A Cost-Benefit Analysis of Blockchain versus Relational Databases for Digitalising and Automating Information Flows in Cross-Border Supply Chains

by

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Thesis presented in partial fulfilment of the requirements for the degree of
Master of Engineering (Engineering Management)
in the Faculty of Engineering at Stellenbosch University
This thesis has also been presented at Reutlingen University in terms
of a double-degree agreement.

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December 2022

Declaration

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Abstract

Global trade is plagued by slow and inefficient manual processes associated with physical documents. Firms are constantly looking for new ways to improve transparency and increase the resilience of their supply chains. This can be solved by the digitalisation of supply chains and the automation of document- and information-sharing processes. Blockchain is touted as a solution to these issues due to its unique combination of features, such as immutability, decentralisation and transparency. Unfortunately, a lack of business cases that quantify the costs and benefits causes uncertainty as to the truth of these claims. This thesis explores how the costs and benefits of a blockchain-based solution for digitalising and automating documentation flows in cross-border supply chains compare to a conventional centralised relational database solution.

A literature review was performed on relevant topics and a case study with semi-structured interviews in a complex cross-border supply chain was carried out to collect data for this research. The data was used to construct two conceptual models that represent alternative solutions for digitising information flows in cross-border supply chains – one based on relational databases and one based on blockchains. An analysis was performed to compare the two models to see which is the better solution. The analysis is in the form of a cost-benefit analysis and was split into a financial and non-financial part. The non-financial analysis used the Architecture Trade-off Analysis Method, as well as the Analytical Network Process method – two scientific methods for making complex multi-criteria decisions. Industry experts validated the analysis to ensure that results that are representative of global supply chains in general are obtained.

Both the financial and non-financial analysis led to more favourable results towards blockchains. It shows lower financial costs, larger financial benefits and a slightly greater utility for the solution's purpose when compared to relational databases. Taking the literature, interviews and analysis into account, a conclusion was made. A more decentralised blockchain-based solution is the preferred solution for addressing the issues of slow and inefficient document-sharing processes in cross-border supply chains when compared to conventional centralised solutions based on relational databases. Although blockchain is still an emerging technology with limitations and challenges, it is already beginning to show its potential in supply chains, with even more room for growing in the future.

Uittreksel

Wêreldhandel word geteister deur stadige en ondoeltreffende handmatige prosesse wat met fisiese dokumente assosieer word. Firmas is voortdurend opsoek na nuwe maniere om deursigtigheid te verbeter en die veerkragtigheid van hul voorsieningskettings te verhoog. Dit kan opgelos word deur die digitalisering van voorsieningskettings en die outomatisering van prosesse wat die vloei van dokumente en inligting fasiliteer. Blokkettings is 'n moontlike oplossing vir hierdie kwessies as gevolg van die tegnologie se unieke kombinasie van kenmerke, soos onveranderlikheid, desentralisering en deursigtigheid. Ongelukkig veroorsaak 'n gebrek aan besigheidsake wat die koste en voordele kwantifiseer onsekerheid oor die waarheid van hierdie eise. Hierdie tesis ondersoek hoe die kostes en voordele van 'n blockchain-gebaseerde oplossing vir die digitalisering en outomatisering van dokumentasievloeie in globale voorsieningskettings vergelyk met 'n konvensionele gesentraliseerde relasionele databasisoplossing.

'n Literatuurstudie is uitgevoer oor relevante onderwerpe en 'n gevallestudie met semi-gestruktureerde onderhoude in 'n komplekse globale voorsieningsketting is uitgevoer om data vir hierdie navorsing in te samel. Die data is gebruik om twee konseptuele modelle te ontwikkel wat alternatiewe oplossings vir die digitalisering van inligtingvloei in oorgrensende voorsieningskettings verteenwoordig – een gebaseer op relasionele databasisse en een gebaseer op blokkettings. 'n Ontleding is uitgevoer om die twee modelle te vergelyk om te sien watter oplossing die beste is. Die ontleding is in die vorm van 'n koste-voordeel-analise en is in finansiële en nie-finansiële dele verdeel. Die nie-finansiële analise het die Architecture Trade-off Analysis metode gebruik, sowel as die Analytic Network Process – twee wetenskaplike metodes om komplekse multikriteria-besluite te neem. Bedryfskundiges het die ontleding bekragtig om te verseker dat resultate verkry word wat verteenwoordigend van globale voorsieningskettings oor die algemeen is.

Beide die finansiële en nie-finansiële ontleding het gelei tot gunstige resultate teenoor blokkettings. Dit toon laer finansiële kostes, groter finansiële voordele en 'n effens groter nut vir die oplossing se doel in vergelyking met relasionele databasisse. 'n Gevolgtrekking is gemaak gebaseer op die literatuur, onderhoude en ontleding. In vergelyking met konvensionele gesentraliseerde oplossings gebaseer op relasionele databasisse, is 'n meer gedesentraliseerde blokketting-gebaseerde oplossing 'n beter oplossing om die kwessies van stadige en ondoeltreffende dokumentdelingprosesse in globale voorsieningskettings aan te spreek. Alhoewel blokkettings steeds 'n opkomende tegnologie met beperkings en uitdagings is, begin dit reeds potensiaal in voorsieningskettings te wys, met selfs meer ruimte vir groei in die toekoms.

Acknowledgements

The author wishes to acknowledge the following people for their various contributions towards the completion of this work:

- to Professor Louis Louw, supervisor at Stellenbosch University, for the continuous guidance and advice,
- to Professor Daniel Palm, co-supervisor at Reutlingen University ESB Business School, and Professor Vera Hummel for the amazing DIME programme and the semester in Germany,
- to Mr. Jörg Bauer for all the admin-related support in Germany,
- and finally to my parents for their continued support and motivation of studying towards a master's degree.

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List of Acronyms

3PL: Third-Party Logistics

4IR: Fourth Industrial Revolution

AES: Advanced Encryption Standard

AHP: Analytic Hierarchy Process

AI: Artificial Intelligence

ANP: Analytic Network Process

AR: Augmented Reality

API: Application Programming Interface

ATAM: Architecture Trade-off Analysis Method

AWS: Amazon Web Services

AZ: Availability Zone

B2B: Business-To-Business

BFT: Byzantine Fault Tolerance

BoL: Bill of Lading

CAD: Computer-Aided Design

CBA: Cost-Benefit Analysis

CBR: Cost-Benefit Ratio

CCM: Cloud Controls Matrix

CGA: Citrus Growers Association

CLI: Command-Line Interface

CMK: Customer Master Key

COO: Chief Operating Officer

COVID-19: Coronavirus Disease

CPS: Cyber-Physical System

CPU: Central Processing Unit

CSA: Cloud Security Alliance

CSV: Comma Separated Values

DAG: Directed Acyclic Graph

DALRRD: Department of Agriculture, Land Reform and Rural Development

DAFF: Department of Agriculture, Forestry and Fisheries

DBaaS: Database-as-a-Service

DBMS: Database Management System

DHT: Distributed Hash Table

DLT: Distributed Ledger Technology

EDI: Electronic Data Interchange

ERP: Enterprise Resource Planning

ETA: Estimated Time of Arrival

EU: European Union

FBA: Federated Byzantine Agreement

GDP: Gross Domestic Product

GDPR: General Data Protection Regulation

GPS: Global Positioning System

GSBN: Global Shipping Business Network

GUI: Graphical User Interface

HA: High Availability

HTTPS: Hypertext Transfer Protocol Secure

IaaS: Infrastructure-as-a-Service

IAM: Identity and Access Management

IBM: International Business Machines

ICT: Information and Communication Technology

ID: Identity

I/O: Input/Output

IoT: Internet of Things

IP: Intellectual Property

IEC: International Electrotechnical Commission

IPFS: Interplanetary File System

ISO: Internation Organization for Standardization

IT: Information Technology

JSON: JavaScript Object Notation

KMS: Key Management Service

MERS: Middle Eastern Respiratory Syndrome

MFA: Multi-Factor Authentication

NFC: Near Field Communication

NPV: Net Present Value

OS: Operating System

OT: Operational Technology

P2P: Peer-To-Peer

PaaS: Platform-as-a-Service

PBFT: Practical Byzantine Fault Tolerance

PDF: Portable Document Format

PLC: Programmable Logic Controller

POC: Proof Of Concept

POD: Port Of Destination

PoET: Proof of Elapsed Time

POL: Port Of Load

POS: Point Of Sale

PoS: Proof of Stake

PoW: Proof of Work

PPE: Personal Protective Equipment

PPECB: Perishable Products Export Control Board

PV: Present Value

RDBMS: Relational Database Management System

RDS: Relational Database Service

REST: Representational State Transfer

RFID: Radio Frequency Identification

ROI: Return On Investment

RQ: Research Question

S3: Simple Storage Service

SaaS: Software-as-a-Service

SARS: Severe Acute Respiratory Syndrome

SLA: Service-Level Agreement

SME: Small and Medium Enterprise

SSD: Solid State Drive

SSL: Secure Socket Layer

STAR: Security, Trust, Assurance, and Risk

TFPI: Trade Facilitation and Paperless Trade Implementation

TLS: Transport Layer Security

TPS: Transactions Per Second

UI: User Interface

UN/CEFACT: United Nations Centre for Trade Facilitation and Electronic Business

UNRC: United Nations Regional Commissions

vCPU: Virtual Central Processing Unit

WEF: World Economic Forum

WSN: Wireless Sensor Networks

WWF: World Wildlife Fund

XML: Extensible Markup Language

XMP: Extensible Metadata Platform

CHAPTER 1

Introduction

The purpose of this chapter is to introduce the research and discuss its need. Firstly, the background and rationale of the research, along with an initial review of the literature is briefly discussed. Next, the problem statement and associated research questions that were formulated are discussed, followed by the research objectives in the following section. This is followed by a discussion of the research design and is succeeded by the research methodology, the scope of the research and any ethical considerations associated with the research in respective sections. Finally, an outline for the thesis is provided to explain how it is logically structured.

1.1 Background and Rationale of the Research

Cross-border supply chains play a critical role in the global trade economy, as shown with the devastating consequences of the coronavirus disease (COVID-19) pandemic when supply chains were disrupted worldwide. One of the largest obstacles that cross-border supply chains face is the increasingly uncertain and challenging business environment. Companies are looking to increase the resilience and responsiveness of their supply chains during times of disruption caused by man-made or natural disasters (Forkel, Clauß, and Schumann, 2019). The reason for many firms being more vulnerable to such disruptions is that they are less vertically integrated than in the past, meaning they rely more on other companies in the global supply chain. Instead of creating products entirely by themselves, as done previously, companies now source materials and parts from various suppliers across the world, thus making them more vulnerable to disruptions experienced by their suppliers (Snyder and Shen, 2007).

A major bottleneck and source of many headaches in cross-border supply chains are paper-based documentation systems. Information is shared among supply chain partners using physical documents such as purchasing orders, inventory reports, and sanitary and phytosanitary (SPS) certificates (L. Thompson et al., 2017). Some implications of such traditional systems are obvious: physical documents shared between companies in different countries or even continents take days or even weeks to arrive and may get easily lost or stolen. Furthermore, physical documents are more subject to fraud, mistakes are difficult to fix and high additional costs are associated with physical paper flows (Australian DFAT and Chinese MofCom, 2001; L. Thompson et al., 2017).

An example of a paperless trading system can be found in the maritime supply chain. The Port of Antwerp uses a blockchain-based digital platform for handling the flow of information and various documents, including electronic phytosanitary certificates that are usually hardcopies. Compared to paper-based systems, the digital platform is faster, more environmentally friendly, more secure and reliable, and enables greater traceability (De Cauwer, 2018).

Supply chain digitalisation and the automation of information flows enable business-to-business (B2B) integration, allowing information to be easily shared between all parties in a supply chain (Korpela, Hallikas, and Dahlberg, 2017). The information allows the past and current status and locations of products, components and raw materials in the supply chain to be determined through a process called *track and trace* (Musa, Gunasekaran, and Yusuf, 2014). This enables end-to-end visibility and allows companies to be more transparent with their data and thus build not only the trust of other companies, but also their customers. Visibility promotes higher quality items, ensures ethical sourcing and working conditions and enables supply chains to react quickly when problems arise.

Effectively using the large amounts of data generated in supply chains daily can lead to more efficient and secure supply chains, effective and even reduced product recalls, reduced counterfeits and reduced environmental impact, among others (Roy, 2019). An example is that food-selling companies can correctly identify where contaminated items come from during a food-borne illness outbreak and discard only those that are contaminated; not their entire stock (Aung and Y. S. Chang, 2014). There is another major topic related to this research: distributed ledger technology (DLT).

A distributed ledger is a type of database that is spread out across an entire network of users. Records are chronologically stored within the database, known as a ledger, and are only approved when consensus is reached among users (Maull et al., 2017). A technology that is present in all DLTs is public key cryptography, which is used to securely create a unique digital identity (ID) for each user. A second technology is a distributed peer-to-peer (P2P) network which is decentralised in that a copy of the ledger is stored on the node of each user. Thus, a single point of failure will not lead to the loss of the database. The third technology is the consensus mechanism used to validate transactions, which allows users on the network to agree on a specific version of the truth, instead of having to place their trust in a third party, such as a bank (El Ioini and Pahl, 2018). These technologies make it extremely difficult to falsify data or successfully disrupt the network.

The specific type of DLT that this research focusses on is blockchain, a well-known DLT which shows promising potential for use within supply chains. Transactions are stored in a ledger that is distributed among users, decentralised because each member has a copy of the ledger and immutable because transactions cannot be changed once stored. A collection of transactions is stored in a block, which is then added to the blockchain. Each block has a unique identifier that links it to the previous block in the chain. A change in an upstream block will thus create a new identifier for that block and invalidate each downstream block of transactions in the chain, making it nearly impossible to successfully tamper with the data (El Ioini and Pahl, 2018).

A major aspect of blockchain is its various models, which describes how it functions. The different models can be loosely described by features from each of the following categories (H. Wu et al., 2017):

1. Network
   (a) Centralised: data is stored at a single location and controlled by a single party.
   (b) Decentralised: data is stored at multiple locations and controlled by multiple parties.
2. Permissions
   (a) Public: accessible by anyone; anyone can make and track transactions; users are anonymous.
   (b) Private: only accessible to those with permission; users are known; controlled by a single party or company.
   (c) Consortium: only accessible to those with permission; users are known; controlled by a group of parties or companies.
3. Data storage
   (a) On-chain: all data is stored on the blockchain, accessible by all users.

(b) Off-chain: data is stored in an external database only accessible by those with certain permissions.

The model also describes the different nodes, such as transaction issuers (regular users) and miners – those that are responsible for creating blocks for each group of transactions and adding them to the blockchain, thus maintaining the network (El Ioini and Pahl, 2018). The consensus protocol that is used to validate each block is also part of the blockchain model. It is important to select the most applicable model for a specific blockchain project, as it will likely have an effect on the success of the project.

An overarching theme in this study is supply chain digitalisation and automation in support of the vision of the Fourth Industrial Revolution (4IR), which is to transform companies to be more customer-oriented, whether it is through e-commerce, digital marketing, social media or the customer experience, according to Schrauf and Berttram (2016). Three concepts are frequently being confused: *digitisation* of information, *digitalisation* of processes and *digital transformation* of industries.

The enabler of the latter two is digitisation, which entails the optimisation of information flow within the supply chain by converting it from analogue to digital, for example, creating digital copies of physical documents (Bloomberg, 2018). Digitalisation is the process of changing a business model to generate new revenue streams and value-producing opportunities through the use of digital technologies and is only possible through the digitisation of information (Gartner, 2020). Digitalisation allows supply chains to be integrated and more transparent to all parties involved – from raw material suppliers to end customers. Additionally, supply chains are also able to cut various costs, reduce lead times, improve flexibility and increase overall efficiency (Korpela, Hallikas, and Dahlberg, 2017).

Digital transformation is much broader, has a larger and further reaching impact than digitalisation and focusses more on the people aspect of supply chains. Digital transformation requires strategic organisational changes that are customer-driven and backed by leadership, as well as the implementation of digital technologies, i.e. digitalisation of various processes (Bloomberg, 2018).

The 4IR builds on previous industrial revolutions (Philbeck and Davis, 2018) and aims to combine various emerging technologies (Schwab, 2017) to create highly flexible and interconnected digital systems that facilitate the real-time flow of information between humans, machines and systems (Ustundag and Cevikcan, 2017; K. Zhou, Liu, and L. Zhou, 2015). An important related term often used to refer to the 4IR, is *Industry 4.0*. It refers to strategic projects in the manufacturing sector that supports the vision of the 4IR (Philbeck and Davis, 2018) and aims to use digital technologies to connect machines, systems, facilities, products and customers for real-time information sharing, resulting in higher levels of efficiency and visibility (Ardito et al., 2019). In 2011, the German government announced their *Plattform Industrie 4.0* initiative as part of their high-tech strategy for 2020 – specifically to improve their competitiveness in the manufacturing industry (Hofmann and Rüsch, 2017). Since then, many other countries have announced similar initiatives (Kagermann et al., 2013), arguably marking the start of the 4IR.

Initial research on the fascinating topic of blockchain and its use cases in the supply chain, briefly discussed below, highlighted the potential of using blockchain to facilitate supply chain digitalisation and automation. The outbreak of the COVID-19 pandemic, also known as SARS-CoV-2, highlighted various issues in supply chains that can be resolved by digitalisation, thus increasing the need for such research.

Good examples of issues related to supply chain digitalisation can be found in the maritime shipping industry. The lack of digitisation, made obvious by the tons of paperwork and documents accompanying various transactions, introduces many problems, including data duplication and inconsistencies, redundancies, lack of transparency and processing costs (Y. Chang, Iakovou, and Shi, 2020). By digitising the information recorded on paperwork and automating information flows, supply chains can become more integrated, efficient and transparent due to information being easily accessible to more parties in the supply chain (Papageorgiou, 2018). A possible tool for supply chain digitalisation is blockchain.

The need for trust in third parties (and thus also the associated costs) are removed due to the decentralised nature of blockchain where each user has an identical ledger containing the transactions made in the supply chain. This enables end-to-end supply chain visibility, which is further enhanced by the public key cryptography used in blockchain, because each user has a unique identity that is linked to any change they make. Thus, everyone is held accountable for their actions. Transactions in the blockchain are also immutable, meaning they cannot be changed once recoded, which prevents tampering and further improves supply chain security (Kouhizadeh and Sarkis, 2018). Additional advantages of blockchain include increased speed, responsiveness and versatility in the types of exchanges it can handle (Cole, Stevenson, and Aitken, 2019).

1.2 Initial Review of the Literature

An initial review of literature regarding supply chain digitalisation and automation and the application of blockchain in supply chains provided insight into current problems experienced in the industry. While much has been done to address some of the problems, there remain certain gaps that can be filled by additional research. Blockchain has been cited in literature as a promising technology for digitalising and automating financial flows as well as information and documentation flows (Zile and Strazdiņa, 2018; Swan, 2015; Q. Lu and X. Xu, 2017; Hackius and M. Petersen, 2017; Scott et al., 2018). Large amounts of research have been done on blockchain for streamlining payments, but research on exploring the potential for streamlining and automating information flows in a more secure way is still lacking.

In their research on digitally enabled sustainable supply chains, Jabbour et al. (2020) noted the lack of research regarding the integration of big data with emerging digital technologies from Industry 4.0. They identified various research gaps related to big data for sustainability applications in supply chains:

- Not much effort has been exerted to use big data for modelling sustainable supply chains.
- The combination of big data with other emerging 4IR-related technologies requires further research, especially when looking at sustainable supply chain management.
- It is still unclear how to build a culture that is data driven and able to foster big data initiatives among supply chain partners.
- The ability of big data predictive analytics to help promote supply chain resilience requires further empirical research.
- Challenges and barriers to implementing big data analytics in the supply chain also requires further research.

