan, 2019). The continuous updating of the as-is state of the supply chain through sensor-data enables frequent synchronization regarding the progress of products throughout the supply chain. Combining the data from different sensors together into a single model to produce a digital overview of the complete supply chain results in better understanding, learning and reasoning of the system's characteristics, providing better insights regarding performance of the system.

The combination of IoT-sensors, blockchain technology and intelligence technologies has the potential to lead to further evolvement of the digitalization trend, since it is able to analyze data from the past and convert it to predict future events. Benefits of such a Digital Chain are the enablement of enhanced; simulation, monitoring, analysis, diagnostics and prediction (Rosen, von Wichert, Lo, & Bettenhausen, 2015), (Zaccaria, Stenfelt, Aslanidou & Kyprianidis, 2018), (Cai, Starly, Cohen, Lee, 2017), (Boschert & Rosen, 2016). The continuous data-updates between the physical and digital space give a Digital Chain an iterative nature, adjusting the model according to the latest updates. Therefore it is able to represent the performance of a supply chain, including; simulation of the behavior of its physical counterpart, monitoring of the ongoing status, diagnosing of patterns, and prediction of future trends (Schleich, Anwer, Mathieu & Wartzack, 2016), (NIC, 2017) (Qi & Tao, 2018), (Angrish et al., 2017). Through utility of a Digital Chain, supply chain decision-making is improved, processes optimization occurs, and aspects such as anticipatory planning and predictive maintenance is enabled (Negri, Fumagalli, Macchi, 2017), (Rosen, von Wichert, Lo & Bettenhausen, 2015). Producing a Digital Chain provides the opportunity for prediction technologies to optimize physical processes, achieve data-driven operation monitoring, diversifying business models and value creation, and develop innovative services (Söderberg, Wärmefjord, Carlson, & Lindkvist, 2017), (Lu & Xu, 2019), (Tao et al., 2018), (Boschert & Rosen, 2016), (Tao, Zhang, Liu & Nee, 2018).

Based on above statements from academics regarding impact of Digital Chains, a preliminary concept design is constructed that includes; the components of a Digital Chain, the role of blockchain technology, advancements regarding insights due to the specific characteristics of a Digital Chain, and impact a Digital

Chain has on supply chains. Figure 2.4 displays this preliminary concept design. This paper focusses on designing a Digital Chain that provides for an environment where supply chain SLOTT performance is improved by reducing dwell-time that occurs in-between processes of different entities. In order to achieve this goal, the advancement regarding predictions is further explored by designing a Digital Chain that allows for upfront forecasting on future arrival times of goods at a specific location.

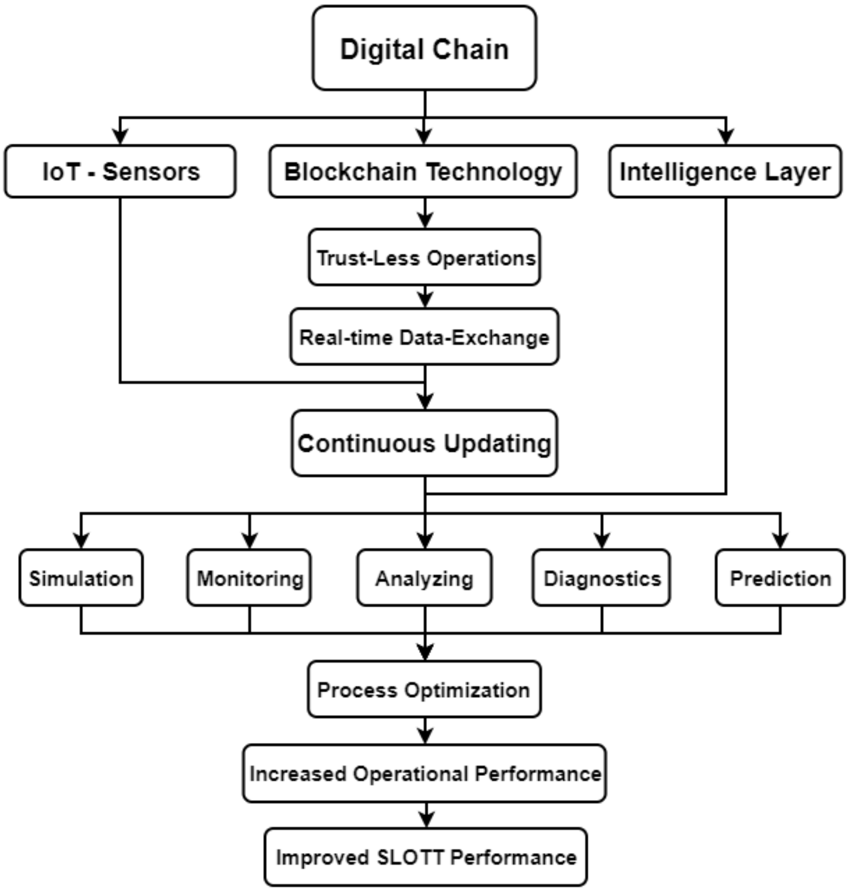


Figure 2.4 Preliminary concept design of a Digital Chain, including its main components, characteristics and impact on supply chains