Vendrell-Herrero et al. (2017) explores the impact of servitisation and digital business models on the publishing industry. Their evidence supports two propositions. The first is that digital servitisation provides greater benefits for downstream firms because they obtain control of the link to consumers, as servitisation reduces the need for certain intermediaries. The second is that upstream firms can benefit more if they have control over key resources that are desirable to the consumer, i.e. novel offers that are difficult to imitate. Since this study is limited to the publishing industry, it may be worthwhile to explore the impact on other industries with different types of products and services.

A comprehensive, yet generic maturity model in terms of digitalisation in the manufacturing industry was developed by Klötzer and Pflaum (2017). Their model consists of five maturity levels:

1. Digitalisation awareness: the company realises the disruptive potential and challenges of digitalisation and takes appropriate preliminary measures.
2. Smart networked products: microelectronics are embedded into physical objects.
3. Service-oriented enterprise: the previously mentioned objects are used to provide smart services alongside their products by using information and communication technology (ICT) to deliver product-service combinations.
4. Thinking in service systems: these services are now aggregated or linked to demand-sensitive systems, where companies start following the “Product as a Service” approach.
5. Data-driven enterprise: companies now use the large amounts of data generated by their products and services to gain useful insights, allowing them to make more informed decisions and be more competitive.

A limitation to their model is that it was only evaluated by German industry experts, which may introduce bias and make it less applicable to enterprises in other regions across the world. Research by Singh Srai et al. (2017) contains a framework of ten different digital scenarios that covers inbound, internal, outbound and end-to-end perspectives of the supply chain. Unfortunately, due to the fact that their paper was published in 2017 and the high rate at which new scenarios for digital technology are discovered, their framework may need to be updated to reflect these new scenarios.

Q. Lu and X. Xu (2017) worked with traceability service providers to use blockchain for supply chain tracking and tracing. Their implementation, however, does not create a new traceability system, but rather replaces the existing centralised system with a blockchain system. Their research is not focused on the cost of implementing blockchain, as it is barely mentioned in their paper. Korpela, Hallikas, and Dahlberg (2017) investigated the requirements and functionalities of using blockchain for digital supply chain integration. Two limitations of their study include that most participating companies were Finnish, thus possibly inducing bias, and that only B2B transactions were considered, leaving out transactions between internet of things (IoT) devices. The study focusses more on supply chain integration in general, so specific costs are not mentioned at all.

Verhoeven, Sinn, and Herden (2018) provide a thoroughly critical discussion of several case studies of blockchain implementation in logistics and supply chain management. Unfortunately, none of these cases provide a clear summary or discussion of the costs associated with implementing the blockchain project in their respective areas.

Hackius and M. Petersen (2017) looked at suitable applications for blockchain in logistics and supply chain management, but also investigated the possibility that blockchain may be less useful than many claim it to be. Their data was collected through extensive surveys, answered by professionals in logistics and supply chain management, and blockchain positions. The results show that the levels of uncertainty surrounding blockchain is high. These results, and the fact that their research does not mention the cost of implementing blockchain shows the need for a business case for blockchain in supply chains.

The researchers mentioned above, along with Tian (2017), H. M. Kim and Laskowski (2018), Cole, Stevenson, and Aitken (2019) and H. Wu et al. (2017), among others, emphasise the potential of blockchain in supply chains. However, few have compared the costs and requirements against the benefits of using blockchain in supply chains for improving information flows, indicating a gap in literature on the topic. A business case for blockchain in supply chains may be the solution.

This concludes the brief background of supply chain digitalisation and blockchain, and the rationale behind the research project. The next section discusses the problem that the research addresses, as well as research questions formulated from the problem statement that the research answers.

1.3 Research Problem Statement and Questions

Security is a major concern in global trade (Hameri and Juha Hintsa, 2009). Existing processes for sharing information throughout cross-border supply chains are still very manual and paper-based, so the risks of fraud, human errors and loss of physical documentation are major (Ganne, 2018). These processes also do not do much to facilitate information sharing between supply chain stakeholders, as there are concerns for the quality, reliability, and privacy of information (Trienekens et al., 2012). These trust issues and the consequent lack of information sharing lead to limited visibility into the supply chain, which makes firms even more vulnerable to risks (Jüttner and Maklan, 2011; Hintsa et al., 2012). The COVID-19 pandemic has further added to these challenges by presenting additional problems such as high levels of uncertainty in supply and demand resulting in widespread disruption (Gruszczynski, 2020).

Digitising and automating these paper-based flows will increase efficiencies, reduce costs and improve visibility, thereby minimising opportunities for fraud and making supply chains more resilient to disruptions (Botton, 2018; WHO, 2019). With digitisation and automation comes the issue of cybersecurity (Bienhaus and Haddud, 2018), so it is vital that data protection and security are prioritised when digitalising and automating global trade (Zimmermann, 2016). A key technology that provides the technical capabilities to deal with many of the problems experienced in supply chains (specifically information sharing and data security), is DLT, such as blockchain (Mohan, Berg, and Poblet, 2020).

Blockchain is presented as a promising solution to these problems, due to its immutability, decentralisation, and security (Q. Lu and X. Xu, 2017; Y. Wang, Han, and Beynon-Davies, 2019), but there is still uncertainty regarding the technology (Hackius and M. Petersen, 2017; Y. Wang, Singgih, et al., 2019; Block and Marcussen, 2020). Centralised relational database solutions are commonly used for storing data and, with the right tools, also offer some of blockchain's features to a degree. Unfortunately, few studies (e.g. Chitti, Murkin, and Chitchyan, 2019; Karaarslan and Konacaklı, 2020) have compared them to blockchain, especially in the context of cross-border supply chains. Of the studies that do look at the costs of blockchain solutions (e.g. Brody et al., 2019; Panuparb, 2019; Odell and Fadzeyeva, 2018), few compare these costs to those of centralised solutions, such as relational databases (e.g. Hedman Surlien, 2018).

In summary, the main problem is the lack of relevant business cases in literature that compare the costs of blockchain to centralised solutions in the context of cross-border supply chains.

The aim of this thesis is to investigate the use of blockchain technology to digitise buyer-supplier relationships in the supply chain by reducing paper flows and digitising information flows, consequently improving supply chain visibility and thus, also efficiency and agility. The main research question (RQ) that this thesis intended to answer was:

> How do the cost and benefits for a blockchain-based solution for digitalising and automating documentation flows in cross-border supply chains compare to conventional centralised relational database solutions?

Broad research questions that emerged from the problem statement and main research question above include:

1. What are the core documents in cross-border supply chains and what do their process flows look like?

2. What is the degree of digitalisation and automation of these process flows, and what challenges are faced when managing these documents?

3. What technologies are currently used to manage these documents and their processes?

4. What alternative blockchain-based solutions exist for managing these documents and their processes, and what do these solutions look like?

5. How does a blockchain-based solution compare to a more traditional centralised relational database solution?

The next section specifies objectives for the research that are meant to answer each research question and address the problem statement.

1.4 Research Objectives

The objectives of this study were formulated to answer the research questions specified above. The main objective was to create a business case for blockchain for improving the flow of document-related information in cross-border supply chains by comparing its costs and benefits to those of conventional centralised solutions. The main objective was split into the following sub-objectives:

I. Identify the critical information flows and their associated documents in cross-border supply chains.

II. Explore current challenges in global supply chains related to these documents, including the degree of digitalisation and automation of these processes.

III. Investigate current best practices for managing these documents and their processes.

IV. Identify and explore alternative blockchain-based solutions for managing these documents and their processes.

V. Compare a blockchain-based solution to a more conventional centralised solution according to the benefits they provide and the costs they incur.

1.5 Research Design

For this research, a pragmatist philosophy was followed instead of a positivist philosophy, which was originally considered. The reason being that a pragmatist world view places more emphasis on the problem at hand and less on the methods that will be used (J. W. Creswell and J. D. Creswell, 2009). The pragmatist philosophy thus enables the researcher to use the methods they see fit, making it a more flexible view. The approach was to be deductive, since the goal is to confirm a theory.

The strategy consisted of a case study and semi-structured interviews that were performed to gather data as these methods allow for more interaction with industry experts. Mixed methods are commonly used to collect data in pragmatist research (J. W. Creswell and J. D. Creswell, 2009), and this was also the case for this research, since blockchain and supply chain digitalisation are relatively new and unexplored areas. A reason for using sequential mixed methods is that the analysis was based on information collected from the interviews. A review of the literature on topics relevant to the research problem was performed to identify existing research on these topics which was used as building blocks for this study. The research design is visualised in Figure 1.1.

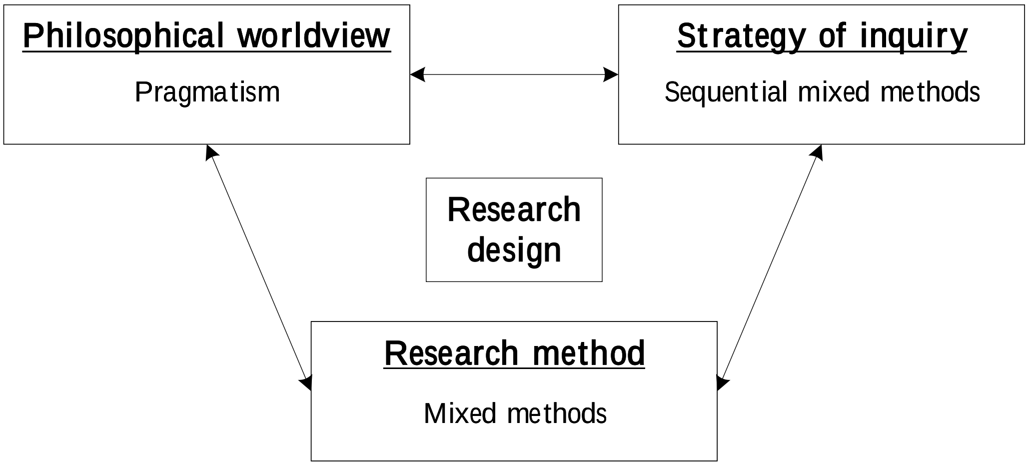

FIGURE 1.1: *The proposed research design.*

1.6 Research Methodology

The research starts out with a literature review on the major topics that were addressed: the 4IR, international supply chains, supply chain digitalisation, blockchain technology, databases and blockchain alternatives. Its purpose was firstly, to explore existing research to gain a better understanding of each topic; secondly, to identify current challenges in international supply chains; thirdly to find out how blockchain can be used in supply chains – specifically how it supports digitalisation and which blockchain models are most applicable to this situation; and fourthly, what alternatives exist to blockchain technology.

Further insight was gained into problems faced in cross-border supply chains by conducting a case study in such a supply chain. It consisted of semi-structured interviews with an expert in that area, the identification of key stakeholders and vital documents, and a mapping of product-, document- and information flows in the supply chain to provide a high-level view. Information from the case study confirmed many of the findings from literature and helped identify areas that could be improved by digitising and automating information flows. The case study and its interviews were used to collect primary data, while secondary data was collected from literature. Next, based on the data collected thus far, as well as a semi-structured interview with a blockchain expert, a blockchain model for sharing documents in cross-border supply chains was developed, as well as a more conventional model.

Using the information from the case study, a type of cost-benefit analysis was performed that compared the cost and benefits of a blockchain solution compared to a more traditional centralised solution. The analysis was split into two parts. Firstly, it looked at financial aspects and used data that is easy to quantify. Secondly, it looked at non-financial aspects that are much harder to quantify. The non-financial analysis used the Architecture Trade-off Analysis Method and the Analytical Network Process method – both scientific methods for making complex multi-criteria decisions. Industry experts validated the analysis to ensure that results that are representative of global supply chains in general were obtained.

Finally, based on the results of the case study, the outcome of the analysis, and the feedback from the validation, a conclusion was drawn on the applicability of blockchain in supply chains. A visual representation of the research methodology is presented in Figure 1.2.

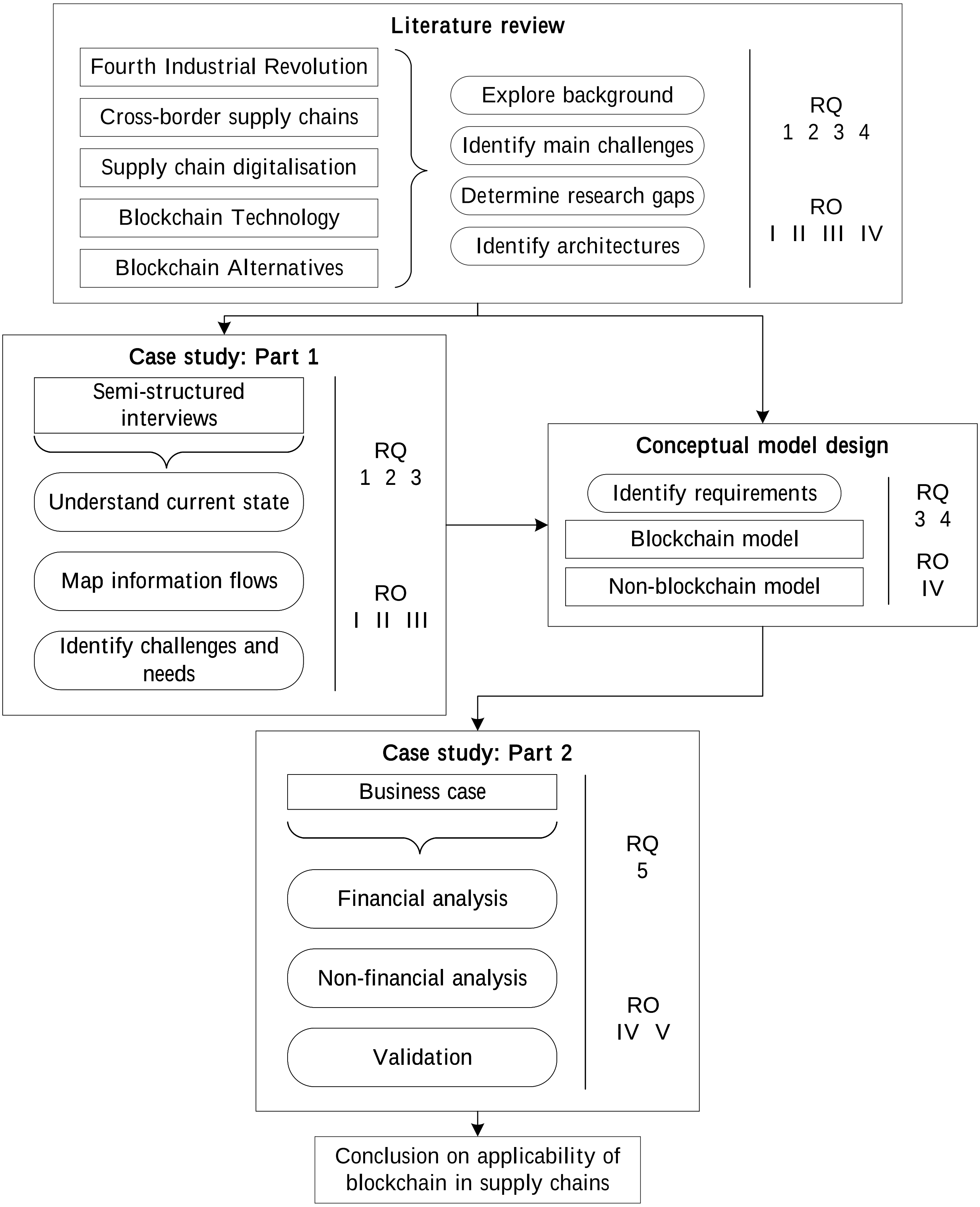

FIGURE 1.2: *The proposed research methodology.*

1.7 Delimitations

The scope of the research was delimited in the following ways:

1. International supply chains, i.e. those that span across country borders, were the subject of this study. Therefore, local supply chains that only operate within a single country were not explicitly considered.
2. While the research aimed to be generic and applicable to multiple industries, the focus of the case study was the fruit exporting industry of South Africa – the reason being that the industry is very important in South Africa and it is a good example of a complex cross-border supply chain with a large number of physical document flows.
3. The supply chain in the case study was covered from South African farms to the importer in the importing country.
4. Although the study addressed many forms of supply chain digitisation, more attention is directed towards the reduction of paper flows, as it has massive potential for being solved by digitisation. The flow of money was therefore not considered, but rather only the flow of information.
5. The technology considered for supply chain digitisation and eventual digitalisation in this study was blockchain, due to its infancy and massive potential in supply chain, as mentioned by various authors in literature.
6. A completely new blockchain model was not developed as part of this research. Rather, existing models and parameters were compared to find the combination that works best for the subject of the case study.

1.8 Ethical Considerations

Part of the interaction with industry experts in this study was conducted through semi-structured interviews to collect data for the case study, as well as for validation purposes. Although the information was not expected to be sensitive, it was handled with confidence and the privacy of individuals and companies involved are respected. Any interviews and case studies as well as correspondence with industry professionals were conducted in a professional manner. Before any potentially sensitive information was collected, ethics clearance was obtained from the Research Ethics Committee for Social, Behavioural and Education Research from Stellenbosch University to ensure that the necessary ethical considerations have been accounted for. An application letter for institutional permission was sent to each organisation, along with a document that contained the questions that were asked in the interview to ensure that the organisations were aware of the information that were shared by their employees. Furthermore, data was only collected and used in the research with the explicit consent of the participants. The implications of plagiarism are understood and were avoided in this study through proper referencing and strict paraphrasing.

1.9 Thesis Outline

The outline of the thesis, with chapters grouped by phase, is visualised in Figure 1.3. Chapter 1 introduces the research and provides some background for the reader to understand what the research is about and why the selected topics were investigated. Chapters 2, 3 and 4 contain a literature review on the main topics covered by this research. The work of other researchers were reviewed to gain a better understanding of the research topics and to determine what has been done in the past, as well as how their work can be used in the future. Chapter 2 focusses on the 4IR and Industry 4.0, and international supply chains, whereas Chapter 3 focusses on supply chain digitalisation, blockchain and its applications in supply chains, and Chapter 4 looks at databases and blockchain alternatives.

Findings from the semi-structured interviews with an expert in a cross-border supply chain on the problems their company experiences in global trade are discussed in Chapter 5. Chapter 6 describes the development of two models for blockchain and relational databases respectively. Chapter 7 contains the analysis that compared the solutions according to various aspects, followed by the validation of the analysis in Chapter 8. Chapter 9 discusses findings from the research, along with a critical discussion on the analysis and provides a final recommendation based on the various aspects of this research. Finally, the thesis draws to a conclusion in Chapter 10 with a summary of what was done, as well as suggestions for future work and a reflection on the research.