3 Analysis & Design

The preliminary concept design provides a foundation on which the next steps towards supply chain SLOTT performance optimization may be built. When a Digital Chain is able to receive continuous data-driven updates in real-time on the current state of the supply chain, it is able connect the data from individual sensors and compare it to historical performance. The result of this comparison provides the opportunity to produce forecasts regarding future arrival times of incoming load at a certain location. As the state of the system is continuously updated, it becomes possible to achieve iterative forecasting of incoming load, as the latest forecast is updated with every new incoming transaction. These continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. When entities are prepared, transition phases between processes become more fluent and swift. Dwell-time is diminished and therefore the SLOTT performance of a supply chain improves. The following chapter displays the design requirements necessary to produce a Digital Chain that is able to create forecasts based on real-time information provided by RFID-sensors, in order to improve on SLOTT performance. During this chapter also the results of a current-state performance analysis of a case-study are shown to provide evidence that undesired dwell-time is indeed present in current supply chains.

3.1 What are the design requirements for a Digital Chain?

The goal of the Digital Chain is to provide an environment where SLOTT performance is improved by reducing dwell-time that occurs in-between processes. In order to achieve this goal, specific design requirements for a Digital Chain design are composed to enable upfront forecasting on future arrival times of goods in actual supply chains. Three major design requirements are briefly explained:

- Use of IoT sensors is required to provide visibility of the flow of goods throughout the supply chain

In order to enable reduction of dwell-time that is present in-between processes, first the existing processes need to be identified and understood. If it is unclear which processes are present within the supply chain, as well as the sequential order of goods passing through these processes, it is not possible to determine if and where dwell-time occurs. A Digital Chain therefore requires the presence of stationary, strategically placed sensors throughout the supply chain, in order to both visualize the flow of goods and divide the supply chain into multiple sections. Regarding the type of IoT-sensors, AUTOID technology is currently the go-to technology to produce visibility, as they provide for both identification of individual products and precise moment of detection. Figure 3.4 displays a generic overview of a supply chain that consists of multiple entities, spread across 'N' locations. Since the entities are located at a certain distance from each other, also transport is present between two locations. The vertical, colored, dotted lines in Figure 3.4 at each location show the moments of detection of that particular entity. During this paper, the supply chain as displayed in Figure 3.4 is used as an example of a generic supply chain.

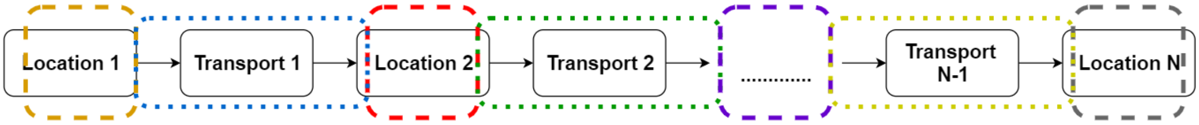


Figure 3.4 Generic overview of a supply chain, including detection points (vertical lines)

- Performance is based on time spend in the supply chain, therefore measurements with regards to time are required

During this research, SLOTT performance is purely based on the amount of time goods spend in the supply chain. The shorter the amount of time goods spend in a supply chain, while processes remain equal, the higher the performance and more efficient a supply chain is. In order to determine the time goods spend in the supply chain, measurements with regards to time need to be performed on multiple checkpoints throughout the supply chain. Through utility of these checkpoints, insights are gained on both performance of individual parts of the supply chain and potential bottlenecks.

- Data acquired by individual sensors is send to an intelligence layer in order to connect data from multiple sensors together and display SLOTT performance of specific parts of the supply chain, as well as the complete the supply chain.

In order to reduce dwell-time that is present in-between processes within the supply chain, first the performance of different parts of the supply chain need to be obtained. This comes down to acquiring data regarding throughput time of different processes or sections by connecting the data from all individual sensors into a single digital overview. This digital overview is created through utilization of an intelligence layer. This intelligence layer is of key importance, as it provides for visibility of the flow of goods and enables for calculation of supply chain SLOTT performance and efficiency.

One of the key features during this research is the design of an Efficiency and Performance Analysis Tool (EPAT) that acts as an intelligence layer. This EPAT is of significant importance during analysis of performance of a supply chain, as it provides for measuring of the SLOTT performance. The goal of the EPAT is to easily display the performance of the flow of specific goods, based on time, in which also possible bottlenecks become visible. The EPAT serves as a data-analysis tool that provides insight in the duration of the flow of goods throughout the supply chain, by transforming the design requirements into measurable Key Performance Indicators (KPIs). Note that an EPAT is specific for a particular supply chain.