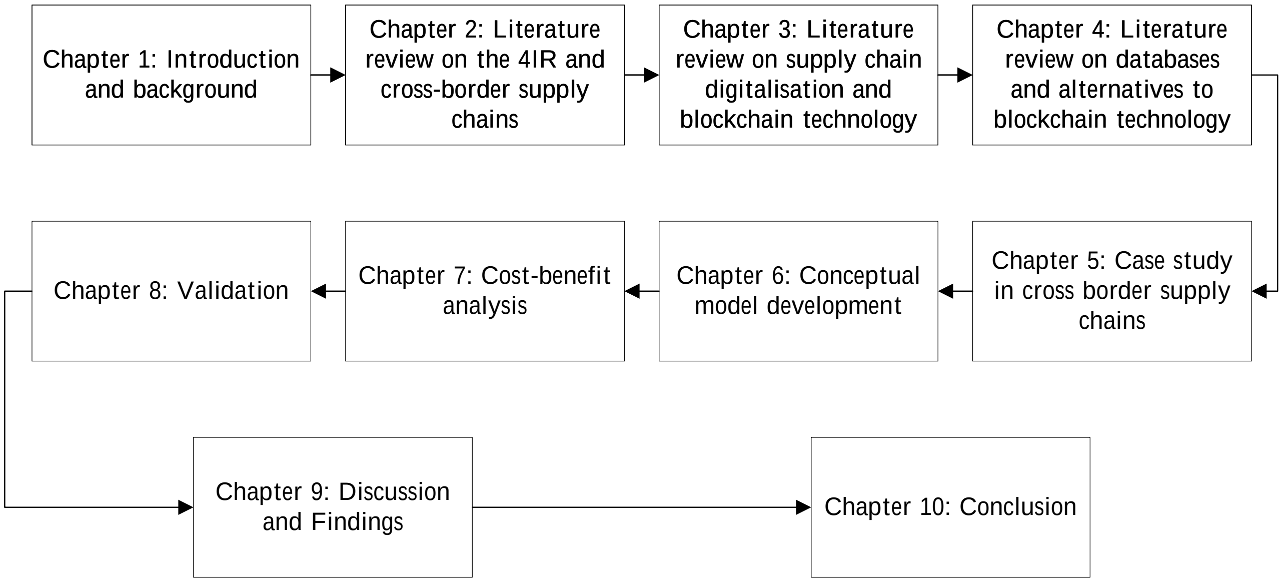

FIGURE 1.3: *The outline for the thesis.*

CHAPTER 2

The 4th Industrial Revolution and Cross-Border Supply Chains

The purpose of the literature review is to (1) explore existing literature on cross-border supply chains, its challenges, and the drivers for streamlining operations through digitisation and automation; (2) explore current state of the art research and related studies on the application of blockchain in supply chains.

The first part of the literature review firstly discusses the industrial revolutions that occurred during the past few centuries, with a focus on the ongoing one: the Fourth Industrial Revolution. Secondly, the concept of international supply chains is explored to identify current issues on the topic and thus also explain the relevance of this research. Papers on these topics were found using Google Scholar, Stellenbosch University's SUNSearch and Elsevier's ScienceDirect. Databases searched include Taylor & Francis Online, SpringerLink, Emerald Insight, ScienceDirect, Scopus, IEEE Explore, JSTOR and Wiley Online Library.

2.1 The Fourth Industrial Revolution

The following section aims to provide a background on the overarching theme that has a major influence on all other sub-themes in this study: the Fourth Industrial Revolution (4IR). Firstly, in Section 2.1.1, the history of the various industrial revolutions thus far is discussed. In Section 2.1.2, the idea behind the 4IR, along with associated concepts, such as Industry 4.0, are discussed. This is followed by descriptions of the key technologies that enable the 4IR in Section 2.1.3. Next, a discussion of the opportunities, challenges and various requirements of the 4IR is found in Section 2.1.4. Finally, in Section 2.1.5, various recommendation and design principles identified in literature are presented.

2.1.1 The history of industrial revolutions

Philbeck and Davis (2018) describe industrial revolutions as drastic and far-reaching changes to everyday systems, the transformation of relationships between humans and technology, and the development of new ways to perceive, act and live. Bigliardi, Bottani, and Casella (2020) focus more on manufacturing, describing industrial revolutions as disruptive breakthroughs that create radical changes in production and related processes. In other words, industrial revolutions are characterised by major technological advances (G. Li, Hou, and A. Wu, 2017) that lead to paradigm shifts (Lasi et al., 2014), resulting in totally new ways of living, working and relating to others (Schwab, 2017). These new ways of thinking and doing enables the development of the next generation of manufacturing technologies (L. D. Xu, E. L. Xu, and L. Li, 2018) that produce major increases in industrial productivity (Rüßmann et al., 2015). Philbeck and Davis (2018) also note that it is often the combinations of emerging technologies that have a profound impact on efficiency, rather than the individual technologies.

The disruptive nature of industrial revolutions and the radical changes that they bring along show the importance of understanding what causes these revolutions, as well as how they usually progress. This can be achieved by looking at previous industrial revolutions, briefly discussed below. A visual summary comparing the complexity and approximate dates of the industrial revolutions is given in Figure 2.1.

The First Industrial Revolution occurred during the late 18th century (Bloem et al., 2014; Drath and Horch, 2014). The use of water and steam to create hydraulic machines and steam engines (Ustundag and Cevikcan, 2017) enabled the creation of heavy mechanical manufacturing equipment (Schwab, 2017), which led to new mechanical production facilities and brought the transition from manual work to mechanical manufacturing processes (Rojko, 2017; Kagermann et al., 2013). The next paradigm shift was at the start of the 20th century (Y. Lu, 2017; Rüßmann et al., 2015). With the Second Industrial Revolution, electricity was the driving power (Lasi et al., 2014) that led to the creation of the conveyor belt and assembly lines (Bloem et al., 2014; K. Zhou, Liu, and L. Zhou, 2015). Coupled with the division of labour and separation of components, these technologies enabled mass production (Schwab, 2017).

It is estimated that the Third Industrial Revolution saw its inception in the late 1960s or early 1970s (Y. Lu, 2017; Bigliardi, Bottani, and Casella, 2020; Kagermann et al., 2013). The programmable logic controller (PLC) started the widespread digitalisation and accelerated the automation of manufacturing processes (Schwab, 2017; Bloem et al., 2014; Lasi et al., 2014; Drath and Horch, 2014). This allowed flexibility in terms of product variety in manufacturing, although production quantity was not yet flexible (Rojko, 2017). As time went by, the usefulness of computers were recognised by increasingly more businesses and governments. This, and the eventual creation of the internet accelerated globalisation and allowed the world to be more interconnected, thus driving humans towards the Fourth Industrial Revolution, discussed in greater detail in the next section (Philbeck and Davis, 2018).

2.1.2 The idea behind the Fourth Industrial Revolution

The Fourth Industrial Revolution is also known as the *Internet Age* (Peters et al., 2017) or the *Digital Revolution* (Philbeck and Davis, 2018). The main purpose is to create intelligent and highly flexible digital production systems that enable the real-time flow of information between humans, machines and systems (K. Zhou, Liu, and L. Zhou, 2015; Ustundag and Cevikcan, 2017). This purpose can be fulfilled by integrating advanced ICT with physical systems to create interconnected cyber-physical systems (CPS) (L. D. Xu, E. L. Xu, and L. Li, 2018; Rojko, 2017). It will allow new levels of productivity, process efficiency, product and service quality, and cost reduction to be reached (Rüßmann et al., 2015). What makes these systems intelligent is the fact that they are self-organising and can thus adapt to their environment to prevent machine breakdowns or consume less power.

Drivers of the 4IR

Schwab (2017) characterises the 4IR as the combination of technologies that make it difficult to distinguish the lines between the physical, digital and biological spheres. Similarly to K. Zhou, Liu, and L. Zhou (2015), Barreto, Amaral, and Pereira (2017) name the defining feature of the 4IR as intelligent networks based on CPS. Lasi et al. (2014) describe the vision of future production as “modular and efficient manufacturing systems [...] in which products control their own manufacturing process”. This implies that, in addition to flexibility in terms of product variety brought on by the

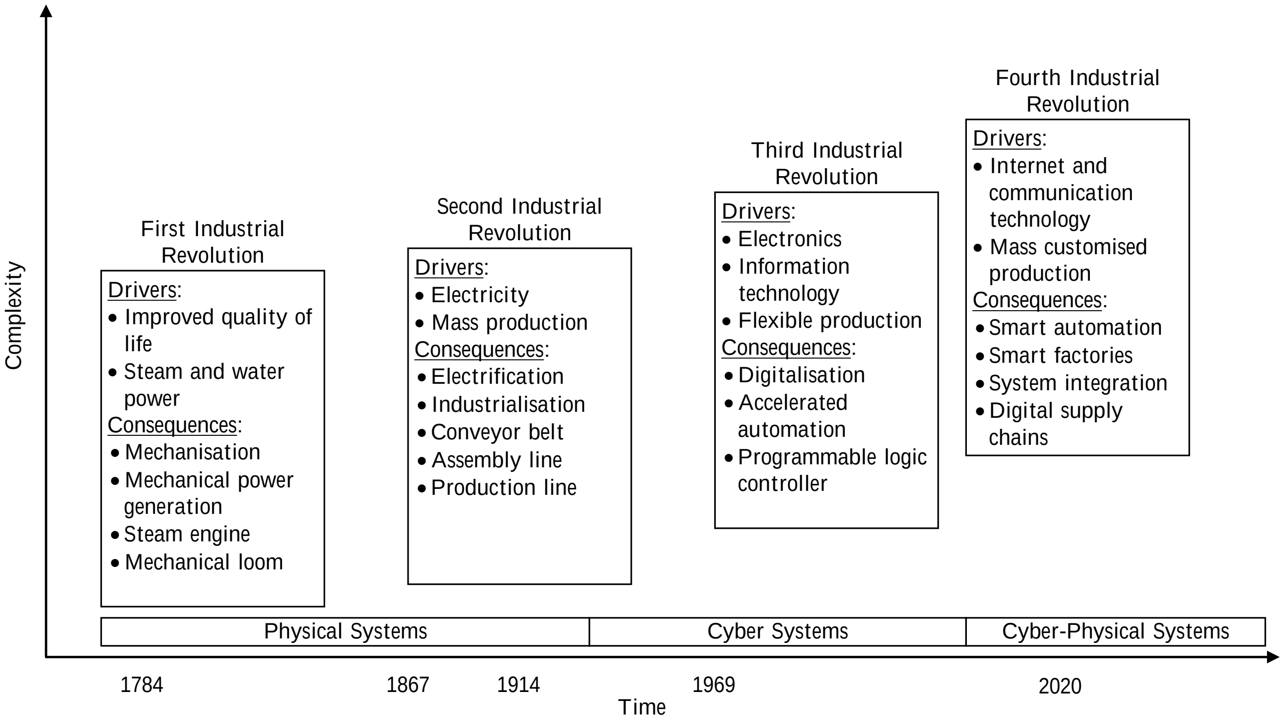

FIGURE 2.1: *An overview of industrial revolutions over the years (based on Bloem et al., 2014; Peters et al., 2017; Rojko, 2017; Drath and Horch, 2014; Kagermann et al., 2013).*

Third Industrial Revolution, the 4IR will bring about flexibility in terms of production quantity, enabling products to be manufactured in small batch sizes, at costs associated with mass production.

The 4IR builds upon technologies developed during the previous revolution (Philbeck and Davis, 2018). The changes currently experienced are not a simple extension of the Third Industrial Revolution, but instead an entirely new and distinguishable revolution. Schwab (2017) provides three reasons for this:

- *Velocity*: the pace of current breakthroughs evolves at an exponential, rather than a linear rate, when compared to previous industrial revolutions.
- *Scope*: more industries feel the disruptive power of the 4IR than any other industrial revolution.
- *Impact*: far-reaching changes brought on by the 4IR lead to the transformation of entire production, management and governance systems.

Greater awareness of the impending Fourth Industrial Revolution began in 2011 when the German government published an article introducing the concept of *Industrie 4.0* as part of their high-tech strategy for 2020 (K. Zhou, Liu, and L. Zhou, 2015; Hofmann and Rüsch, 2017; L. D. Xu, E. L. Xu, and L. Li, 2018). The term appeared again in 2013 when *Plattform Industrie 4.0* was officially launched at the Hannover Messe trade fair (K. Zhou, Liu, and L. Zhou, 2015; Kagermann et al., 2013). The strategic goal of the Industrie 4.0 initiative is to improve Germany's international competitiveness in manufacturing (Culot et al., 2020) by promoting the use of digital technologies (G. Li, Hou, and A. Wu, 2017; Griffiths and Ooi, 2018) to connect machines, systems, facilities, products and customers to share real-time market and operational information (Ardito et al., 2019). The introduction of the Industrie 4.0 initiative is widely regarded as the start of the 4IR (Roblek, Meško, and Krapež, 2016; G. Li, Hou, and A. Wu, 2017). Although these two terms are often used interchangeably, there is a difference. Industrie 4.0 (Industry 4.0 in English) is an important component of the 4IR and has a greater focus on the *manufacturing* industry, whereas the 4IR concerns many other industries as well (Philbeck and Davis, 2018).

In response to Germany's Industrie 4.0, various other countries developed similar high-tech strategies. One of the most frequently cited initiatives is *Made in China 2025* (Culot et al., 2020) by the Chinese government in 2015, that aims to make China a strong manufacturing power before 2025 by utilising advanced information technology (IT) and industrial manufacturing (G. Li, Hou, and A. Wu, 2017). Another highly cited initiative is from a country on the other side of the world. The US government uses *Advanced Manufacturing* to describe their strategy for obtaining a competitive advantage in the manufacturing industry (Holdren et al., 2012).

Initiatives from other countries include "Society 5.0" as part of Japan's Revitalisation Strategy (G. Li, Hou, and A. Wu, 2017; Culot et al., 2020), "Manufacturing 3.0" in South Korea (Culot et al., 2020; Kagermann et al., 2013), "Industrie du Futur" in France (Rojko, 2017), "Smart Industry" in the Netherlands (Ardito et al., 2019), "Catapult – High Value Manufacturing" in the United Kingdom (Ardito et al., 2019; Kagermann et al., 2013) and finally, "Factories of the Future" by the European Commission (Culot et al., 2020). All these initiatives revolve around the 4IR and depend on a combination of the technologies discussed in the next section.

2.1.3 Technologies associated with the Fourth Industrial Revolution

Technology – specifically the integration of various technologies – is a key driver of the 4IR. This section discusses various enabling technologies of the 4IR and their applications. The potential of each of these technologies on its own barely scratches the surface of its capability when integrated with other key technologies. Thus, it is important to identify the combinations of technologies that will be most useful in the context of the 4IR.

The **Internet of Things (IoT)** is one of the most recurring key technologies mentioned in literature (Vaidya, Ambad, and Bhosle, 2018; Ghadge et al., 2020; Tjahjono et al., 2017). A simple explanation of the IoT is a network of devices that communicate with one another to achieve a common goal (G. Li, Hou, and A. Wu, 2017). These devices rely on sensory, communication, networking and information processing technologies to record, transfer and process data between devices and use standard communication protocols to communicate (L. D. Xu, E. L. Xu, and L. Li, 2018). A wide array of devices can be used to create an IoT network by connecting them to another device via the internet. Some of these include radio frequency identification (RFID) devices, global positioning systems (GPS), sensors, actuators, laser scanners and mobile devices with Wi-Fi, Bluetooth, near field communication (NFC) or cellular network connectivity (L. D. Xu, E. L. Xu, and L. Li, 2018). IoT enables subjects to be intelligently identified, located, tracked, monitored and managed (K. Zhou, Liu, and L. Zhou, 2015) and allows events to be triggered autonomously and in real-time (G. Li, Hou, and A. Wu, 2017).

Another frequently recurring term is **cyber-physical systems**, considered, along with IoT, as critical to Industry 4.0 (Kagermann et al., 2013; Drath and Horch, 2014; Bigliardi, Bottani, and Casella, 2020; Tjahjono et al., 2017). Lee (2008) defines CPS as, "integrations of computation with physical processes. Embedded computers and networks monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa." Thus, physical systems and processes in the real world are seamlessly integrated with digital computation, communication and control systems and processes in the virtual world (Vaidya, Ambad, and Bhosle, 2018; Roblek, Meško, and Krapež, 2016; Bartodziej, 2017). Sensors, actuators, control processing units and communication devices enable the physical and digital worlds to be integrated (Hofmann and Rüsch, 2017).

In the era of the 4IR, the need for data sharing across company boundaries and different geographical areas is increasing (Rüßmann et al., 2015). **Cloud computing** enables information to be easily processed on virtual platforms at different locations owned and managed by the company itself or a third party service provider. The cloud is accessible from devices with an internet connection and does not require specific software to be installed on the device (Schröder, Indorf, and Kersten, 2014). Cloud computing provides various services at a low cost with high levels of performance (K. Zhou, Liu, and L. Zhou, 2015; L. D. Xu, E. L. Xu, and L. Li, 2018). These services include Software-as-a-Service (SaaS), Platform-as-a-service (PaaS) and Infrastructure-as-a-Service (IaaS) (K. Zhou, Liu, and L. Zhou, 2015), enabling companies to reduce their IT investment by using the resources of other companies and paying only for what they use (Menon and Shah, 2019). The main takeaway of cloud computing is the ease and speed of information sharing between different actors, thus making its benefit to the 4IR evident.

Big Data refers to massive collections of data that are simply too large for conventional data-processing systems to manage. In the context of the 4IR, the scale and complexity of modern-day production systems, as well as enterprise- and customer-management systems mean that large amounts of data from many different sources are collected and need to be analysed and used for real-time decision-making (Rüßmann et al., 2015). Big data can be described using four dimensions (G. Li, Hou, and A. Wu, 2017; Witkowski, 2017):

- Volume: massive amounts of data are collected from multiple sources.
- Variety: different types of dynamically changing and unstructured data from various types of devices are collected.
- Velocity: new data is generated at tremendous speeds and data analysis is carried out in near real-time.
- Value: some data has greater value than other data, so it is important to differentiate between the data.

The analysis of big data has various benefits to manufacturing companies in the context of Industry 4.0. These include the optimisation of processes, reduction of costs and improvement of operational efficiencies (K. Zhou, Liu, and L. Zhou, 2015) and it can provide a significant competitive advantage to those companies that can utilise big data analysis (Ustundag and Cevikcan, 2017). Companies will also experience improvements in productivity by being able to provide the right information to the right user at the right time (Menon and Shah, 2019).

Artificial intelligence (AI) aims to transfer behaviour associated with human beings, such as thinking, reasoning, learning and decision-making to machines to create more intelligent and autonomous machines (G. Li, Hou, and A. Wu, 2017; Bartodziej, 2017). Some applications of AI are already seen in everyday life in the form of self-driving cars and drones, virtual assistant software on most mobile phones and translation and investment software (Schwab, 2017). An important part of AI is machine learning. It provides computers with the ability to find underlying patterns in data without explicitly being programmed to do so. Machine learning algorithms are trained on existing datasets using an iterative process to build a machine learning model, that can then be used to predict future outcomes, thus enabling computers to adapt and make reliable decisions based on new data (G. Li, Hou, and A. Wu, 2017).

In contrast to traditional subtractive manufacturing technology that creates a desired shape by removing layer by layer of a material, **additive manufacturing** creates the desired shape by printing layer by layer of a material (G. Li, Hou, and A. Wu, 2017). The physical three dimensional object, based on a digital model created using computer-aided design (CAD), is built up in layers or connected with other products using materials such as polymers, ceramics or metals (Ustundag and Cevikcan, 2017). A very common form of additive manufacturing is *3D printing*, mostly used for rapid prototyping and the production of individual components (Rüßmann et al., 2015). What makes additive manufacturing extremely useful for the 4IR is the ability to produce small batches of customised products in complex, yet lightweight designs (Vaidya, Ambad, and Bhosle, 2018).

Autonomous vehicles use traditional vehicle production techniques, but advanced sensors, radar, lasers and GPS allow these vehicles to be operated without manual human inputs (G. Li, Hou, and A. Wu, 2017). Similarly, **autonomous robots** are able to perform computations, communicate with one another and control their processes autonomously (Bartodziej, 2017). As these robots become more intelligent, they will work safely alongside humans, providing assistance where needed and learning from the humans (Rüßmann et al., 2015). Alternatively, they can also work where humans cannot, such as dangerous or high risk environments. Autonomous robots are immune to human error and will complete tasks with more precision, speed and safety (Vaidya, Ambad, and Bhosle, 2018).

Augmented reality (AR) enables the user of the AR device to interact with virtual objects overlaid in the real world in real-time (Syberfeldt et al., 2016). This guides workers to improve their decision-making and work procedures by receiving real-time information in their field of view. A simple application is a repairman wearing AR glasses that displays visual instructions on how to repair a certain machine (Rüßmann et al., 2015). A person with less experience may thus also be able to perform certain actions with AR instructions. Another example is the use of AR for virtual training that teaches operators how to safely interact with machines (Rüßmann et al., 2015).

Banks (1998) define **simulation** as, “the imitation of the operation of a real-world process or system over time.” Real-time data will be used by simulation programs to create a virtual model of a real-word process or system that allows operators to find problems, test changes or any additions, or find optimal machine settings before being implemented in the real word (Rüßmann et al., 2015). Other advantages include (Bekker, 2019):

- Testing changes or additions to a system, as mentioned above, does not disrupt its operations.
- Time-consuming processes can be tested in a much shorter period of time.
- Various alternatives can be evaluated.

Each of these technologies will be useful in the 4IR, but the correct combinations of these technologies are key to unlocking greater potential. The 4IR bring various opportunities and challenges. It is important to identify them and define the requirements to be a meaningful participant of Industry 4.0.

2.1.4 Opportunities, challenges and requirements of the Fourth Industrial Revolution

As with any industrial revolution, various opportunities present themselves, along with the associated benefits. Unfortunately, a plethora of challenges and risks also appear, along with some drawbacks. Additionally, it is important to be aware of the impact that the 4IR will have on various parties.

Opportunities and benefits

Industrial revolutions have the potential to raise global levels of income and improve the quality of life for people worldwide. Schwab (2017) discusses the benefits to supply chains. Long-term gains in efficiency, effectiveness and productivity (Tjahjono et al., 2017), and a reduction in transportation,

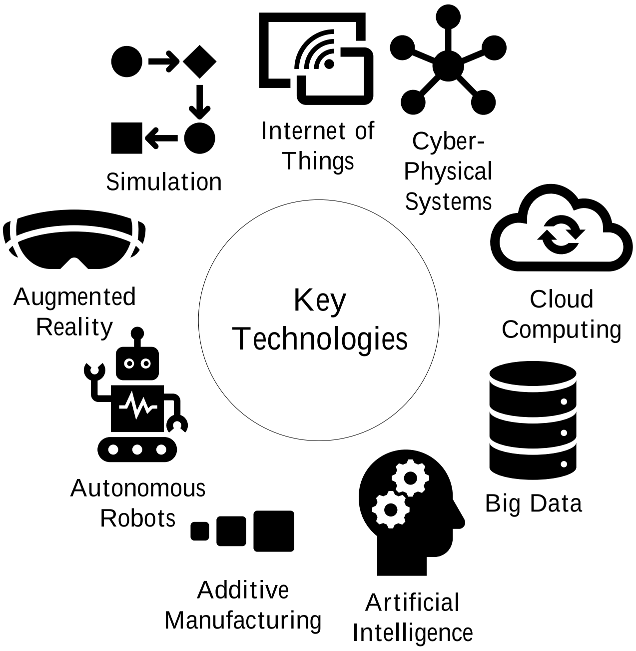

FIGURE 2.2: *Key enabling technologies of the Fourth Industrial Revolution.*

communication and trading costs will eventually lead to new markets and drive economic growth – thus not only being beneficial to supply chains, but also the entire world.

Kagermann et al. (2013) and Wee et al. (2015) expect higher levels of productivity and flexibility, thus enabling the mass customisation of products, one of the major perceived benefits of the 4IR. Personalisation will allow companies to closely meet customer demands and thus create greater value. Furthermore, time- and cost-to-market will be reduced (Rojko, 2017) and product quality and lead times are expected to improve (Culot et al., 2020). Rüßmann et al. (2015) mention the domino effect that some possibilities will have. Data from multiple machines will be gathered and analysed, making processes faster, more flexible and efficient, which will enable higher quality products to be produced at lower costs. This will lead to increased productivity in the manufacturing sector, greater industrial growth and a change in the workforce profile. All of the previously mentioned benefits will alter worldwide competitiveness, an indicator of a population's prosperity.

The 4IR is more consumer-oriented than previous industrial revolutions (Roblek, Meško, and Krapež, 2016; Schwab, 2017). It aims to change relationships between consumers and producers, and help customers easily adapt to smart product characteristics. Consumers are growing more aware of how important the quality and reliability of information and privacy of personal data are (Roblek, Meško, and Krapež, 2016). Tjahjono et al. (2017) mention the benefits of integration, one of the design principles discussed in Section 2.1.5. These include:

- Vertical networking of smart production systems: the use of CPS to create reconfigurable factories that are flexible and able to quickly react to changes in customer demand.
- Horizontal integration via a new generation of global value chain networks: allows greater transparency, enabling the manufacturer to quickly identify any changes in customer requirements and show how the production process accommodates those changes.
- Through-life engineering support across the entire value chain: information is shared and big data is utilised throughout the value chain, enabling innovation and technical improvements to

be present at all stages of a product's life.

- Acceleration through exponential technologies: the use of key technologies mentioned in Section 2.1.3 leads to reduced costs, increased flexibility and higher levels of customisation.

Challenges and drawbacks

There are, unfortunately, various issues that may arise with the 4IR. According to Brynjolfsson and McAfee (2014), greater inequality through the disruption of labour markets is a great concern. A good term to describe this is *technological unemployment* (Peters et al., 2017). As automation progresses, more and more workers are displaced by machines, widening the gap between returns on capital and returns on labour. They do point out that this displacement can also lead to a net increase in safer and more rewarding jobs.

Schwab (2017) mentions that inequality due to the 4IR is not only a key economic concern, but also the greatest societal concern. He also emphasises that people will be more vital than capital in the future of production. Thus, putting people before capital will mean companies and industries are looking for ways reduce inequality, and not simply ignoring it for capital gains. Schwab (2017) also goes on to discuss how technology and innovation disproportionately benefits populations. Those that benefit most are the "... providers of intellectual and physical capital – the innovators, shareholders, and investors ...", i.e. the wealthy. Specifically referring to high-income countries, he mentions that there is strong demand for jobs at high and low skill levels, but weak demand for those in the middle.

A completely different issue noted by Bloem et al. (2014) is security loss. Their report focusses on the integration of IT and Operational Technology (OT), and in it they point out that many of the components used in those and similar systems have outdated hardware and software, thus increasing the security risk of the system with each component added. The reason for them being outdated is that their manufacturers are focussed on creating newer versions and consequently not offering enough support for current versions. This makes the systems vulnerable not only to cyber attacks, but also physical failures.

K. Zhou, Liu, and L. Zhou (2015) mention various challenges, but focusses on CPS. The first challenge is the cooperation between different systems, such as the physical-, information- and computing systems. For the physical system to function correctly, the computing system needs to make accurate and real-time decisions with information from the physical system that is relayed through the information system. The latter must have ubiquitous communication access to all components in the physical system to connect them to the computing system. The second challenge is CPS modelling and model integration. CPS models are extensive and complex because they need to take the physical environment, software and hardware platforms, and network models into account. Models of digital and physical processes differ significantly, so it may be required to develop a new CPS modelling language that integrates these two dimensions.

The third challenge is the integration of CPS, which refers to the different types of components, methods and tools that need to be integrated. K. Zhou, Liu, and L. Zhou (2015) mention that each of the fields included in CPS has its own set of models, languages and methods, which makes the integration between them a greater challenge. The fourth and final challenge associated with CPS is its verification and testing. Due to its extensive reach and massive impact on the entire manufacturing system, it is vital to thoroughly validate and test the CPS before it is implemented. What makes this even more challenging is the lack of consistent standards.

L. D. Xu, E. L. Xu, and L. Li (2018) discuss even more challenges related to the 4IR. These include technical challenges such as scalability of networks to accommodate more devices and a wider variety and larger volume of transactional data, and IoT issues when large amounts of data is transferred over a network from many different sources. The 4IR revolution integrates existing technology with newer ones, which may be a significant issue when standards between the technologies differ. Another risk is information security and privacy protection (Roblek, Meško, and Krapež, 2016; Kagermann et al., 2013; Barreto, Amaral, and Pereira, 2017). IoT automatically collects massive amounts of personal and private information, unlike traditional ICT systems where it is entered manually. As more IoT systems are implemented and processes grow more interconnected, the need for improved cyber security increases.

The opportunities and challenges above can be realised or overcome with the right approach to the 4IR. The next section focusses on the requirements of the 4IR and discusses recommendations by other researchers for approaching the 4IR to ensure a successful outcome.

2.1.5 Approaches to the Fourth Industrial Revolution

The 4IR has many potential benefits and drawbacks, as discussed in Section 2.1.4. The way in which the 4IR is approached will determine whether or not the realised benefits outweigh the drawbacks. It is important to know what the requirements are for successfully adapting to the 4IR, as well as how it should be approached.

Various researchers provide recommendations to certain parties for approaching the 4IR. G. Li, Hou, and A. Wu (2017) discuss coping methods for firms. Firstly, they have to change their current cost-saving, mass production processes to intelligent, digital and automatic processes (Ardito et al., 2019). Secondly, firms must adjust their strategic goals and enterprises should change their attitudes towards competition. Thirdly, organisational structures should be updated to be more efficient, flexible and humane. Finally, human resource management should be more flexible, staff training should be improved and managers should help staff to improve their capabilities.

G. Li, Hou, and A. Wu (2017) also discuss coping methods for governments. Firstly, they should implement a development plan, such as Industrie 4.0 in Germany. Secondly, it is critical to upgrade public facilities and infrastructure to be more intelligent and interconnected. Thirdly, more should be done to attract top talent, as they are the most competitive development resource. A fourth recommendation is that the industry should be guided in a direction that promotes efficiency, environmental protection, energy saving, humanisation and differentiation. Finally, more should be done to address social inequity, such as skills training courses and higher middle-class wages.

According to Rüßmann et al. (2015), producers must set priorities and upgrade the workforce by identifying key areas for improvement and then select the technologies that can drive the improvement (Ardito et al., 2019). Producers must also do strategic workforce planning and investigate the impact that the 4IR may have on its workforce. Rüßmann et al. (2015) state that suppliers must leverage technologies by selecting a business model for its new products or services, building a technological foundation for its offers, building the right organisational structure, developing partnerships and participating in the development of standards. A final recommendation from Rüßmann et al. (2015) is that technological infrastructure must be upgraded so companies can rely on it for real-time data and education must be adapted to promote entrepreneurial approaches and improve IT skills and innovation abilities of workers.

In the literature, multiple design principles concerning the 4IR are identified. These are elements and features that must be kept in mind when developing systems and process for managing the 4IR. They are as follows:

- Interoperability, the ability of systems to communicate, understand and use the functionality of one another (Chen, Doumeingts, and Vernadat, 2008; Y. Lu, 2017 Rojko, 2017);

- Integration (Culot et al., 2020), specifically the three types:
    1. Horizontal: integration of IT systems in various stages of manufacturing and business planning processes, and thus also *between* different companies in a supply chain (L. D. Xu, E. L. Xu, and L. Li, 2018; Bartodziej, 2017; Ghadge et al., 2020),
    2. Vertical: integration of IT systems at various hierarchical levels *within* a company, from actuator and sensor level, to corporate planning levels (L. D. Xu, E. L. Xu, and L. Li, 2018; Bartodziej, 2017; Ghadge et al., 2020),
    3. End-to-end: total integration of the digital and physical worlds across a product's value chain and across different companies throughout the entire engineering process for end-to-end support (L. D. Xu, E. L. Xu, and L. Li, 2018; Bartodziej, 2017);
- Digitalisation of internal processes, product components, communication channels and other parts of the supply chain (Pfohl, Yahsi, and Kurnaz, 2015);
- Decentralisation of power to promote faster decision-making than with traditional organisational hierarchies (Lasi et al., 2014; Culot et al., 2020);
- Virtualisation of systems and processes by creating digital models that can be used for testing any potential changes (Culot et al., 2020; Y. Lu, 2017);
- Autonomy of machines and systems as they make decisions and learn by themselves (Pfohl, Yahsi, and Kurnaz, 2015; Culot et al., 2020);
- Transparency and availability of real-time information and greater visibility in the supply chain to support collaborative and efficient decision-making (Pfohl, Yahsi, and Kurnaz, 2015; Culot et al., 2020; Y. Lu, 2017);
- Modularity of production facilities that increase flexibility by being able to autonomously adjust production quantities (Pfohl, Yahsi, and Kurnaz, 2015; Y. Lu, 2017);
- Collaboration between humans and machines, and between all stakeholders, enabled by the key technologies of the 4IR (Pfohl, Yahsi, and Kurnaz, 2015; Ghadge et al., 2020).

These are the most frequently occurring design principles mentioned in the literature. New systems and processes will need to be designed and old systems and processes adapted with these elements in mind, as they are key characteristics associated with the 4IR.

2.1.6 Conclusion on the Fourth Industrial Revolution

2022 is still part of the early years of the 4IR and there are high levels of uncertainty regarding the outcome. The ever-changing technological environment is experiencing rapid advancements. Some technologies may work well together without people knowing about it and may only become evident later. As the revolution progresses, new opportunities or challenges can emerge, which will cause further changes and possible disruptions. Therefore, it is important to be prepared for the 4IR by understanding how it will impact the world, embracing the emerging technologies and ensuring an appropriate approach is followed.

2.2 Cross-Border Supply Chains

This section explores global supply chains to gain a better understanding of what they are, how they work and the challenges that they face. Section 2.2.1 aims to explain what cross-border supply chains are, their benefits and drawbacks, and other key related terms. Section 2.2.2 looks at the current state of international supply chains, how they changed over time and certain trends that are currently present. Section 2.2.3 discusses various challenges and problems faced by companies in cross-border supply chains. This section also discusses various sources of disruption and risk and presents some strategies that currently exist to deal with these issues. The effect of the COVID-19 pandemic on cross-border supply chains in discussed in Section 2.2.4, that presents a brief history of the viral outbreak and discussion of how supply chains need to react, according to experts. Finally, Section 2.2.5 looks at requirements for a global supply chain to be successful in the digital age.

2.2.1 What is a cross-border supply chain?

A definition of a *supply chain* that is often cited in literature (e.g. Altay and Ramirez, 2010; Msimangira and Venkatraman, 2014) is that of Mentzer et al. (2001), who define it as, “a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer.” Based on this definition, a cross-border supply chain, also known as an international or global supply chain in many cases, is one that spans the globe, thus crossing the borders of multiple countries, meaning that participants are located in different countries. Raw materials may be sourced from an African country, products using those raw materials may be manufactured somewhere in Asia and the final products may be sold in North America. In contrast, organisations in a local supply chain have suppliers and manufacturers in the same region as the organisation itself.

There are various drivers of cross-border supply chains. The main one is globalisation – the “integration of local and national economies into a global, unregulated market economy”, according to Guttal (2007). Globalisation is in turn driven by the consumer’s demand for quality products at lower prices (Mascaritolo and Holcomb, 2008). These demands encourage companies to find low-cost sourcing, manufacturing, logistics, and other operations that may only be available in other countries or regions (Hameri and Juha Hintsa, 2009).

There are many reasons why companies choose to be part of global supply chains, rather than relying solely on local suppliers and manufacturers. By sourcing from countries where raw materials are in greater supply, and offshoring labour-intensive manufacturing tasks to countries where labour and production costs are lower, companies are able to cut various costs (Baldwin, 2012). Furthermore, companies can outsource activities to specialists, thus ensuring higher quality results at the expense of having less control over the process (Baldwin, 2012). Being part of a cross-border supply chain enables an organisation to spread their risks among different parties (Eckert and Hughes, 2010). For example, when a natural disaster occurs in the region where the organisation is based, having a supplier or manufacturer in a different region is beneficial, as they are less likely to be affected. Global supply chains allow companies to be more competitive, since it gives them access to more suppliers, manufacturers and markets in which to sell their products or services (Hameri and Juha Hintsa, 2009).

In an international supply chain, there are various distinct, but interconnected entities, such as exporters, importers, inspection companies, insurance companies, banks and customs administrators, among others (Hameri and Juha Hintsa, 2009). Other stakeholders include suppliers, manufacturers, retailers, logistics service providers, port authorities and governments (Markmann, Darkow, and Von Der Gracht, 2013). Types of organisations that play a massive role in economic growth and are also highly involved in global supply chains, are small and medium enterprises (SMEs). They supply goods and services to large companies and provide many job opportunities in all economies, yet SMEs do not receive much support from governments. They also face greater pressure to be more competitive in domestic and global markets (Kumar and Singh, 2017), thus, forcing them to join a cross-border supply chain to stay competitive.

In general, global and modern supply chains are much more complex than traditional and domestic supply chains due to various reasons. Trienekens et al. (2012) discuss characteristics of food products and production processes that contribute to the complexity and dynamism of modern food supply chains, although it is also applicable to other global supply chains. Firstly, there are various actors that need to collaborate for the end product to be successful. Secondly, precedence relationships between different processes require transparency and thus reliable information, which can dramatically increase complexity when there are many relationships. Thirdly, and more applicable to food supply chains, certain product characteristics, such as quality deterioration and variation in fresh foods add complexity to scheduling and pricing. Finally, transparency and providing partners and consumers with reliable and accurate information further increases complexity.

Markmann, Darkow, and Von Der Gracht (2013) list globalisation, the implementation of lean structures and process and the variety of stakeholders in supply chains as reasons for increased complexity and thus also risk. Delays can be caused by ever-changing regulations, customs requirements and compliance or risk issues that further add to the complexity (Downes, 2019). Another disadvantage of an international supply chain is that products are handled by many parties as it moves down the supply chain across various borders, thereby increasing the risk to product safety and security (Marucheck et al., 2011). Furthermore, the fact that supply chains are more global and interconnected mean that they are more vulnerable to disruptions in an area where a stakeholder is situated (Butner, 2010).

The importance of transparency, visibility and collaboration in international supply chains

Some concepts are vital for global supply chains to function smoothly. Supply chain transparency is defined by Hofstede et al. (2004) as, “the extent to which all its stakeholders have a shared understanding of, and access to, the product-related information that they request, without loss, noise, delay and distortion.” Harbert (2020) identifies two elements of supply chain transparency:

- Visibility: gathering reliable and accurate information from all parties in the supply chain,
- Disclosure: sharing the information with internal and external stakeholders at a required or desired level of detail.

In food supply chains, for example, transparency allows consumers to know the origin and history of their food (Trienekens et al., 2012), thus reassuring them of the safety of their food.

Another concept that plays a massive role in global supply chains is *visibility.* As previously mentioned, it is one of the enablers of transparency. Supply chain visibility is described as the ability to identity, locate and determine the status of entities flowing through the supply chain when required using messages that describe certain events, including the planned and actual dates and times of these events (Francis, 2008). Visibility is key to dealing with supply chain risks (Hintsa et al., 2012), as it provides greater insight into the supply chain and allows problematic points to be identified. An example of how visibility can be beneficial to supply chains is that it enables companies to identify the source of an issue and quickly recall the right products from the correct location when needed to minimise damage (Trienekens et al., 2012).

A third important concept in cross-border supply chains is *collaboration.* Companies need to work together with other stakeholders in their supply chain to identify and mitigate risk by sharing information with their partners (Trienekens et al., 2012), and involving suppliers and buyers in decision-making (Kumar and Singh, 2017). Collaboration is required among supply chain members to realise end-to-end visibility, since they need to share information among one another (Jüttner and Maklan, 2011). Through a series of interviews with senior supply chain executives, Butner (2010) found that top supply chains are improving their visibility by collaborating with other parties.