From the design requirements the following KPIs were constructed:

- Actual performance of the individual entities of the supply chain, based on time [h];

Performance of internal process of individual entity: $(t_{Location\ i\ OUT}$ - $t_{Location\ i\ IN})$, i≥ 1
Performance of cross-enterprise transition process: $(t_{Location\ i\ IN})$ - $(t_{Location\ i-1\ IN})$, i≥ 2

- Actual performance of the complete supply chain, based on time [h];

$$\sum_{i=1}^{N}(t_{Location\ i\ OUT} - t_{Location\ i\ IN}) + \sum_{i=2}^{N}(t_{Location\ i\ IN} - t_{Location\ i-1\ OUT}) \quad , N \geq 2, i \geq 1$$

- SLOTT Efficiency of the complete supply chain, compared to current service-levels [%];

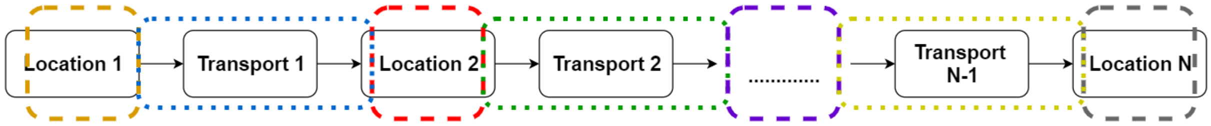
$$\frac{\Delta t_{Total\_percentileX}}{\Delta t_{Service\text{-}level}} \text{ X } 100$$

3.2 Current-State Performance through EPAT

In order to display the impact of utilization of a Digital Chain, future-state performance should be compared to current-state performance. In order to facilitate this comparison, the following research question is answered; ‘Wat is the current-state performance, through use of a case-study?’. During this current-state performance analysis the KPIs of the current-state are calculated based on historical data from RFID-sensors that are already installed at the facilities of the case-study. In order to calculate the KPI’s an EPAT is designed, that acts as an intelligence layer, in order to transform raw sensor-data into a digital overview of the SLOTT performance of the supply chain.

Table 3.1 below shows the results of the EPAT of the current state for a particular sub-flow of the analyzed supply chain during the case-study. Table 3.1 displays the participants, the sequential order, the duration at each entity, the total duration time and the efficiency compared to the current service-level of 240 hours. This 240 hours service-level is considered the benchmark of efficiency of the supply chain, and both current- and future-state results are compared to the service-level in order to obtain their efficiency.

Table 3.1 Display of the KPI of Flow 1, Location 1→Location 2 → Location 3



Percentile #:	TD (h)					Total time [h]	Efficiency* [%]
	Location 1	Location 1→ Location 2	Location 2	Location 2 → Location 3	Location 3		
Median	16	15	45	21	59	155	155
75th	29	17	78	43	87	255	94

* Efficiency is relative to a Service-Level of 240 [h], which is 100%

Table 3.1 shows that the results are divided into percentiles; the value of a percentile displays the percentage of tags of which the maximum time spend in the supply chain is equal to this value. In order to determine an ‘average’ throughput time of products passing through the supply chain, establishing a baseline value is necessary. The median-value results have been verified as a suitable baseline through an expert-analysis conducted by operators of the enterprise behind the analyzed supply chain. Through numerical verification it became clear that the EPAT is only able to represent reality till a certain upper-limit (due to the summation of multiple percentile values); the upper-bound results display the most undesirable measured outcome. For this example, the upper-bound value of the EPAT is found at the 75th percentile.

Table 3.2 shows the current-state results of the EPAT for all eight of the analyzed sub-flows of the case-study. The results of each sub-flow are depicted within one column. For example, Flow 1 with final destination Location 3 has a median value of 155 hours, a 55th percentile value of 172 hours, … and an upper-bound percentile at the 75th percentile with a value of 255 hours. If the total duration time of a percentile of a specific sub-flow is below the current service-level objective of 240 hours the background of the cell is green, if it exceeds 240 hours its’ background is red.

Table 3.2 displays that for the median value of most of the sub-flows, the required service-level is reached. However, looking at the upper-bound performance of these flows paints a different picture; none of the upper-bound values is able to reach the requested service-level. From the results of the current-state performance the following conclusion is derived: Since the processes are equal for both the median and upper-bound value of a sub-flow, but their performance differs significantly, it is concluded that dwell-time is present during the processes. This dwell-time causes a decrease in SLOTT performance of the supply chain, which results in the inability for the upper-bound values to meet the service-level requirements for all analyzed sub-flows.

Table 3.2 Overview of the performance of all sub-flows, divided into percentiles, including comparison towards required service-level

		Flow 1					**Flow 2**			
		3	**4.2**	**4.3**	**4.4**		**4.1**	**4.2**	**4.3**	**4.4**
Percentile #:		**Duration [h]**					**Duration [h]**			
Median		155	382	195	202		198	154	218	155
55th		172	512	201	332		217	193	232	167
60th		188	651	212	371		235	215	243	205
65th		202	1006	347	385		258	228	260	232
70th		225	1123	426	417		279	249	274	247
75th		255	1311	449	469			261		
80th			1695	474	642			273		
85th			2124	515	868					
90th										
95th										
100th										

3.3 Future-State Digital Chain Design

During this section of the paper, the following research sub-question is answered: What should a Digital Chain design, that combines IoT-sensors and blockchain technology, look like? In order to ensure that the service-level requirements are met, dwell-time between entities needs to be diminished. This chapter covers the future-state design of a Digital Chain that combines blockchain technology, IoT-sensor technology and the EPAT as an intelligence layer. This design is intended to provide real-time visibility and data-exchange with regards to the whereabouts of goods within a supply chain, in order to enable forecasting of future arrival times of these goods to prevent the occurrence of dwell-time. This chapter covers the translation from advantages and impact of Digital Chains in theory into a design that may be used in actual industries in the near future. During this chapter, the philosophy of Digital Chains is translated into a future-state design that includes the required steps necessary to make it tangible and applicable for real-life cases. The future-state Digital Chain design is displayed in Figure 3.5. Paragraph 3.3.1 explains this module design to more extend.