The next section discusses the current state of global supply chains and looks at how they are changing, as well as best practices, trends and various influences.

2.2.2 The current state of cross-border supply chains

Over time globalisation has dramatically increased the levels of international trade in the world, consequently amplifying the need for cross-border supply chains for companies and economies to be competitive.

Trienekens et al. (2012) focus on how the food industry has changed – specifically consumers. They are more likely to buy products that are safe, healthy and of high and consistent quality and require these standards to be satisfied. When things go wrong, it's necessary to be able to respond effectively and quickly. This can only be done if the correct information is available, thus emphasising the need for transparency in supply chains. Another change that was noticed in consumers is that each has their own set of specific demands and wishes regarding products (Canever, Van Trijp, and Beers, 2008), consequently leading to the trend of mass-customisation, one of the drivers of the 4IR as mentioned earlier. Global sourcing, cost reduction and lean manufacturing initiatives have made modern supply chains more complex and vulnerable to risk and disruptions, since they are associated with fewer resources to absorb unexpected shocks (Mascaritolo and Holcomb, 2008).

According to Myers and Cheung (2008), global supply chains are becoming less push-oriented and more demand-driven or pull-oriented. The focus is therefore on understanding customer needs and adapting supply chains to cater for actual demand levels instead of forecasted demand or scheduled production. Understanding customer needs enables companies to achieve higher service levels, thus resulting in greater customer loyalty. Butner (2010) mentions relatively recent changes to supply chains at the time their research was published:

- Supply chains are spreading geographically due to globalisation;
- Increasingly more companies are becoming involved in supply chains;
- The range of activities that are outsourced is broadening; and
- Product portfolios are expanding rapidly.

Manavalan and Jayakrishna (2019) look at a large time frame when discussing changes in supply chains. Since 2000, supply chains have been integrated using mobile devices and digital applications and have experienced high levels of automation. As supply chains expanded globally, competition increased, motivating companies to reduce all forms of waste. This eventually led to the concept of lean manufacturing, a philosophy that aims to improve quality and efficiency in supply chains by completely eliminating waste and non-value adding routine activities. More recently, supply chains have been focussing on sustainability from social, environmental and economic perspectives.

In support of transparency, many organisations, especially those in the food industry, are looking to improve their supply chain's track and trace capabilities (Wognum et al., 2011), a process concerned with the provenance and whereabouts of items in the supply chain (Van Dorp, 2002). Tracking refers to the identification of a product and its current state in a downstream direction from the supplier to the end user. Tracing, in contrast, refers to determining the path an item has followed and its point of origin in the supply chain in an upstream direction from end user to supplier (Musa, Gunasekaran, and Yusuf, 2014). Traceability in supply chains is necessary, because any issues with products need to be identified, the source located and the problem resolved as quickly as possible. The large number of companies in international supply chains that handle the products means that there are many points for potential problems, thus increasing the difficulty of implementing a successful track and trace system throughout the entire supply chain (Wognum et al., 2011).

Information sharing between parties in supply chains is an enabler of many other processes. According to Hameri and Juha Hintsa (2009), collaboration and networking between organisations and governments involved in a global supply chain is seen as a key success factor, which is of course enabled by information sharing. Visibility is also possible when supply chain partners participate in information sharing activities and enables companies to effectively respond when unexpected events occur (Jüttner and Maklan, 2011). Myers and Cheung (2008) discuss a study that found three unique qualities of leading supply chains:

1. Agility: the ability to quickly react to unexpected changes in supply or demand;
2. Adaptability: allows them to adjust to changes in the market structure and environmental conditions; and
3. Alignment: the interests of all stakeholders of the supply chain network are aligned to optimise performance.

These qualities are only possible when information and various types of knowledge are shared among different nodes in the supply chain. Myers and Cheung (2008) conclude the idea by stating that the flow of knowledge is the key to enabling a supply chain to become a true value chain for all stakeholders.

2.2.3 Challenges in cross-border supply chains

This section focusses on the various challenges faced by organisations that have supply chains spanning the globe. It starts off with a discussion of common problems and issues, followed by certain risks and possible disruptions that companies need to be aware of and finally ends with a look at existing solutions and strategies.

Obstacles to overcome

Challenges, problems and different issues identified in literature are loosely grouped into various categories. The first category relates to the flow of information and collaboration between supply chain partners. Wognum et al. (2011) mention a common challenge for organisations aiming to improve their transparency. It is difficult to convince supply chain partners to follow a shared supply chain approach that has a common strategy development and integrated management- and information systems. There are also concerns regarding the availability of data when required, as well as the quality and reliability of information that is shared throughout the supply chain (Trienekens et al., 2012).

Collaboration with suppliers, distributors, customers and other stakeholders is challenging, especially for SMEs, since they usually have fewer systems in place that facilitate such collaboration (Kumar and Singh, 2017). The authors also mentions various other coordination issues identified by other researchers (e.g. information sharing and agreeing on a vision and goals with supply chain members, supply chain risk or reward sharing, development of reliable suppliers, data integration between internal functions, reliable logistics systems, etc.). Similarly, they also list responsiveness issues found in literature (e.g. information sharing and information systems issues, the use of emerging technologies, among others).

A common supply chain risk mitigation strategy is risk sharing, where collaborating parties jointly absorb disruptions, enabling greater flexibility to all parties in the supply chain, instead of causing a single party to experience disruption, consequently affecting the rest of the supply chain negatively. Unfortunately, a lack of trust and collaboration are obstacles to achieving flexibility in this way (Jüttner and Maklan, 2011). Myers and Cheung (2008) mention the importance of relations within supply chains, emphasising that strong, cross-national relationships enable innovative environments that create a competitive advantage for those involved. This is only possible when knowledge is shared between companies. Unfortunately, this is quite controversial because many supply chain partners are less prone to participate in activities that would benefit their partners more than it would their own company – even if it will have a net positive influence on the supply chain. Often, these partners see themselves as competing among one another, instead of other supply chains, which hinders collaboration.

Another problem identified by Myers and Cheung (2008), is the disproportionate reward that buyers and suppliers receive when sharing knowledge. While both parties win, suppliers enjoy significantly more benefits than buyers. The authors attribute this to two possible reasons: the current prevalence of demand-driven supply chains and the fact that buyers tend to be more lean that suppliers, thus having less room for improvement. Msimangira and Venkatraman (2014) briefly discuss three major problems relating to supply chain integration. The first problem is that many managers pursue integration approaches that are favoured by senior management and not necessarily based on best practices. The second issue is the lack of information sharing across companies in supply chains, which leads to the third problem: a lack of integration among supply chain partners.

Two problems identified by Osborn and Nault (2012) fit into the first category. Conflict between partners is caused when their goals do not align or are unclear. Opposing goals are unfortunately quite common, since many parties act in their own best interests and not necessarily those of the entire supply chain. The other problem relates to the accuracy of information. They specifically mention inaccuracies due to manual data entries, point of sale (POS) data where speed is prioritised over accuracy, and lapses in judgment during forecasting.

Through a series of interviews with senior supply chain executives, Butner (2010) found key issues that summarise the current state of supply chain management, two of which belong to this category. Supply chain executives are struggling with the massive amounts of data available to them. The challenge is identifying, capturing, analysing and acting on the right information and making it available to those that need it. Another issue is customer intimacy. Companies tend to have better relationships with their suppliers than with their customers, since customer interaction seems more expensive and time-consuming. However, in the era of the 4IR where demand-driven customer-focussed supply chains are predominant, collaborations with customers are increasingly important.

The last set of issues in this category are those identified by Mohan, Berg, and Poblet (2020) relating to the real-time flow of information. First, is organising the sharing of information. Systems need to be in place where supply chain partners can access the data they require. Second, is deciding who has the ability to control the flow of information. Third, is how confidential supply chain information of firms will be protected. The fourth issue is updating and sharing the information in real-time. These issues were identified with the COVID-19 pandemic in mind, but are also widely applicable to global supply chains during non-disruptive times.

The second category of challenges is concerned with materials, resources and products. A major problem in many supply chains, especially prevalent in the food industry, is the quality variability of products (Trienekens et al., 2012). Reducing such variability will allow companies to add greater value to their products and better meet consumer demands. This problem is also referred to by Kumar and Singh (2017), who state that organisations, especially SMEs are under pressure to improve product quality and features to keep up with customer demands. They also mention that resource scarcity is a major problem that SMEs face when competing in the global supply chain environment.

An important issue brought up by Osborn and Nault (2012) falls into the second category of problems. They describe the bull-whip effect, “a phenomenon in which order variability increases as it moves upstream in the supply chain”, as a cause of unexpected demand fluctuations. This variability makes is difficult to maintain the appropriate levels of inventory, leading to either inventory excess or shortages. Higher inventory levels are useful for acting as a buffer during times of uncertainty, but it also incurs holding costs, reduces liquidity and increases product security risks. Lower inventory levels, a key aspect of the lean philosophy, can be useful for increasing efficiency, but exposes organisations to the possibility of shortages or stock-outs, where readily available supply is not enough to cover demand.

Mascaritolo and Holcomb (2008) also mention the availability of fewer resources to absorb any unexpected shocks in demand and attribute it to global sourcing, cost reduction and manufacturing initiatives that follow the lean philosophy.

The third category of challenges consists of standards and regulatory issues. High compliance standards are increasing due to growing governmental and public concerns regarding management practices of public interest such as environmental impact, financial accounting and supply chain security (Hameri and Juha Hintsa, 2009). Complying to multiple supply chain standards has various cost implications – both for compliance and non-compliance. Wognum et al. (2011) mention a common problem is the focus on legal requirements aimed at promoting environmental and social sustainability. As many of these requirements require certain information to be made available, the challenge is to reduce the costs and increase the benefits of sharing that information.

Trienekens et al. (2012) point out the problem of choosing whether to integrate similar standards and remove any redundancies to increase supply chain efficiency or to develop new and more complex standards to stand out from competitors. They also mention the challenge of finding the correct balance between formal (legal contracts) and informal (agreements, trust, commitment) governance mechanisms between supply chain partners. The vast number of regulations and compliance requirements that companies have to deal with have become a major challenge to supply chain executives, with some describing it as a “five-fold” increase in governmental actions (Daugherty, Closs, and McConnell, 2016).

An emerging problem that came to light as the 4IR drew closer, is the lack of reliable standards for information exchange regarding the various emerging technologies associated with the 4IR (Monostori, 2018). These standards are especially critical to manage autonomous systems with a degree of artificial intelligence. One of the key areas that require further research, as identified by Marucheck et al. (2011), is for organisations to work with governments to develop new standards and regulations with the aim of improving safety and security throughout supply chains. A lack of collaboration is often present and leads to conflicting governmental regulations and industry standards.

The fourth category contains issues experienced by supply chain parties when national borders are crossed. To prevent illegal border-crossing activities, border security is constantly being increased. This makes the process of crossing into certain countries time-consuming. Looking at the U.S.-Mexico border, Cedillo-Campos et al. (2014) discuss how border security has been greatly enhanced since the terrorist attacks on 11 September, 2001. The border-crossing process consists of various steps and multiple checks and detailed inspections that can take up to a few hours. To add to the problem, shipments of goods that need to cross the border are accompanied by paperwork and other physical documents that need to be checked, which is also time-consuming.

In surveys with various top corporate, supply chain, logistics, operations, and procurement executives, Downes (2019) identified common issues experienced by shippers when passing through customs. These include: border delays, incomplete or incorrect customs paperwork, reduced visibility, long shipment times, expensive shipping costs, strict customs procedures, unforeseen costs and extra or too much paperwork. Another problem that the author identified is with regulatory requirements that organisations have to deal with in cross-border supply chains. The regulations are country specific, constantly changing and becoming ever-more complex, making it challenging to keep up.

According to some participants of the series of interviews and surveys by Daugherty, Closs, and McConnell (2016), it is increasingly difficult to comply with continually changing border-crossing regulations and trade controls. They also complained about inconsistent customs outcomes where a certain shipment is allowed at some times, but denied at other times, despite similar conditions.

The fifth category deals with general costs, tariffs and financing issues. Apart from high administration costs for traceability systems and the large investments it requires, Wognum et al. (2011) also mention the problem of justifying the price of sustainably-made products, mostly prevalent in the food supply chain. They explain that the social and environmental sustainability dimensions of products are not directly observable by customers, thus making it difficult to show them that products are more expensive in order to cover the sustainability costs.

Linking to the previous problem, Kumar and Singh (2017) mention the pressure that companies, especially SMEs, face to reduce their prices. What makes this challenging are the costs associated with sustainable production that have led to an increase in prices. They also refer to financing obstacles that organisations experience and that the adverse effect is much worse for SMEs than for larger companies. De Goeij (2020) attribute these financing obstacles mostly to unclear communication between large buyers and SME suppliers. A lack of trust towards the buyer or a poor explanation of their offer may cause suppliers to reject an attractive offer. In contrast, insufficient knowledge on the supply side may lead to a supplier accepting a poor offer.

Another problem in global supply chains is distribution costs. The sheer distance that materials and goods travel when moving through an international supply chain presents various challenges of which distribution cost is one. Yang (2013) notes that the greatest single expense in logistics systems is usually distribution costs, mostly due to the rapid inflation of wages, freight rates and transportation costs. Likewise, Downes (2019) mentions issues related to the current tariff environment in cross-border supply chains, as well as increasing freight rates and other shipping related costs.

Butner (2010) found that cost containment was by far the main priority for participants. The author writes about how costs are shifting too rapidly for conventional supply chain strategies to keep up. They mention sudden wage inflation, commodity price spikes and credit freezes as examples of these costs. The author goes on to explain that top-performing suppliers are moving away from efficient cost-cutting supply chains to more agile and responsive strategies to be able to quickly adapt to rapidly changing conditions. This partly addresses the problem that many supply chains are purely cost driven, when other factors, including service and quality should also be factored into the strategy (Daugherty, Closs, and McConnell, 2016).

The sixth category is security challenges. At the time of writing their paper, Hameri and Juha Hintsa (2009) saw new facility security measures taking up most of the security expenses, while expecting the cost of IT-related security measures to rise in the future. They saw theft as the largest security problem with terrorism concerns expected to increase over time. Since then, global supply chain security requirements have increased, leading to improved quality and risk reduction with the side effects of increased costs and delays due to security measures.

In their paper about security risks in cross-border supply chains, Hintsa et al. (2012) discuss the challenge of finding the balance between efficiency and security in supply chains, mentioning that many authors believe that information is critical in doing so. They state that although security improvement programs lead to higher freight fees and need investments in additional security technology, it will enhance supply chain resiliency in the long run, due to improved relationships between partners and increased information transparency.

Regarding the security of information throughout global supply chains, Osborn and Nault (2012) identify the problem of decreasing information flows between partners due to concerns for information leaks. While this is mainly due to lack of trust, improved data security measures may go a long way to increasing trust between partners. This problem may also be solved by security measures that remove the need for trust. Downes (2019) also briefly mentions that one of the problems many shippers face when transporting goods across borders is product- and information security.

The seventh category looks at challenges caused by the global and complex nature of international supply chains. The distance of the route that many goods travel along and the number of actors in global supply chains are just two of the factors that contribute to its complexity. Freight delays are quite common problems that can cause disruptions downstream in the supply chain. Another problem is information delays where data that was useful is now discarded because it did not reach the intended recipient in time (Osborn and Nault, 2012).

The complexity of global supply chains brings up issues that organisations face when designing supply chains. With so many available options, it is extremely challenging to make the right decision regarding the number and location of production facilities, capacity planning and supplier selection, for example (Meixell and Gargeya, 2005). Other barriers that organisations have to overcome to truly utilise global supply chains are cultural differences and languages in different regions of the world, problematic infrastructure in developing nations, questionable quality of suppliers and lack of certain technologies.

Butner (2010) states that supply chains are increasingly vulnerable to risks and disruptions as they grow globally and become ever-more interconnected. A minor delay upstream in the supply chain can propagate downstream and cause serious disruptions in supply chains that are not properly managed. Global expansion has led to various issues such as unreliable delivery, longer lead times and insufficient quality. Manavalan and Jayakrishna (2019) point out that companies starting to compete in the global market now face greater competition due to a much larger number of competitors when compared to domestic markets. On top of that, some organisations struggle with adapting to foreign markets that may differ substantially from domestic markets.

The eighth and final category contains problems related to the workforce and systems within companies. The speed at which new technologies emerge make it challenging for companies, especially SMEs, to do proper research, planning and eventually implement these technologies. Furthermore, many SMEs experience problems with human resource development and when developing new products (Kumar and Singh, 2017). The authors also mention the constraints that supply chain managers need to work with due to flat organisational structures and a lack of expertise. Meixell and Gargeya (2005) support the last point by naming insufficient worker skill levels as an issue in developing markets.

Marucheck et al. (2011) identify future research directions related to product safety and security in global supply chains. One issue is the need for improved tools and methodologies that enable more efficient management of information across the entire life cycle of a product. A second issue is the current selection of technologies available for tracking and tracing goods throughout the supply chain. Emerging technologies may provide superior tracing abilities than existing solutions which do not offer end-to-end supply chain traceability.

Daugherty, Closs, and McConnell (2016) discuss how talent may cause issues for supply chain managers. The pace at which supply chains change means that the demand for highly skilled supply chain professionals is increasing. The first challenge is hiring someone that is capable of dealing with the various problems that are presented to them. The second challenge is retaining employees and properly developing and utilising their talent. They mention the trend among younger generations in the workforce to move between jobs in search for new opportunities or greater rewards.

Risks and possible disruptions

The next part of this section contains a discussion on the various risks and disruptions that companies in cross-border supply chains face, which can potentially lead to major problems when it occurs. Peck (2006) describes supply chain risks as anything that impedes or presents a hazard to the flow of information, materials or products from the initial suppliers to the delivery of the finished product to the end-user. Monostori (2018) discusses these types of risks by referring to three different categories into which they can be classified.

Demand-side risks are caused by disruptions downstream in the supply chain. Examples include transportation and warehouse issues, inaccurate forecasts and thus possible shortages or excess stock, or improper supply chain coordination. This part of the supply chain is also where the bull-whip effect can originate. Aeppel (2010) say that this phenomenon occurs when downstream inventories are significantly increased or reduced. This demand volatility propagates upstream in the supply chain, increasing in effect the further back it goes, consequently leading to spikes in the need for materials and parts. Supply-side risks occur upstream in the supply chain and include supply risks, capacity problems, changes in technology or product designs, unacceptable quality and logistical delays (Monostori, 2018). Catastrophic risks include natural disasters, socio-political issues, pandemics, economic crises and terrorist attacks.

Markmann, Darkow, and Von Der Gracht (2013) name increased complexity caused by globalisation and lean structures and processes as the main drivers of supply chain risks. Disruptions may be caused by natural disasters, man-made accidents or intentional crimes including terrorism, theft and cyberattacks. They mention that the causes of these risks are not always well or equally understood by affected parties, which hinders their ability to mitigate the risks. To further challenge companies, the lack of up-to-date and accurate information, along with inexperienced risk advisors are also quite common problems.

Altay and Ramirez (2010) focus on the disruptive potential of natural disasters and mention that the consequences tend to worsen as the complexity and density of global supply chains grow. It is nearly impossible to understand what effect a disruption of one organisation's activities has on those of another organisation in the same supply chain. Therefore, visibility is key to understanding how companies in a supply chain is affected by disruptions. The authors also discuss how firms grow more vulnerable to disruptive events as they grow more dependent on suppliers and consumers, and keep pursuing lower levels of inventory with the goal of increasing cost efficiency. Similar to Chopra and Sodhi (2014), Altay and Ramirez (2010) say that companies find it difficult to justify consuming resources to proactively manage the risk of disruptive events, since they do not occur frequently and are hard to predict and manage.

Marucheck et al. (2011) discuss vulnerabilities of supply chains in several industries, with a focus on product safety and security. Food supply chains handle mostly perishable products that need to reach consumers long enough before expiring. A second issue is the global and highly interconnected nature of food supply chains that makes them vulnerable to more risks. Pharmaceutical supply chains deal with the possibility that the ingredients for their products may be contaminated or substituted as they flow downstream. Counterfeit drugs and secondary distributors that resell pharmaceuticals present additional safety problems to these supply chains. Supply chain vulnerabilities are driven by various factors, including dependence on single suppliers or suppliers in the same regions, global sourcing, common parts in different products, centralised inventories and customer dependence (Monostori, 2018; Chopra and Sodhi, 2014).

Existing risk mitigation strategies in supply chains

The final part of this section is used to discuss various types of solutions and strategies that are currently used to deal with the above-mentioned challenges and risks. Chopra and Sodhi (2014) state that organisations have two choices for managing the risk in their supply chain. The first is reducing risk while improving performance and the second is reducing risk while limiting the impact on cost efficiency.

Referring to the first option, Chopra and Sodhi (2014) claim the key to higher cost efficiency and reduced risk is by controlling the amount of complexity in the supply chain, which entails containing the impact of the disruption to a small part of the supply chain. This choice presents two strategies. The first is segmenting the supply chain by finding the correct level of centralisation and decentralisation, outsourcing certain processes, while performing others in-house and using different techniques for producing high and low cost- and demand goods. The second is to regionalise the supply chain by having multiple suppliers, manufacturers and other partners in different geographical regions, where a disruption in one region will not affect other regions. Unfortunately, the first set of strategies involves higher costs in the short term.

The second choice presented by Chopra and Sodhi (2014) is for organisations that do not want to sacrifice cost efficiency. The first strategy is to reduce the concentration of resources by increasing the number of facilities where resources are kept and using less common parts in products. The second strategy is to rather overestimate the probability of disruptions, as it was found to be much better for the long term than underestimating or ignoring it.

Ivanov, Dolgui, Sokolov, and Ivanova (2017) name two basic approaches to dealing with supply chain risks. A proactive approach aims to prevent the risk from occurring by putting defence mechanisms against possible disruptions into place, but does not provide for recovery activities if the risk does occur. A reactive approach aims to prepare the supply chain for dealing with risk when they do occur by adjusting processes and structures in the event of a risk. The authors imply that it is necessary to follow a combination of these two approaches, since disruptive events are not entirely avoidable, so reducing the probability of such an event and having a recovery plan for when it does occur, is recommended.

Msimangira and Venkatraman (2014) propose three solutions that may help improve supply chain management integration. These include two-way communication between partners to improve information sharing in the supply chain, the adoption of a holistic approach by upper management to shop floor workers and finally, the forming of strategic alliances between supply chain members that foster a culture of openness and honesty.

R. Liao and Fan (2020) provide four recommendations for expanding visibility across the entire value chain to make supply chains more resilient. Although these recommendations are made with the COVID-19 pandemic in mind, they are also highly applicable to other unexpected events that cause large scale disruption. The recommendations include:

- **Digitisation of information**. Wet signatures and paper printouts require personnel to be on site and coordinate with others in person. During a pandemic where physical presence is not possible, operations that depend on such physical assets face serious disruptions that can have massive cost implications. Digitising this information is thus vital to not only saving on costs, but also increasing visibility and managing risks.

- **Supplier data privacy assurance**. Suppliers need the ability to control who receives what data from them, as this will make them more likely to share information with other partners without fear of losing competitive advantage.

- **Providing greater incentives for suppliers to share their data**. Many buyers offer supply chain finance programs as a way of motivating suppliers to share their data. Unfortunately, these programs are only available to Tier 1 (direct) suppliers. Thus, these programs need to be made available to Tier 2 suppliers and beyond.

- **Starting to implement initiatives immediately**. By starting early with data sharing solutions and supply chain finance programs, companies can start to benefit and will be better prepared for future disruptions.

The next section looks at the effect of the COVID-19 pandemic on global supply chains and discusses how the world is expected to change.

2.2.4 The effect of the COVID-19 pandemic on cross-border supply chains

This section explores the impact that the COVID-19 pandemic had on international supply chains. First the history of the virus is briefly discussed, followed by how the pandemic has affected the world. Next, the section looks at how the world has reacted and is expected to handle the pandemic in the future. The section ends with recommendations for organisations to adapt their supply chains for surviving in the long term.

A brief history of COVID-19

On 31 December 2019, the World Health Organisation (WHO) received reports of a pneumonia of an unknown cause that was detected in the city of Wuhan in Hubei province, China (WHO, 2020). By 7 January 2020, the virus was identified as belonging to the coronavirus family, which include the Severe Acute Respiratory Syndrome (SARS) and Middle East Respiratory Syndrome (MERS) that the world has encountered in recent years. The first death related to the novel coronavirus was reported on 11 January (Muccari, Chow, and Murphy, 2020).

Only two days after the previous event, the first case of the novel coronavirus outside of China was reported in Thailand on 13 January (WHO, 2020). On 31 January the WHO declared the 2019-nCoV outbreak a global public health emergency with more than 9,000 cases worldwide (Muccari, Chow, and Murphy, 2020). On 11 February, the WHO officially gave the novel coronavirus disease the name of *COVID-19* (WHO, 2020).

On 3 March 2020, it was reported that health workers began experiencing shortages of personal protective equipment (PPE) such as masks, gowns, goggles, gloves and hand sanitizer, thus endangering their lives. By 7 March, COVID-19 had spread to 100 countries, infecting over 100,000 people. The alarming rate at which the virus spreads, the severity of the global situation and the lack of action in many areas led the WHO to declare the COVID-19 outbreak as a pandemic on 11 March, marking the first time that a coronavirus has caused a pandemic (WHO, 2020).

Consequences of the COVID-19 pandemic

Since its outbreak, the COVID-19 pandemic has affected the world in many ways. This part of the section focusses on its effect on international supply chains. The COVID-19 pandemic has exposed the vulnerabilities of complex and interconnected global supply chains across many industries – specifically those built on lean manufacturing principles (Park, K. Kim, and Roth, 2020; J. Lin and Lang, 2020). A surge in demand for essential goods, along with panic buying, hoarding and the misuse of PPE have led to widespread disruption in global supply chains (Park, K. Kim, and Roth, 2020). When looking at the production and distribution of PPE, major barriers exist that limit supply levels:

1. Shortages in raw materials, such as unwoven polypropylene that is used in N95 masks;
2. Not enough production lines that are capable of producing PPE materials;
3. High concentration of PPE manufacturers in Southeast Asia, where the outbreak occurred;
4. Export bans in certain countries on masks and other key materials due to domestic shortages; and
5. Other bottlenecks, including trade restrictions, quarantine measures, social distancing and limited workforce capacity.

To curb the spread of COVID-19, many governments imposed travel and trade restrictions, closed borders and forced non-essential businesses to shut down temporarily to restrict the movement of people and goods (Barua, 2020; Gruszczynski, 2020), which have had a devastating effect on global economies. The impact of the COVID-19 pandemic can be described by various waves.

The first wave can be loosely categorised as demand-side shocks on supply chains (Hobbs, 2020). The demand for essential goods, such as food and medicine surged, while demand for non-essential and luxury goods plummeted as consumers were more cautious in spending their money due to high levels of uncertainty (Gruszczynski, 2020). The spike in demand was further fuelled by panic-buying and hoarding behaviour. Most supply chains that provide food and other essential items are focussed on cost efficiency and are built around just-in-time principles that rely on low levels of stock and the continuous flow of products. The spike in demand, along with the disruption in the flow of products has thus made it nearly impossible for supply chains to keep up with the demand for essential items.

The second wave is mostly related to supply-side shocks and stems from the effect of lockdowns and restrictions on the movement of material, goods and people (Barua et al., 2020). As demand stabilises and becomes more predictable, the problem now shifts to supply. Trade controls are put into place to ensure that there is enough supply for domestic markets. However, this has greatly reduced exports and imports of goods, as well as services such as tourism and travelling. Consequently, many countries – especially those that are highly dependent on international trade – are concerned about potential food and PPE shortages due to the export restrictions in countries that mass-produce these items (Gruszczynski, 2020). Further disruptions to the supply of all types of goods are caused by labour shortages, transportation delays and the fact that many non-essential businesses and factories were ordered to shut down (Hobbs, 2020).

As the number of waves increase, the expected time frame of the impact also increases. Thus, as the third wave arrives and distortions in production, trade, investments and the flow of materials, goods and people continue, the impacts leave a longer lasting impression (Barua, 2020). Aggregate supply is decreasing due to the previously mentioned production shocks. Despite the increased demand for essential items and decreased demand for non-essential items, aggregate demand is also decreasing, since the majority of world production and trade consists of non-essential goods and consumers are spending their money more responsibly due to high levels of unemployment and income uncertainty (Barua et al., 2020). Ironically, these conditions cause many companies to reduce their workforce in an attempt to survive, leading to increased levels of unemployment and a reduction in income levels.

The fourth wave comes with long-term consequences. As became evident at the start of the COVID-19 pandemic when factories, production facilities and other business in China and other parts of Southeast Asia were shut down, many companies throughout the world realised that their global supply chains are overly dependent on globalisation (Barua, 2020; Park, K. Kim, and Roth, 2020). Major changes are experienced in global sourcing, production and trade as firms reduce their dependence on other countries by diversifying their supplier base, shortening their supply chains and moving activities closer to home (Gruszczynski, 2020). In the long term, stricter rules and regulations regarding immigration and travel, along with more trade and investment barriers will emerge. Stricter hygiene and biosafety requirements may also pose additional challenges to supply chains. Overall, a shift in worldwide production is expected as patterns of de-globalisation emerge (Barua, 2020; Gruszczynski, 2020).

In their study on the role of global supply chains in the impact of the COVID-19 pandemic on gross domestic product (GDP) growth, Bonadio et al. (2020) note that even countries that are not directly affected by the COVID-19 pandemic can be indirectly affected, since most supply chains cross borders in some way or another and are thus vulnerable to disruptions in other regions. The authors found that foreign shocks are transmitted through global supply chains and have a greater effect on countries that are tightly integrated into international supply chains. A trend that was noticed is the renationalisation of global supply chains as companies start using local suppliers and manufacturers. The authors found that, in most cases, renationalisation actually leads to a greater GDP contraction than the combination of domestic shocks (i.e. directly affected by the pandemic) and transmission of shocks through global supply chains (i.e. indirectly affected). They conclude on renationalisation as only being beneficial to countries with less severe lockdowns that have a smaller impact on domestic supply chains.

Looking at the future of global supply chains in the wake of COVID-19, a few patterns are expected to emerge. International relations and economic cooperation will change based on how countries reacted to the pandemic, leading to new relationships and trade agreements. As mentioned earlier, stricter regulations and new trade barriers may bring additional challenges to supply chains (Barua et al., 2020). A major pattern that has already started to emerge before the pandemic, is the reduction of dependence on China, the world's supply, demand and manufacturing superpower (Barua, 2020). The change started due to increasing Chinese labour costs and is now accelerated as companies realise the problem of being dependent on players in a single region. The trend is known as regionalisation and refers to eliminating single-source dependencies by sourcing, assembling and delivering from regions or countries closer to their market (Buatois and Cordon, 2020).

On a more extreme scale than regionalisation, the trend of de-globalisation may emerge where the production of essential goods will be done domestically to increase independence on other countries during an emergency (Barua, 2020). A consumer trend that has been ongoing in food supply chains that is expected to accelerate is the idea of purchasing locally produced food as it has economic, environmental, social and health benefits (Hobbs, 2020). This idea will be strengthened due to shortage concerns caused by empty shelves and long queues at stores. Local food suppliers have few global dependencies and are thus able to keep their supply constant when many international food producers experience disruptions.

Future expectations

The key to dealing with the uncertainty caused by the pandemic is supply chain visibility (Kilpatrick and Barter, 2020; Buatois and Cordon, 2020). The first thing that companies should focus on is improving visibility in their supply chain to be able to identify potential risks related to their own facilities, their direct suppliers and parties further upstream. An overview of the entire supply chain will enable organisations to understand the impact of a disruption on the various parties of the supply chain (Buatois and Cordon, 2020). Due to the complex and global nature of modern supply chains, the key to end-to-end supply chain visibility is digitalisation.

Multiple authors provide recommendations on developing new policies. Barua et al. (2020) say that policy measures should be as inclusive as possible to ensure that the number of economies, activities or agents that benefit from it, is maximised. New measures must be driven by innovation and not based on less effective traditional policies. They also say that measures must be collaborative with other countries or regions, as more may be achieved by teamwork.

With a focus on food supply chains, Hobbs (2020) mentions the importance of ensuring that agricultural and food supply chains, along with the enabling services, such as logistics and maintenance are deemed as essential businesses and their employees as key workers. New regulations may not encumber the operation of essential international supply chains. Furthermore, panic-buying and hoarding behaviour must be better understood to develop policy responses that supply chains can follow to prevent such behaviour from occurring. The author also mentions problems that vulnerable populations face, including food shortages, high prices and unsafe conditions. New policies should therefore focus on ensuring that food and other essential non-food items are available to these populations.

The final section of this chapter discusses the main requirements for global supply chains to improve their sustainability and to ensure that they are successful in the future.

2.2.5 The future of cross-border supply chains

This section summarises recommendations by various authors on how international supply chains need to adapt to be more sustainable and future-proof to ensure they can keep operating successfully in the future. Although many of the ideas have been mentioned in Sections 2.2.2 and 2.2.3, this section aims to summarise these requirements and present them with the previously identified problems and challenges in mind.

Critical success factors

Hameri and Juha Hintsa (2009) identify collaboration between companies within a network and governments as a key success factor, noting that some basic requirements for this include automated data collection, improved data transparency, better data security and information management in complex supply chains. Trienekens et al. (2012) also hit on the importance of transparency, but focus on the food and agriculture supply chains. Transparency relies on ICT to facilitate the reliable exchange of information, quality and safety standards to protect public health and safety, and governance mechanisms between supply chain partners. Therefore, companies should focus on improving these aspects of their networks.

Regarding supply chain resilience, Ivanov, Dolgui, Sokolov, and Ivanova (2017) say that investing in proactive risk measures can help avoid most disruptions, but they also emphasise the importance of having reactive recovery policies when such disruptions are unavoidable. Jüttner and Maklan (2011) go into more detail by discussing four resilience capabilities that can help organisations to contain risks. Flexibility allows supply chains to effectively adapt to changing environments such as unexpected fluctuations in demand, for example by switching to more cost-effective suppliers or to reallocate capacity when required. One way to increase flexibility is to use multiple suppliers, instead of depending on a single supplier (Altay and Ramirez, 2010).

The authors also mention how critical visibility is to supply chain resilience. Visibility into the supply chain allows companies to react to risks in time and take the correct action before it is too late. The main enabler of visibility is information sharing between all partners in the network, which links to the next capability. Collaboration is vital for containing risks and solving various problems. Through constant communication and working together, these companies can reduce the impact of disruptions. This point is also echoed by Kumar and Singh (2017), who state that SMEs require collaboration with other partners, information sharing throughout the supply chain, and greater involvement of suppliers and customers in decision-making processes for effective coordination. This is essential for avoiding delays, unnecessary costs and quality problems.

Myers and Cheung (2008) hit on the importance of knowledge sharing across borders. Although suppliers may benefit more than buyers from sharing their information, both parties still enjoy benefits.

Companies must thus encourage partners to share knowledge for the greater good of the supply chain. The authors mention that the disproportionate benefits may cause tension, so suppliers must be willing to address it.

Marucheck et al. (2011) identified four areas in which companies in global supply networks can improve. Firstly, new regulations and standards that are aimed at improving safety and security need to be developed in collaboration with governments and industry associations. Secondly, better tools and methodologies for managing all information regarding the stages of a product's life cycle are required, as this will enable companies to trace any problems back to their origin. Thirdly, new technologies that are more capable than existing systems for tracking and tracing products throughout global supply chains are required, as this allows the impact of any quality or safety problems to be dampened. Fourthly, time and effort must be invested to improve supplier relationships in such a way that safety problems due to pressure to reduce costs and increased complexity can be avoided.

In order for supply chains to become smarter, they need to overcome certain challenges (Butner, 2010). Flexibility is vital for adapting in volatile environments or to unexpected changes. Visibility is critical for improved planning, real-time decision-making and execution, and awareness of risks in the supply chain. Risk management must be more comprehensive to account for new risks that increased complexity and interconnectivity. More should be done to determine customer needs and usage patterns by interacting with consumers during the entire life cycle of the product. Finally, vast cross-border supply chains need to be integrated for improved efficiency, as it tends to decline as these networks grow larger and more complex.

The importance of digital technologies

An idea that is abundantly mentioned in literature is *digitalisation*. Yang (2013) talk about the benefits of ICT in sharing digital information and mention the increasing need for effective ICT systems as supply chains become longer, more complex and start crossing more country borders. Mohan, Berg, and Poblet (2020) discuss how digital infrastructure can play a key role in extending supply chain visibility, which increases overall resilience to disruptions such as the COVID-19 pandemic. They specifically mention how DLTs, like blockchain, provide the technical capabilities to deal with many of the problems experienced in cross-border supply chains – particularly those related to information sharing.

To effectively prevent or manage supply chain risks, companies require visibility of these risks. While the risks of the company's own facilities and their direct suppliers may be visible, this visibility must be extended to both ends of the supply chain to be truly aware of all the risks in the network. Kilpatrick and Barter (2020) state that this requires a more digitised approach than most companies are currently using. They describe the emergence of digital supply networks (DSN) that are specifically designed for being more resilient towards disruptions and have the ability to reconfigure themselves to dampen the impact of disruptions. The traditional view that supply chains are linear is left behind and organisations are connected to each function of the supply network. This enables end-to-end visibility, collaboration, responsiveness, agility and network-wide optimisation.

In their article discussing how global supply chains will change after COVID-19, J. Lin and Lang (2020) emphasise the key role of digitisation in building stronger, smarter and more resilient supply chains. They specifically mention how new supply chain models need to support the digitisation of paperwork associated with global trade and how this will improve buyer-supplier relationships that still rely heavily on time-consuming paper-based systems. Digital technologies will not only increase supply chain resilience to future shocks, but may also ensure privacy for information shared throughout the supply chain (R. Liao and Fan, 2020).

2.3 Chapter Summary

Key findings from the first part of the literature review can be summarised as follows. Digitalisation and automation play a large role in the Fourth Industrial Revolution, which will transform industries through certain digital technologies, such as IoT, CPS, AI, autonomous robots and more. The main opportunity for the 4IR is higher levels of productivity, flexibility and efficiency, while the largest barrier seems to be the disruption that it will cause. Literature presents various approaches to the 4IR, but the main idea is that firms must be open to change.

Cross-border supply chains face a range of challenges, the most pressing being issues with information flows and collaboration; standards and regulations; costs; security challenges; and the general complexity. A lack of visibility into the supply chain puts stakeholders at risk when disruptions occur. This is caused by limited and inefficient information flows between stakeholders, among other reasons. By making it easier to share information and increasing trust between stakeholders, such information flows can be made much more efficient, resulting in reduced costs and increased responsiveness. A recent event that accelerated the digitalisation of global supply chains was the COVID-19 pandemic, which highlighted certain drawbacks of globalisation. It forced firms to find solutions to problems that have been on the horizon for a while, but became more severe as the pandemic broke out.