Time-limitations of this research however did not allow for an in-depth design that works out every detail of all components present, for example use of specific programs to connect all aspects together to ensure automation. Therefore it has not been possible to produce a complete Digital Chain, but only certain components. Aspects that are included within the Digital Chain future-state design, but that are not covered to full extend during this research, are either based on knowledge obtained from literature or derived from current existing implementations of that particular technology.

3.3.1 Module Design

As displayed in Figure 3.5, products with RFID tags attached to them move through the supply chain, and in doing so they pass stationary, strategically placed RFID-sensors. When a tag is in detection range of a sensor, the data from this tag is read and send to the Local Data-Management Layer. The device that is part of the Local Data-Management Layer consists of hardware and software, is connected to the internet and possesses processing power/ is able to perform (moderate) operations on its own. During installation of this device two main aspects need to be addressed; the hardware set-up and the software set-up. The hardware set-up consist of the technical set-up with regards to antenna placement and locations, and of configuration and optimization of the RFID hardware. During the technical set-up aspects such as determining the detection range, avoidance of possible signal-jammers and the physical installation are addressed. During configuration and optimization processes the hardware is tuned and tweaked until optimal performance is achieved.

During the software set-up of the system the base for enabling data-management through the use of blockchain technology is provided. The first steps of the software set-up are the creation of a blockchain address, and the integration and connection of the device with a blockchain through use of an API. Note that the middleware device will most likely be a simple node, which means that it is able to send and receive transactions, but it does not store a copy of the blockchain and does not participate in the consensus mechanism of the blockchain. The creation of the blockchain address will most likely occur before the device is physically installed, as the address needs to be known by the Global Data-Management Layer operator in order to connect a blockchain address to a specific RFID detection device and therefore location. Due to the cryptographic characteristics of blockchain technology, addresses are created pseudonymously, which means that is difficult to obtain the identity behind an address if it is not known beforehand.

The code required to connect and integrate the software from the device itself with the blockchain API is also generated upfront. There are two ways the required code may be integrated on a Device Management Layer; locally on the device itself or through connection with a third party over the internet. Connecting the device with a controlling party over the internet is preferred in this situation, since it provides the opportunity to implement changes and updates without a need for being physically present