The first chapter of the literature study reviewed two main topics. The first theme was the Fourth Industrial Revolution. It started off by exploring previous industrial revolutions, which then led to the idea behind the 4IR to understand why it is happening and what it entails. The technologies that play a large role in the 4IR were discussed, along with various challenges, opportunities and requirements of the 4IR. Finally, various recommended approaches for utilising the 4IR successfully were mentioned.

The second theme was cross-border supply chains. To understand the topic better, the idea behind global supply chains, as well as their benefits, drawbacks and various participants were explained. The status quo of cross-border supply chains was summarised, followed by a discussion on the various challenges and issues experienced by organisations in these networks. The COVID-19 pandemic and its impact on international supply chains were looked at, followed by a discussion on recommendations and expected changes for the future of global supply chains.

Chapter 3 continues the review of literature by looking at two other major themes: supply chain digitalisation and the use of blockchain technology in cross-border supply chains.

CHAPTER 3

Supply Chain Digitalisation and Blockchain

The second part of this literature review addresses two other topics that are highly relevant to this research. The first topic is *supply chain digitalisation* and explores the use of digital technologies to transform supply chains from a series of linear and discrete steps to integrated and interconnected networks. The second topic is *blockchain*, an emerging technology that shows great potential for improving and securing information flows throughout supply chains.

3.1 Supply Chain Digitalisation

This section discusses how supply chains are expected to change during the 4IR. It starts off by distinguishing between the three terms “digitisation”, “digitalisation” and “digital transformation”. Next, the importance of digitalisation is discussed to convey why it is necessary for supply chains to adapt in the digital era of the 4IR. Various benefits and opportunities associated with supply chain digitalisation, as well as challenges and problems are brought up. The 4IR technologies that enable digitalisation are discussed, including their applications, benefits and drawbacks. Next, the concept of paperless trade is addressed to highlight its role in supply chain digitalisation. Finally, the section ends off with a discussion of general requirements and enablers of digitalisation.

3.1.1 Digitalisation and its importance in supply chains

One of the most important elements of the 4IR is *digitisation*, which optimises information flows within the supply chain by converting data from an analogue to digital format, for example creating digital copies of physical documents, photos or videos (Bloomberg, 2018; Klötzer and Pflaum, 2017; Parviainen et al., 2017). While digitisation is a key feature of the 4IR, it is not a new concept. The era of the 3IR introduced the concept, but focussed only on basic digitisation, for example connecting actuators in a manufacturing facility to a computer that communicates with other stations. The new era of digitisation during the 4IR focusses on advanced digitisation that enabled decentralised information sharing and automation. An example is connecting actuators directly to other stations using sensor technology, thus eliminating the need for a centralised computer that links them (Schniederjans, Curado, and Khalajhedayati, 2020).

Digitalisation is the process of changing a business model to generate new revenue streams and value-producing opportunities through the use of digital technologies and is made possible by the digitisation of information (Gartner, 2020). It is more than simply investing in digital technology; it is about using the digitised resources to change business models to include automating processes and turning existing products or services into digital variants, thus creating a competitive advantage over the physical counterparts, which adds additional value to the offerings of a business (Parviainen et al., 2017; Karabulut, 2020). In short, digitalisation is about moving a business from a physical to a digital environment (Isaksson, Wennberg, et al., 2016).

TABLE 3.1: *Digitisation, digitalisation and digital transformation (adapted from Karabulut, 2020).*

	Digitisation	**Digitalisation**	**Digital transformation**
Focus	Transformation of data	Processing of data	Efficient use of information
Goal	Optimisation of information flows	Automation of business processes	Change in the way companies think and operate
Activity	Conversion of physical documents from an analogue to a digital format	Use of digital technologies to create new revenue streams	Creation of new business models and a change of mindsets
Tools	Computers and related software, scanners, microphones	Digitised resources, ICT systems and applications	Emerging digital technologies
Challenge	Materials	Finances	Human resources

Digital transformation has a larger scope than digitalisation. It requires strategic organisational changes that are customer-driven and backed by leadership, and includes the widespread implementation of digital technologies, e.g. the digitalisation of various processes (Bloomberg, 2018). Digital transformation is about adapting entire organisations to be more digitally oriented by changing the company's strategy, processes and organisational culture (Büyüközkan and Göçer, 2018; Gomez, Grand, and Grivas, 2015). These changes include new leadership approaches, different ways of thinking and working, the creation of new types of business models, improved ways of interacting with suppliers, partners and customers, and changes in how companies compete in global markets (Agrawal and Narain, 2018; Büyüközkan and Göçer, 2018). These three connected concepts are compared in Table 3.1.

Drivers of supply chain digitalisation

The business environment in which supply chains operate is experiencing massive changes. In line with the 4IR that is changing supply chains to place more emphasis on consumers, many of these changes relate to consumer behaviour and demands. Trends such as growing expectations, individualisation and customisation have been noticed in the consumer behaviour (Bienhaus and Haddud, 2018; Alicke, Rexhausen, and Seyfert, 2017). They expect increased availability, global consistency, shorter lead times, and a more personalised experience (Markovitch and Willmott, 2014; Markovitch and Willmott, 2014; Agrawal and Narain, 2018). Consumers are growing more aware of the products they consume and are demanding more information regarding the environmental and social sustainability of products (Kittipanya-Ngam and Tan, 2020).

Due to the increase in digital technologies and access to the internet, the trend towards servitisation is emerging, where companies create more value by increasing the number of services they offer or even replacing traditional products with digital services (Vendrell-Herrero et al., 2017; Alicke, Rachor, and Seyfert, 2016). New production methods use digital technologies, thus requiring improved connectivity and information sharing (Bamberger et al., 2017). Online shopping has given consumers access to a variety of digital platforms selling various different products, thus expanding the reach of supply chains to different parts of the world (Alicke, Rachor, and Seyfert, 2016; Agrawal and Narain, 2018).

Globalisation continues to expand supply chains by increasing the area it encompasses, the number of stakeholders involved and the diversity of the markets it serves, consequently making global supply chains more complex. The complexity puts pressure on companies to increase their competitiveness by transforming their approach to be more adaptive and connected along the value chain (Zangiacomi et al., 2020). Digitalisation is a major driver of competitiveness and enables companies to innovate in order to be more competitive (Zimmermann, 2016).

The extended nature of global supply chains makes them more vulnerable to disruptions in different areas of the world. Thus, as supply chains continue expanding into different geographical areas, the chances of being affected by man-made or natural disasters increase. This volatile business environment calls for companies to digitalise their supply chains to be more responsive and resilient (Forkel, Clauß, and Schumann, 2019). The COVID-19 pandemic has increased the speed of digital globalisation, which entails the digital transformation of economies, resulting in new ways of consumption, commerce, investment and management (Schilirò, 2020).

Another factor that changes the business environment is the increasing complexity of products. The combination of hardware, software, sensors, data storage and microprocessors make products smarter, able to communicate with other objects and will lead to an improved user experience (Klötzer and Pflaum, 2017). Combining smart products with data-driven supply chain processes enables self-organising and self-optimising systems to be developed and allows companies to deliver services alongside their products (Pflaum, Bodendorf, et al., 2017), which links back to the concept of servitisation.

Traditional supply chains are not equipped to deal with the changing business environment described above. While Chapter 2 discusses the challenges experienced in cross-border supply chains, it is necessary to narrow the focus to problems that have the potential to be solved through digitalisation. One such problem is the flow of paper throughout the supply chain. J. Lin and Lang (2020) state that the relationship between many buyers and suppliers is predominantly paper-based, meaning physical documents are exchanged when conducting business. These paper-based systems are subject to increased human errors, losses and delays (Carlan et al., 2018; Karabulut, 2020), among other problems.

Lack of visibility and transparency are problems that are present in most supply chains (Menon and Shah, 2019). Traditional supply chains are made up of mostly discrete steps connected in a linear fashion (Büyüközkan and Göçer, 2018). Consequently, most actors tend to only interact with their direct neighbours, leading to limited visibility. As these supply chains grow in complexity, visibility and transparency become even more important for companies to be able to understand what is going on in their supply chains and thus be better prepared for possible disruptions. The problem with traditional supply chains is that many do not have adequate systems in place for collecting, managing and utilising data that is accurate and reliable and sharing it between different partners (Carlan et al., 2018; Schrauf and Berttram, 2016). Thus, the correct information is not always available when required (Strandhagen et al., 2017).

A problem frequently mentioned in literature is the decreasing effectiveness of the cost-cutting, waste-reducing lean philosophy that many supply chains follow (Pflaum, Prockl, et al., 2018; Klötzer and Pflaum, 2017). Such a philosophy seems to be reaching its boundaries in many supply chains as they undergo various changes in the business environment. These efficient supply chains are able to cut costs and reduce waste, but only in predictable circumstances. Many traditional supply chains are thus not able to quickly react to unexpected changes in their business environment, which requires them to focus more on flexibility and agility (Menon and Shah, 2019). Consequently, an emerging trend is to move away from lean manufacturing towards a more agile and flexible strategy (Wyciślak, 2017).

Deloitte (2020) emphasises the importance of improving visibility to better deal with supply chain risks in wake of the COVID-19 pandemic. Without visibility into potential problems throughout the entire supply chain, companies aren't able to respond and manage them adequately. The key to end-to-end supply chain visibility lies in digitalisation (Kilpatrick and Barter, 2020). Büyüközkan and Göçer (2018) state that any organisation should digitalise their supply chain if they wish to survive the 4IR and compete with others. The various benefits, but also the inevitable challenges brought on by digitalisation are discussed in the next section, along with its impact on the world and the desired state of future digitalised supply chains.

3.1.2 Benefits, challenges and the desired state of supply chains in the future

Many benefits can be enjoyed by companies choosing to implement digitalisation projects in their supply chains. From literature, three broad categories of benefits have been identified. The first category relates to connectivity, communication and collaboration between different parties in the supply chain. Digital technologies allow various companies that are spread out across the globe to be connected to one another (Bienhaus and Haddud, 2018). This global interconnectivity enables easier communication between all actors in cross-border supply chains, allowing them to collaborate and share knowledge with much greater ease than previously possible at a lower cost (Kayikci, 2018; Zangiacomi et al., 2020; OECD, 2017).

The second category concerns the real-time exchange of data and information that is accurate, reliable and available when needed. Modern digital ICT systems are vital for supply chains, as they enable massive amounts of data to be captured, stored, analysed, utilised and shared throughout the supply chain (Strandhagen et al., 2017; Schniederjans, Curado, and Khalajhedayati, 2020). Furthermore, the combination of various digital technologies makes the real-time flow of information possible (Alicke, Rexhausen, and Seyfert, 2017; Parviainen et al., 2017), thus ensuring the availability of information when it is required, which also speeds up various processes. The automation of data-handling processes not only makes it easy to collect, store and process data, but also ensures higher quality information that is accurate, reliable and free from human errors (Menon and Shah, 2019).

The third category pertains to business models and product- and service-offerings. Digitalisation creates the possibility of developing brand new business models that modernises the approach followed by supply chains by taking advantage of the broad range of digital technologies that are emerging alongside the 4IR, along with changing consumer expectations (Hänninen, Smedlund, and Mitronen, 2018). A new business model that is frequently mentioned in literature is the multi-sided digital platform, for example the e-commerce company, Amazon.com, who links consumers directly to an independent supplier base (Hänninen, Smedlund, and Mitronen, 2018). Another type is the sharing economy, such as those by Uber and Airbnb, where assets and services are shared between private users (Wyciślak, 2017).

These three broad categories lead to additional benefits when realised. New business models, products and services make supply chains more customer-driven and enables companies to streamline their customer experience, while creating greater value for customers (Strandhagen et al., 2017). As mentioned previously, digitalisation enables consumers to participate directly in international trade through the use of digital trade platforms (OECD, 2017), giving them access to new products and services. The quality of life of consumers can be improved by providing access to more information and better services, as well as offering tools for health and education (Schilirò, 2020; Parviainen et al., 2017).

Digitalisation facilitates information sharing, as mentioned earlier. Companies can improve transparency of information in the supply chain by sharing reasons for decisions on cost, inventory and customer service with other stakeholders, including consumers (Alicke, Rexhausen, and Seyfert, 2017). Higher levels of information transparency builds trust between supply chain partners and consumers (Bienhaus and Haddud, 2018). Transparency also enables information, goods and finances to be traced back through the supply chain, which makes it easier to tackle fraud, corruption, counterfeiting and other illegal forms of business (Ferrantino and Koten, 2019; L. Thompson et al., 2017).

As more information becomes available as it is shared throughout the supply chain, visibility into the needs and challenges of other stakeholders will increase up to the point where the entire supply chain is visible to all participants (Schrauf and Berttram, 2016; Seyedghorban et al., 2020). The increased levels of visibility support complex decision-making (Bienhaus and Haddud, 2018), allowing organisations to make informed data-driven decisions and consequently be more flexible and thus better prepared for dealing with risks and unexpected events (OECD, 2017; Alicke, Rachor, and Seyfert, 2016). Improved decision-making and the real-time flow of data reduces uncertainty in the supply chain (Ali, Gongbing, and Mehreen, 2018) and also increases its resilience (Kayikci, 2018).

Digitalisation of supply chains leads to higher levels of productivity (Singh Srai et al., 2017) and also provides opportunities for increasing it even further (Kittipanya-Ngam and Tan, 2020). Digital technologies will make supply chains more efficient (Pflaum, Prockl, et al., 2018; Fruth and Teuteberg, 2017), allowing them to cut costs, reduce lead times and operate with greater speed in general (Alicke, Rexhausen, and Seyfert, 2017; Parviainen et al., 2017). By taking advantage of the access to massive amounts of information, companies can become more responsive to changes in regulations or market demands, thus allowing them to deliver higher quality products and services that better meet the needs of consumers (Calatayud et al., 2019).

Challenges of supply chain digitalisation

Despite its opportunities, digitalisation also presents various challenges and obstacles that need to be overcome for successful supply chain digitalisation and eventual digital transformation.

The first issue is the disruptive nature of digitalisation. Although radical changes such as new business models (Bienhaus and Haddud, 2018), different leadership styles (Schniederjans, Curado, and Khalajhedayati, 2020) and the establishments of new organisational structures and behaviour patterns (Pflaum, Bodendorf, et al., 2017) will cause massive disruption, they will eventually allow the benefits of digitalisation to be realised. Another source of disruption is increased competition due to new players in the market that don't need to run existing businesses based on legacy business models (Bamberger et al., 2017). As Accenture (2014) says, "Digital is too different" – most companies struggle to transform their existing business to its digital counterpart (Pflaum, Bodendorf, et al., 2017).

The increased flow of data and information throughout the supply chain, as well as the automation of transactions mean this data is vulnerable to cyberattacks and unintentional leaks if the ICT systems that handle it do not have adequate security (Bienhaus and Haddud, 2018; Fruth and Teuteberg, 2017). Therefore, the systems handling this data must ensure data security and privacy (Carlan et al., 2018). This is made more difficult as the number of actors that handle information at various stages in the supply chain increases, thus creating multiple points of potential breaches (WHO, 2019).

Digitalisation is still a relatively new concept for some companies, and even though many are aware of it, they do not realise the revolutionary impact that it will have on their supply chains (Bienhaus and Haddud, 2018). Consequently, these companies do not plan properly for digital transformation and lack an appropriate digital strategy (Parviainen et al., 2017) that frames investments and specifies which technologies will be implemented (Zangiacomi et al., 2020). For many organisations, the lack of a clear business case creates uncertainty (Calatayud et al., 2019), causing confusion as to what exactly digitalisation and digital transformation entails. This in turn leads to, for example, companies concentrating on new technologies, while ignoring the vital role that people play in the transformation (Attaran, 2020).

Failing to grasp the importance of digitalisation means organisations will lack the expertise required to successfully implement and take advantage of digital technologies and the vast amounts of data generated (Schniederjans, Curado, and Khalajhedayati, 2020). Employees will not have sufficient technical skills for coping with the increasing technological and organisational complexity (Zangiacomi et al., 2020), as technology is developed at a greater rate than the skills of employees. Therefore, organisations do not leverage enough of the available data to gain important insights, improve processes, uncover value and experience all the benefits of digitalisation (Chase Jr, 2016; Alicke, Rexhausen, and Seyfert, 2017).

The next obstacle is the size of the investment required, as well as the associated operating costs of adopting new technologies and transforming a traditional supply chain into a digital one, as mentioned by various authors (e.g. Bamberger et al., 2017; Zangiacomi et al., 2020; Carlan et al., 2018). When specifically looking at data protection and security, Zimmermann (2016) found that high investment and operating costs were major concerns among industry experts. Digitalisation projects are even more expensive in low-income and lower-to-middle-income countries, where ICT and the cost of capital is significantly more expensive than in upper-to-middle-income countries (Banga and Te Velde, 2018).

The final major challenge is the requirements for digitalisation. This includes a lack or limited access to the internet and other types of ICT (Banga and Te Velde, 2018; Calatayud et al., 2019), outdated information systems capabilities or resources (Carlan et al., 2018) and insufficient internet speeds (Zimmermann, 2016), which are more apparent in developing countries (OECD, 2017). Other obstacles are the development of new digital standards (Kittipanya-Ngam and Tan, 2020), policies (Banga and Te Velde, 2018) and legislation (L. Thompson et al., 2017) that are required for managing these emerging digital technologies.

3.1.3 The role of technology in the digital supply chain

Technologies that play a large role in the 4IR are also one of the key enablers of supply chain digitalisation. This section discusses the applications of some of the technologies discussed in Section 2.1.3 and their role in transforming traditional supply chains into their digital counterparts. Digital technologies will enable improved data-driven decision-making, increased servitisation, radical changes in competitiveness, the transformation of business models and eventually the replacement of traditional organisational structures and behaviour patterns (Pflaum, Prockl, et al., 2018).

In the context of digitalisation, IoT allows the automated collection and analysis of useful data from smart objects (Menon and Shah, 2019). It has a wide variety of applications in industries such as logistics (tracking physical objects in real-time), food supply chains (tracking and forecasting the shelf life of products), warehouse management (monitoring stock availability) and energy management (monitoring and optimising energy usage in real-time) (Manavalan and Jayakrishna, 2019). Sensors, actuators and RFID technology play a large role in IoT, as it is used to detect physical phenomena, convert the analogue signal to digital, and then send the data to other devices connected via the internet (Schniederjans, Curado, and Khalajhedayati, 2020). Furthermore, CPS, which is vital for digital supply chains, relies heavily on the interconnectivity and flow of information that is made possible by IoT (Klötzer and Pflaum, 2017).

Big data is generated by IoT and other related technologies. Organisations that effectively collect, analyse and process these massive amounts of data obtain useful insights into customer behaviour (Singh Srai et al., 2017) that inspires new products and services, and employee behaviour to improve efficiency (Hanifan, Sharma, and Newberry, 2014). Big data analytics plays a key role in business intelligence (Ferrantino and Koten, 2019), supporting everyday decision-making and even enabling autonomous decisions (Schrauf and Berttram, 2016). Other applications include improved strategic planning, process optimisation (Attaran, 2020), more accurate demand forecasting, better quality control and predictive maintenance (Calatayud et al., 2019).

Cloud computing can be used alongside IoT and big data to create greater value for organisations.

It enables the integration of various actors in the supply chain, giving everyone access to relevant information, which ensures the continuous flow of information. This guarantees more accurate and recent data, which improves supply chain visibility (Gomez, Grand, and Grivas, 2015). Resources can be shared over the internet with minimal management efforts (Menon and Shah, 2019). Wyciślak (2017) mention that the end-user does not need to know the location and configuration of the system to be able to access it, thus making a network of virtual services easily accessible to users anywhere in the world (Büyüközkan and Göçer, 2018). Cloud computing helps companies educate employees, raise the contribution of stakeholders in the supply chain and increase access to various applications (Hanifan, Sharma, and Newberry, 2014).