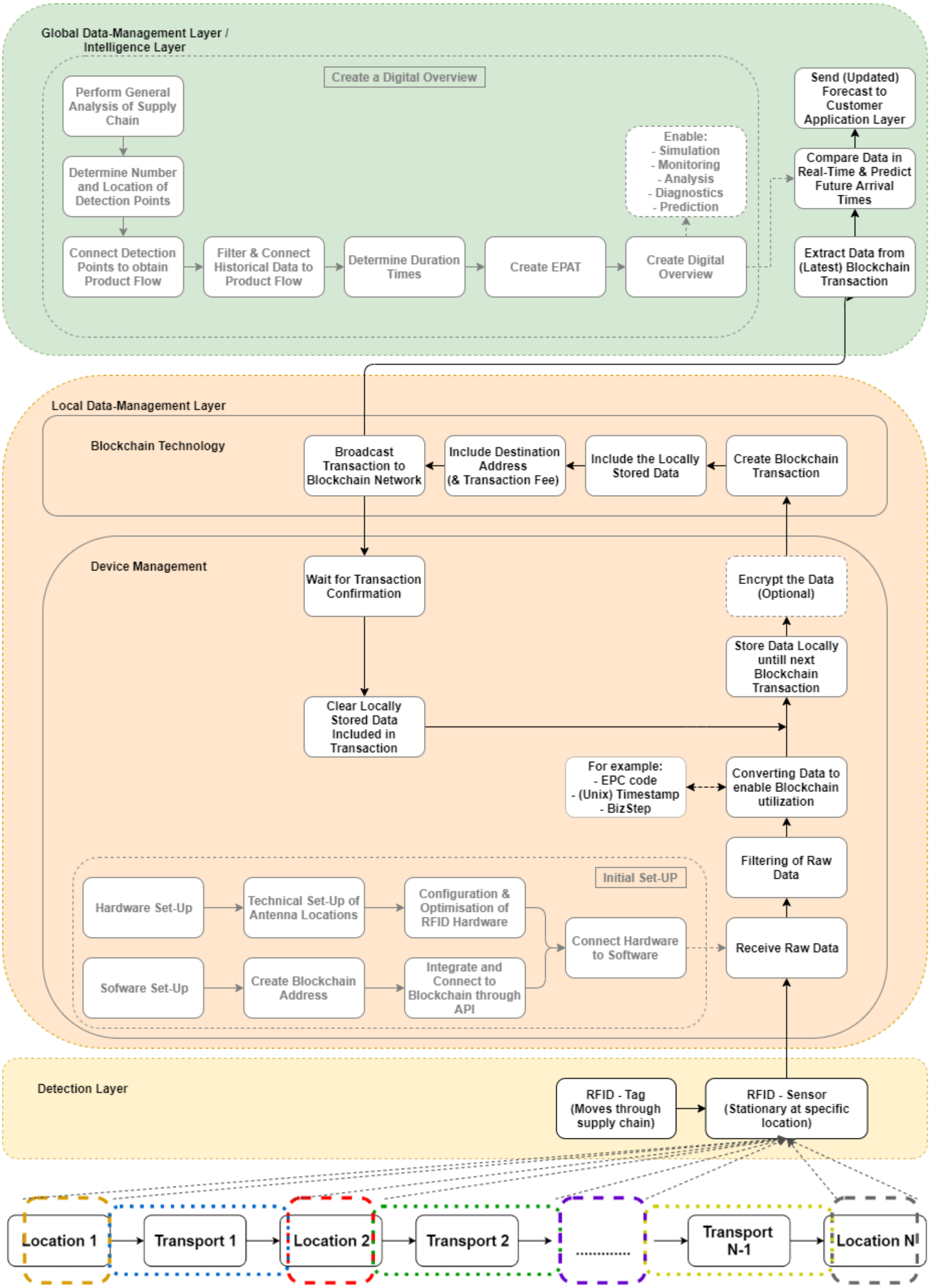


Figure 3.5 Module design of a future-state model of a Digital Chain

at the device. As entities within a supply chain may be spread across the world, this may reduce the time needed to update the system drastically. Also new addresses may be generated after the passing of a certain predetermined period of time, increasing the difficulty of connecting the address to an entity and therefore improving on privacy. When an address is linked to a company, competitors might benefit from this information. In order to avoid this linking of addresses to companies, blockchain addresses should be changed on a regular basis.

Once the initial set-up is completed, raw data can now be processed. During Device Management, the first processing steps with regards to filtering and handling of the data are executed. First, raw data is received from the RFID sensor. After receival, first the data is filtered and/ or events are constructed in order to remove unwanted and unnecessary information. RFID-sensors are able to send and receive multiple signals per second, however not all these signals are useful for further processing. For example, if a tag passes a sensor when passing through a docking-door during inbound operations, it could be detected over a dozen times within a second. In order to reduce the amount of data that needs to be send, the middleware application only keeps the data from the first signal, all other signals belonging to one particular tag are removed. The data that remains is now transformed to ensure that it can be send via a blockchain transaction. The information that is required depends on the specific application, during this research the aspects that were of importance are the Electronic Product Code (EPC), the UNIX timestamp and the BizStep of a tag. The EPC of a RFID tag acts as a identifier for that specific tag, ensuring that each RFID tag has an unique identity and is therefore individually recognizable (Tutorialspoint, 2020). A UNIX timestamp the result of converting the date and time of detection into a single number; the UNIX timestamp of a particular date and time is calculated as the number of seconds that have passed since the UNIX Epoch, which is January 1st 1970 00:00:00 (Unixtimestamp, 2020). The BizStep of a tag displays whether it is the first time a tag is detected by a certain IoT-sensor (BizStep = Entering), or the last time a tag is detected by a certain IoT-sensor (BizStep = Exiting). It is important that these three aspects are converted consistently, in order to ensure usability in downstream processing steps. The result of the conversion could have a structure that resembles a CSV file. In this design, the data would be structured in the following way:

- EPC code ; UNIX Timestamp ; BizStep= Entering

After conversion of the data, it is stored locally on the device until it is included in the next blockchain transaction. It is likely that more than one tag is detected during the period of time between transactions. So eventually, a list of tag-data is produced that might look like the following:

- EPC code1 ; UNIX Timestamp ; BizStep= Entering
- EPC code2 ; UNIX Timestamp ; BizStep= Entering
- …
- EPC codeN ; UNIX Timestamp ; BizStep= Entering

Optionally this data can be encrypted to ensure no-one except those entitled are able to obtain the original data. When using a permissioned blockchain, access to data could be authorized upfront, while encrypting the data in permissionless blockchains provides an extra layer of privacy. Once the predetermined time-period has passed, a new blockchain transaction is generated. The locally stored data is included within the transaction, and after adding the destination address and including the required fee (when making use of permissionless blockchains) the transaction is broadcasted to the network. Within the Local Data-Management Layer, a couple of actions remain to finish the cycle. The device waits until the transaction is confirmed, after which it removes the data that was included in the blockchain transaction from the locally stored data. A new list is generated and the Local Data-Management cycle repeats itself. The data that is included into a confirmed blockchain transaction is now available for use in the Global Data-Management Layer.

During the processes of the Global Data-Management Layer, data from a multitude of Local Data-Management Layers is combined and connected, in order to produce a Digital Chain of the supply chain that is able to increase the level of intelligence to the system. Note that the intelligence layer of a Digital Chain is similar to the EPAT, as designed during the case-study. Producing a Digital Chain starts with performing a general analysis of the supply chain. During this general analysis, different participants are identified, the processes each entity executes are understood and the flow of goods becomes clear. By determining the number of detection points present in the system, alongside aspects such as obtaining their location and understanding to which sequential process-step they belong, insights are obtained regarding the product flow. Connecting these detection points together enables the possibility to simulate the product flow. Filtering-out data that does not match the product flow, in combination with connecting historical data to the model, enables monitoring and analysis of the performance of the supply chain. Connecting the data together provides the opportunity to determine the duration times of different processes and process-steps. At this point a digital overview of the system is produced, based on historical data, that is able to simulate and monitor the processes within the supply chain. It also enables analysis of the performance of the data, provides the opportunity to identify possible bottlenecks through diagnostics, and is able to make predictions regarding performance based on historical performance.

When data is extracted from the blockchain layer, it consists of just tag information, a timestamp and a BizStep. Through the use of the blockchain address it is send from, this loose data can be connected to a specific readpoint, linking the data to a specific point in the product flow. This data can now be converted and connected to the known product flow of the supply chain. The data from the blockchain transaction can now be compared to the historical results of the Digital Chain. In order to predict the future arrival times of tags at specific locations, forecasts regarding which products are to be expected where and at what time, are now constructed. Since blockchain transactions occur every pre-determined period of time, the forecast is updated with every incoming transaction.

3.4 Numerical Estimation Impact Digital Chain

During this section, the following research sub-question is answered: ‘What is the impact of the design when applied to the case-study?’. As mentioned before, during this research a complete Digital Chain was not constructed. Therefore the future-state design remains mostly qualitative and impact remains theoretical. However, a numerical estimation of the effect of a Digital Chain that is able to diminish dwell-time is possible through scenario-testing of the results of the EPAT of the case-study. Table 3.2 displays the results of both the current-state analysis and expected future-state performance. The bottom part of Table 3.2 shows the results of all analyzed sub-flows of the case-study when dwell-times are diminished between the median value and the upper bound value, including a safety-level of 1.5 in order to accommodate for hurdles that are present during implementation in actual supply chains.

Table 3.2 Overview of both the current-state and future-state performance of all sub-flows, divided into percentiles, including comparison towards required service-level

Current-State										
		Flow 1					**Flow 2**			
		3	**4.2**	**4.3**	**4.4**		**4.1**	**4.2**	**4.3**	**4.4**
Percentile #:		**Duration [h]**					**Duration [h]**			
Median		155	382	195	202		198	154	218	155
55th		172	512	201	332		217	193	232	167
60th		188	651	212	371		235	215	243	205
65th		202	1006	347	385		258	228	260	232
70th		225	1123	426	417		279	249	274	247
75th		255	1311	449	469			261		
80th			1695	474	642			273		
85th			2124	515	868					
90th										
Future-State										
		Flow 1					**Flow 2**			
		3	**4.2**	**4.3**	**4.4**		**4.1**	**4.2**	**4.3**	**4.4**
Percentile #:		**Duration [h]**					**Duration [h]**			
Median		155	382	195	202		198	154	218	155
55th		161	426	197	246		204	167	223	159
60th		166	472	201	259		211	174	226	172
65th		171	590	246	263		218	179	232	181
70th		179	629	272	274		225	186	236	185
75th		189	692	280	291			189		
80th			820	288	349			194		
85th			963	302	424					
90th										
		Max. Upper-bound Improvement [h] & [%]								
		66	1161	213	444		54	79	38	62
		26%	55%	41%	51%		19%	29%	14%	25%

From Table 3.2 it becomes clear that reduced dwell-times have a positive effect on supply chain SLOTT performance. From the current-state performance it becomes clear that none of the eight sub-flows is able to meet its service-level for the upper-bound values. However, from the results of the future-state performance calculations it becomes clear that five out of the eight sub-flows are able to meet the required service-level for the complete range of goods passing through the supply chain when they are able to diminish dwell-time. The results of this current-state / future-state comparison display that elimination of dwell-time may lead to significant improvement with regards to supply chain SLOTT performance. These results indicate that further research towards design of actual Digital Chains could lead to further evolvement of supply chain performance.

4 Discussion

4.1 Qualitative Impact Digital Chain

The future-state module design displays that once a Digital Chain of a supply chain is produced, through enhancements in simulation, analysis, and diagnostics of the system, insights are obtained with regards to performance and bottlenecks. The Digital Chain design provides the opportunity to compare new data to historical performance data in real-time, to predict when products will arrive at a certain location. Through continuous updates from the IoT-sensors, the current state of the system is constantly being updated, and alongside it the forecast regarding future arrival times. Every time a transaction occurs on the blockchain, the intelligence layer derives this data and compares it to historical values in order to provide predictions. The continuous updates of the state of the system enable the possibility to provide iterative forecasting of incoming load, as the latest forecast is updated with every new blockchain transaction.

The continuously updated forecasts ensure that future arrival times are predicted upfront, providing downstream entities of the supply chain with the possibility to prepare themselves with regards to future incoming load. For example, sufficient handling capacity to accommodate proper handling of goods can be assigned upfront, which leads to fluent and swift transitions between processes, resulting in process optimization across the supply chain. An important aspect of this process optimization is diminished dwell-time of goods passing through the supply chain, which results in increased operational performance and therefore improved SLOTT performance of the supply chain. Figure 4.1 builds upon the preliminary concept design, which was produced by combining statements from academics, and provides a global overview of the characteristics of a Digital Chain and its’ impact on supply chains.

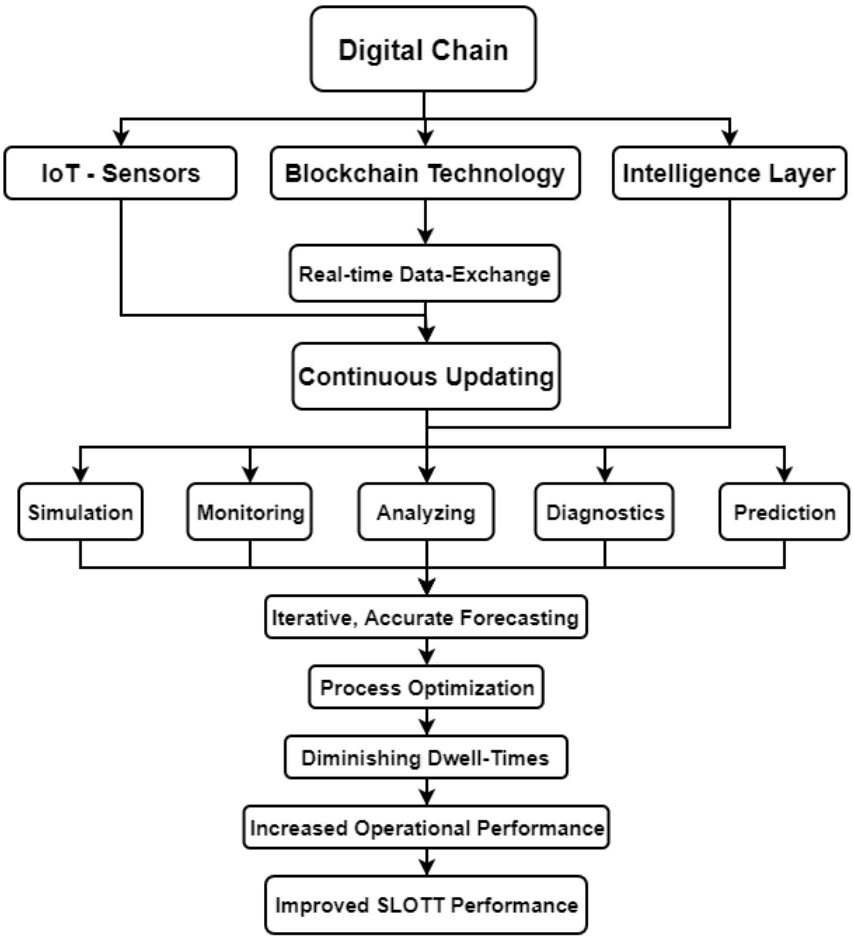


Figure 4.1 Global overview of the characteristics of a Digital Chain and its’ impact on supply chains

4.2 Quantitative Impact Digital Chain

The results of the EPAT show that most benefits regarding Digital Chains mentioned in theory are similar to those in practice. The RFID infrastructure as present during the case-study provides sufficient, useful data to create a digital overview of the supply chain. Before this analysis, only part of the functionality of the RFID infrastructure was used by the participants of the analyzed supply chain. Each entity within the supply chain used, and had access to, only the data that was of concern to them. Little information is shared between entities, and each participant focuses on complying with their own contractual agreements instead of on aspects that cover the complete supply chain. During analysis of the case-study, access to the data of multiple entities was obtained, and by connecting the data from numerous sensors to each other an EPAT of the supply chain could be created, to increase the visibility of the flow of goods and create a digital overview of the SLOTT performance of the entire supply chain.

The EPAT enables more insight into the overall performance of the supply chain and is able to identify if and where possible improvements might be possible within specific parts of the supply chain. The EPAT also shows that the throughput time of products per entity differs significantly between the central tendency and the upper bound values, which results in a decrease in SLOTT performance of the system. From the comparison between current-state and future-state SLOTT performance it became clear that utilization of a Digital Chain has a positive effect on supply chain performance. From the current-state performance analysis it became clear that none of the eight sub-flows are able to meet its service-level objective for the upper-bound values. However, from the results of the future-state performance calculations it becomes clear that, due to diminished dwell-time, SLOTT performance of this particular supply chain improves between 14-55% compared to the current-state, depending on the sub-flow. As a result, five out of the eight sub-flows of the future-state supply chain are able to meet the required service-level for the complete range of goods, within the boundaries of the EPAT, passing through the supply chain. To compare, during current-state performance none of the sub-flows are able to meet the required service-level for the complete range of goods.

5 Conclusion & Recommendations

This research focused on obtaining an answer to the following research question; ‘What are the design characteristics to develop a Digital Chain, based on combining IoT-sensors with blockchain technology, to improve supply chain SLOTT performance?’. This paper demonstrates that a Digital Chain-solution should be considered as an interesting proposition to improve supply chain Service-Level Objectives regarding Throughput Times (SLOTT) performance in the near future due to the advancements regarding visibility and business intelligence it accompanies. The combination of IoT-sensors, blockchain technology, and an intelligence layer enables the design of a Digital Chain that provides for accurate, iterative forecasting of future arrival times of incoming load in supply chains. If a Digital Chain is able to receive continuous data-driven updates on the actual state of the supply chain in real-time, it is able to connect the data from individual sensors and produce forecasts regarding future arrival times of incoming load. The continuous updates, facilitated by data-collection through IoT-sensors and real-time data-exchange through utilization of blockchain technology, enable the ability to adjust a forecast if unforeseen delays occur during a process. These iterative forecasts provide participants of the supply chain with visibility on the whereabouts of products and enables the opportunity to prepare themselves upfront with regards to future incoming load, thereby facilitating for proper and swift transitioning and processing of goods. The insights gained in the performance of different entities, together with the ability to prepare upfront, are expected to result in a reduction of dwell-time of products, and therefore improves upon supply chain SLOTT performance. However, more research towards Digital Chain applications is necessary to provide a definitive answer on what the actual impact of Digital Chains on supply chain performance will be.

This paper presents a future-state Digital Chain design that is based on the combination of RFID-sensors, blockchain technology, and an intelligence layer. The future-state module design displays all steps required to turn raw data of numerous RFID-sensors into a forecast that predicts future arrival times of goods within a supply chain. However, a complete, fully functioning Digital Chain was not constructed during this research, as not all individual aspects from the future-state module design have been connected to each other due to time-limitations. Therefore the proposed future-state design remains overall qualitative and more research towards the construction of Digital Chains in actual supply chains is required to provide quantitative insights regarding the impact of Digital Chains on SLOTT performance in supply chains.

In order to also provide quantitative analysis of SLOTT performance during this research, an Efficiency and Performance Analysis Tool (EPAT) was designed for a specific case-study, which consists of eight different sub-flows. This EPAT acts as an intelligence layer that produces a digital overview of the supply chain and provides insights regarding the presence and impact of dwell-time on performance. Through use of the EPAT, aspects such as identification of bottlenecks, visibility of individual and supply chain-wide SLOTT performance, and prediction of duration were enabled. Data-analysis based on the results of the EPAT provided a current-state performance analysis which showed that dwell-time is indeed present and negatively impacts SLOTT performance. The design of the EPAT also allowed, through scenario-testing, for a numerical estimation on the impact of Digital Chains on SLOTT performance when they are able to diminish dwell-time in supply chains. Therefore it was possible to produce a current-state / future-state comparison, to highlight the differences in SLOTT performance of the supply chain. From the comparison between current-state and future-state performance it became clear that the reduction of dwell-time is able to improve the SLOTT performance of this particular supply chain between 14-55%, depending on the sub-flow. This performance improvement ensures that five out of eight sub-flows are able to meet the service-level requirements for the complete range of tags, within the boundaries of the EPAT, instead of none of the sub-flows in the current-state.

In order to understand the true potential of Digital Chains, the author recommends further research on various aspects concerning designing Digital Chains. In general, currently little research is conducted on the application of Digital Chains in actual supply chains. More research towards applications of DT technology in supply chains is requested to better understand the actual impact Digital Chains might have on processes, decision-making and performance, but also on the issues that present themselves alongside the transition towards utilization of Digital Chains. Secondly, more research is also requested regarding the combination of the different technologies required to construct a Digital Chain. During this paper the steps necessary to transform raw data into forecasts are displayed, however the software required to combine RFID-technology and blockchain technology is currently missing. Likewise, the combination of the intelligence layer with data-driven 'intelligence' technologies such as Artificial Intelligence and Machine Learning should be researched to more extend in order to achieve forecast optimization and aspects focused on providing an additional level of control, such as the enablement of dynamic asset and resource allocation based on the provided forecasts.

The last topic of recommendations regarding future research covers the results of the business-case. From the results of the EPAT it became clear that two types of improvements are present that would positively influence SLOTT performance of the supply chain; performance of internal processes of individual entities and overall efficiency of the complete supply chain. This research has focused on the overall SLOTT performance of the supply chain, however the design of the EPAT also provides the ability to focus on the performance of individual processes and/or entities. Conducting specific research on the internal processes of entities, such as in-depth analysis of the process-steps and performance as present within each entity, could lead to the identification and resolving of bottlenecks during the internal processes, leading to a higher level of performance.

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