Artificial intelligence plays a key role in the automation of operations and decision-making without human intervention (Strandhagen et al., 2017; Calatayud et al., 2019). Applications of AI include risk assessment and analysis of big data, which helps improve supply chain management, predict possible disruptions and reduce various costs (Forkel, Clauß, and Schumann, 2019). Machine learning can help automated business decision rules to adapt over time (Schilirò, 2020). In the food supply chain, basic AI is used to improve food sorting, to monitor personal hygiene of workers and to assess the state of equipment. More advanced AI is applied to food safety for quicker decision-making that is less prone to human error and bias (WHO, 2019).

Additive manufacturing – specifically 3D printing – makes the rapid production of prototypes, small scale items and spares possible, which allows manufacturing to become smaller-scale, closer to its markets and able to deliver mass-customisation of low volume products at relatively low costs (Singh Srai et al., 2017; Iddris, 2018). This allows on-demand production (Strandhagen et al., 2017), fewer layers of suppliers, less transportation and thus allows supply chains to be shortened, which reduces supply chain complexity (Ivanov, Dolgui, and Sokolov, 2019). 3D models can be shared over the internet and adapted when needed, consequently making the design and production processes more flexible and scalable (Banga and Te Velde, 2018).

Robotics is used to automate manual and mostly repetitive tasks, such as vehicle assembly, agricultural harvesting, picking, packing and unloading to reduce costs and improve productivity (Attaran, 2020; Calatayud et al., 2019). For more advanced tasks, collaborative robots increase the efficiency of human workers by working alongside them with enhanced accuracy and speed (Singh Srai et al., 2017; Menon and Shah, 2019). Closely linked to robotics, are autonomous vehicles and drones. Self-driving trucks that are transporting goods are able to monitor its environment, the condition of its freight and determine any maintenance requirements, as well as optimal routes (Schrauf and Berttram, 2016). This will lead to faster and more reliable delivery, the elimination of human error and reduced emissions. Drones are useful for last mile delivery, i.e. delivering goods or services to the end-user at a reduced cost with increased efficiency (Kittipanya-Ngam and Tan, 2020).

AR improves the efficiency of processes in warehouse management by displaying real-time picking and packing instructions for workers through a wearable device to make it faster as less error prone (Schniederjans, Curado, and Khalajhedayati, 2020). Work instructions for manufacturing and assembly operations through AR technology also enhances the decision-making of operators (Strandhagen et al., 2017). AR and VR are also useful for employee training (Kittipanya-Ngam and Tan, 2020) and testing experimental products during the design process, where alternatives can be compared, samples can be tested and collaboration between stakeholders is easier (Büyüközkan and Göçer, 2018).

3.1.4 Paperless systems

A large part of supply chain digitalisation is the digitisation of information flows, i.e. going paperless. In cross-border trade, many transactions remain paper-based due to various reasons, including mandatory physical copies of certain documents in various transactions (Karabulut, 2020). The World

Economic Forum (WEF) describes paperless trading as "the digitisation of [...] information flows, including making available and enabling the exchange of trade-related data and documents electronically" (L. Thompson et al., 2017). Modern ICT is applied to simplify and automate international trade procedures (Duval and Mengjing, 2017) by ensuring the dependence on physical documents are eliminated and all information flows occur on a single platform (Karabulut, 2020).

Paper-based trade is littered with inefficiencies and delays. International trade is a long and complex process that involves many parties in various areas of the world. Physical documents that are circulated between them need to travel long distances through the hands of multiple parties and are subject to losses and delays (Karabulut, 2020). Furthermore, mistakes on the paperwork and damage thereof can be costly in terms of additional costs and productivity losses (Carlan et al., 2018). Human resource requirements are higher for paper-based trading, which leads to greater costs, lower productivity and makes it more susceptible to human errors (Karabulut, 2020). In general, paper-based trading is expensive, even if no additional costs are incurred due to delays or mistakes, and remains a major expense for traders (Australian DFAT and Chinese MofCom, 2001).

Removing dependence on paper-based documents presents various benefits, such as direct savings through lower compliance costs for traders, and indirect savings from lower inventory costs and faster movement of goods (Australian DFAT and Chinese MofCom, 2001). Karabulut (2020) mentions various benefits of electronic documents, including time and cost savings due to shorter processing times at customs, reduced number of documents or files, decrease in human errors, prevention of counterfeiting, and improved transparency. Many authors mention that paperless trading will allow SMEs to participate in international trade due to the reduction of costs and complexity (e.g. L. Thompson et al., 2017; Duval and Mengjing, 2017). The real-time flow of information allows much greater levels of transparency and enables better traceability to reduce fraud and other trading crimes (L. Thompson et al., 2017).

Various paperless trade measures have been implemented in certain regions. A common measure is the electronic single window system, which aims to make trade opportunities more efficient and cost-effective. The required documents and information are submitted through a single portal and are then distributed to all the relevant stakeholders and regulatory bodies (Malaket, 2016; L. Thompson et al., 2017). The United Nations Regional Commissions (UNRC) Global Survey on Trade Facilitation and Paperless Trade Implementation (TFPI) include other paperless trade measures, such as electronic automated customs systems, electronic submission portals for trade-related documents (e.g. customs declarations, trade licences and cargo manifests) and the electronic exchange of certain documents between countries (e.g. certificate of origin, and sanitary and phyto-sanitary certificates) (Duval and Mengjing, 2017).

One of the main barriers to paperless trading is the lack of consistent international standards regarding the exchange of electronic documents between trade partners (Karabulut, 2020). Legislation in many regions still require physical copies of documents to accompany electronic versions (WHO, 2019). Not only will this need to be repealed, but new legislation must be passed to support electronic transactions (Australian DFAT and Chinese MofCom, 2001). Another massive barrier in the lack of supporting infrastructure and IT capacity, which is required by parties on both ends to successfully transmit electronic documents (L. Thompson et al., 2017; WHO, 2019).

3.1.5 Recommendations for pursuing digitalisation

The importance of formulating an appropriate strategy for digital transformation is emphasised by multiple authors (e.g. Vendrell-Herrero et al., 2017; Alicke, Rexhausen, and Seyfert, 2017; Hanifan, Sharma, and Newberry, 2014). Organisations must align their core business activities with their strategic goals (Bienhaus and Haddud, 2018). They must review the current state of their company, reduce non-value-adding business activities and identify the gap between their current state and the desired future state (Parviainen et al., 2017). It is vital to develop a roadmap for reaching the desired state by setting out the necessary implementation steps. Projects should be rolled out in a series of small, detailed pilots, rather than large scale projects with a limited set of technologies (Markovitch and Willmott, 2014; Schrauf and Berttram, 2016).

Collaboration with other stakeholders in the supply chain is another requirement for successful digital transformation. According to Carlan et al. (2018), collaboration between private and public sectors, as well as different supply chain stakeholders is key to developing, adopting and scaling new technologies. Similarly, Calatayud et al. (2019) mention that supply chains require a high level of collaboration for its full 4IR implementation due to process fragmentation and the large number of stakeholders in a supply chain. Subsequently, increased collaboration and flow of information requires data protection and security to be a core part of the implementation strategy (Fruth and Teuteberg, 2017).

Since digitalisation is expected to change business models, organisations will have to define new tasks, roles and responsibilities in their organisational structure. Recruitment must focus on attracting talent that already possess the necessary skills, behaviour and insights (Bienhaus and Haddud, 2018). Current employees must receive ongoing training to educate and improve their analytical and IT skills, and to help them better understand the new environment (Zimmermann, 2016; Banga and Te Velde, 2018; Chase Jr, 2016). The organisation's culture must also be changed to one that is willing to carry out the effort required for digital transformation (Schrauf and Berttram, 2016).

It is necessary for organisations to invest in infrastructure to expand their capabilities to be able to support the digitalisation of their supply chain. Managers must be aware of the top technological developments in their industry and how these technologies apply to their supply chains (Brinch and Stentoft, 2017). New methods for exchanging, storing and managing information are required for integrating and analysing data for improved decision-making to further increase an organisation's capabilities (Zangiacomi et al., 2020). A necessary capability mentioned by Wyciślak (2017), is the co-existence of lean and agile practices in a value chain. Although digitalisation requires organisations to be less lean and more agile, the size of the change will be different for every supply chain, meaning both practices must be supported.

Finally, the necessity of relevant policies and legislation is stressed by various authors. Policies that will influence country-specific conditions and contribute towards an improved investment environment, firm capabilities, ICT infrastructure, new financing opportunities and participation in global trade are required to digitalise supply chains (Banga and Te Velde, 2018). Legislation must be adapted to facilitate the flow of electronic documents and other digital information, while preventing countries or regions from becoming uncompetitive (OECD, 2017).

3.2 Blockchain Technology

A notable emerging technology that is either missing or only briefly mentioned in many papers discussing technologies of the 4IR, is blockchain technology. This section delves deeper into the topic by first looking at the basics of blockchain, such as its history, how it works, as well as its structure and main components. Secondly, this section covers the features and benefits of blockchain in general and also the various types of blockchains that exist. Thirdly, the general challenges associated with blockchain are discussed, followed by its potential and existing applications.

Defining structures in economic, legal and political systems across the world, e.g. contracts, transactions and records, perform vital actions, such as protecting assets, establishing and verifying identities, recording events and governing interactions between various parties. Unfortunately, these tools have not kept up with the digital transformation that is currently prevalent in economies around the globe (Iansiti and Lakhani, 2017). Most traditional systems that facilitate the flow of information are centralised, meaning that all data and information are controlled and managed by an additional third party, rather than the two primary parties involved in the transaction (Yli-Huumo et al., 2016). The parties thus have to put all their trust in the third party. These types of systems are vulnerable to information asymmetry, where participants do not have access to the same information. The system administrator controls the data, which makes it more susceptible to fraud or bribery if the administrator is dishonest. The other major risk is a single point of failure, where the entire system is left vulnerable to disruption when a single part of it is compromised (Tian, 2017).

A promising technology that is currently still emerging, is blockchain technology – cited by some as having the same revolutionary potential as the internet (Crosby et al., 2016; Iansiti and Lakhani, 2017). Swan (2015) goes on to explain how blockchain may be the 5th disruptive computing paradigm, following the mainframe in the 1970s, the personal computer in the 1980s, the internet in the 1990s and social and mobile networking in the 2000s. Many of the features of blockchain technology can fill the gap in traditional systems (Korpela, Hallikas, and Dahlberg, 2017).

Blockchain is a distributed chronological database of transactions that is shared among participants across a decentralised P2P network in a trustless environment (Crosby et al., 2016; Y. Chang, Iakovou, and Shi, 2020; Y. Wang, Singgih, et al., 2019; Block and Marcussen, 2020; Ganne, 2018; Larson, 2018). The database is secured by cryptography and governed by a consensus mechanism (Swan, 2015). Transactions are only added to the ledger when consensus among a majority of participants on the validity of the transaction is reached (Crosby et al., 2016). Due to blockchain's use of cryptographic techniques, once a transaction is recorded, it becomes nearly impossible to change, meaning that a comprehensive and verifiable record of transactions is accessible by all participants of the blockchain at any time (Gatteschi et al., 2018). The inner workings of blockchain and its various features and related technologies are discussed in greater detail in subsequent subsections.

Blockchain and the term *distributed ledger technology* (DLT) are often used interchangeably, which is inaccurate. Blockchain is a subset of DLT and is in fact the most well-known and tested implementation of the technology (Ganne, 2018). A DLT is, in turn, a type of distributed database (refer to Figure 3.1). The main idea of the latter is that there is no central "master database", since it is distributed across a P2P network of participants. DLT adds a consensus mechanism to the distributed database, which allows the ledger to be updated according to majority consensus among participants. Blockchain goes further to group transactions in blocks and linking them in a sequential tamper-evident chain using cryptographic methods (Hewett, Lehmacher, and Y. Wang, 2019). Figure 3.2 shows the difference between a centralised ledger where data is stored and only accessible from a central server and a distributed ledger where data is stored on each participant's device.

3.2.1 The basics of blockchain

Blockchain was introduced in 2008 by Satoshi Nakamoto (Hackius and M. Petersen, 2017; Iansiti and Lakhani, 2017) in a paper titled, "Bitcoin: A Peer-to-Peer Electronic Cash System", with the main goal of solving the double-spending problem without relying on trusted third party intermediaries (Bunduchi, 2019; Ganne, 2018). The double-spending problem occurs when digital currencies are spent more than once because the digital file representing the token is duplicated or falsified (Ganne, 2018). The paper by Nakamoto (2008) introduced Bitcoin, described as, "A purely peer-to-peer version of electronic cash [that] would allow online payments to be sent directly from one party to another without going through a financial institution." This enables payments using a decentralised virtual currency, which is recorded in a public ledger stored on the devices of and accessible by all users.

The virtual currency, Bitcoin in this case, is known as a cryptocurrency, defined by the WEF as "any digital asset or 'token' that can be mined, purchased or transacted within a blockchain or distributed ledger network" (Hewett, Hanebeck, and McKay, 2019). The key feature here is the use

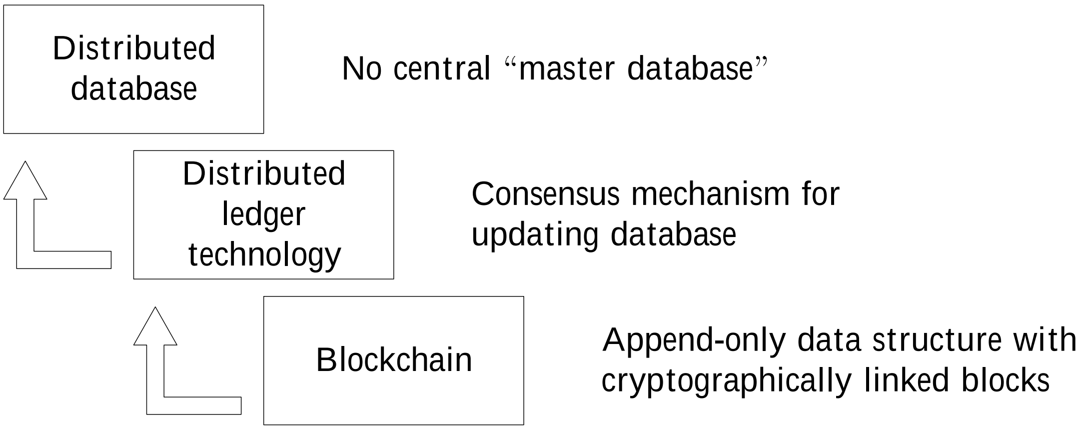

FIGURE 3.1: *The relationship between distributed databases, DLT and blockchain (adapted from Hewett, Lehmacher, and Y. Wang, 2019).*

of cryptography to secure the transactions of the virtual currency. Blockchain was thus introduced as the underlying technology of Bitcoin and this application has since become known as *Blockchain 1.0*, the first generation of the technology, which focusses on currency and digital payment systems (Sternberg and Baruffaldi, 2018).

The second milestone in blockchain history was marked by the creation of Ethereum in 2013, when a person by the name of Vitalik Buterin presented his idea for a blockchain system that could facilitate decentralised applications (Ganne, 2018). The main feature is the concept of smart contracts, coined by Nick Szabo in 1994, but only brought into the blockchain context in 2015 when Ethereum was launched (Block and Marcussen, 2020). In short, a smart contract is a computer program that automatically executes the terms of a contract when certain conditions are met (Ganne, 2018). Smart contracts, along with transactions beyond currency including stocks, bonds, loans, titles and property are the premise of *Blockchain 2.0*.

The newest generation, *Blockchain 3.0*, expands applications beyond the currencies, finances and markets to include sectors such as supply chain, government, health, science, education, culture, art and more (Swan, 2015; Gatteschi et al., 2018). These applications are aimed at improving the quality of life, promoting general transparency of processes, protecting human rights and increasing efficiency of various systems in the previously mentioned sectors (Gatteschi et al., 2018). Figure 3.3 summarises the focus of each blockchain generation.

Blockchain structure

The name *blockchain* comes from the structure of the ledger where transactions are grouped into blocks and each of these blocks are linked one after the other in a chronological chain. The first blocked in known as the genesis block, whereas each subsequent block is known as the parent block to its immediate neighbour downstream in the chain (Zheng, S. Xie, H. Dai, et al., 2017). Figure 3.4 is a visual representation of the block structure. Each block has a header and a body, of which the former contains the following (Nakamoto, 2008; Zheng, S. Xie, H. Dai, et al., 2017; Y. Wang, Han, and Beynon-Davies, 2019; Bunduchi, 2019; Scott et al., 2018):

- **Block index**: shows the block's position in the chain.
- **Parent block hash**: links the current block to its parent (i.e. the previous block) by using a 256-bit hash value that points to the specific block.

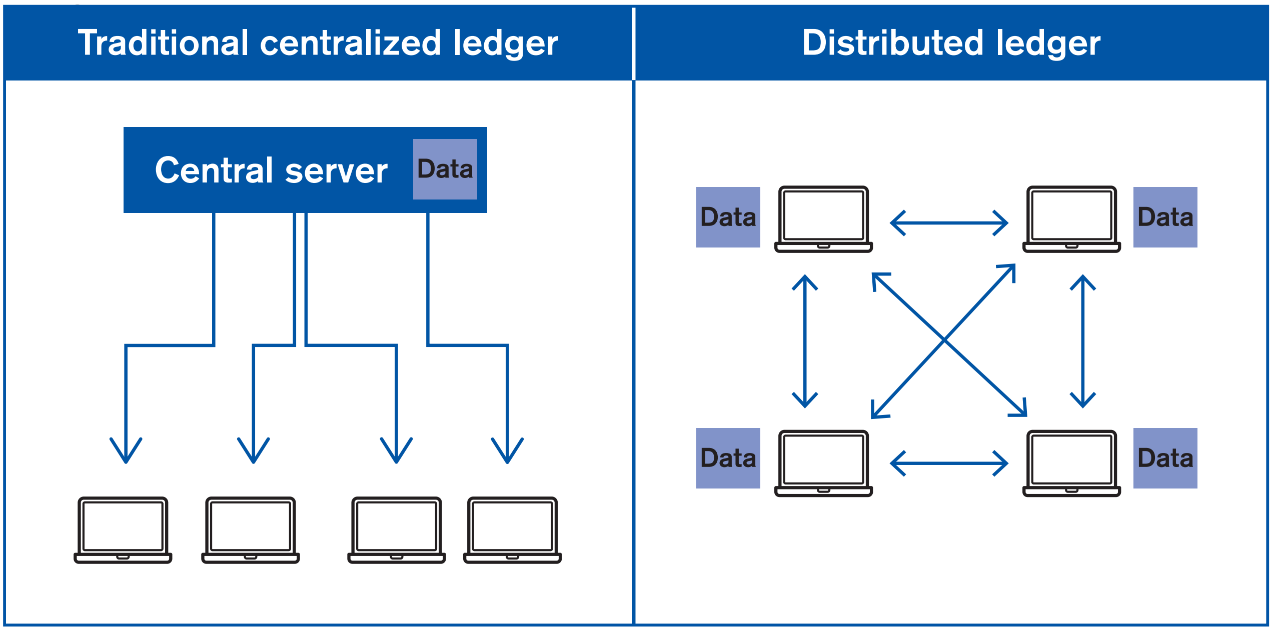

FIGURE 3.2: *The difference between centralised ledgers and distributed ledgers (Ganne, 2018).*

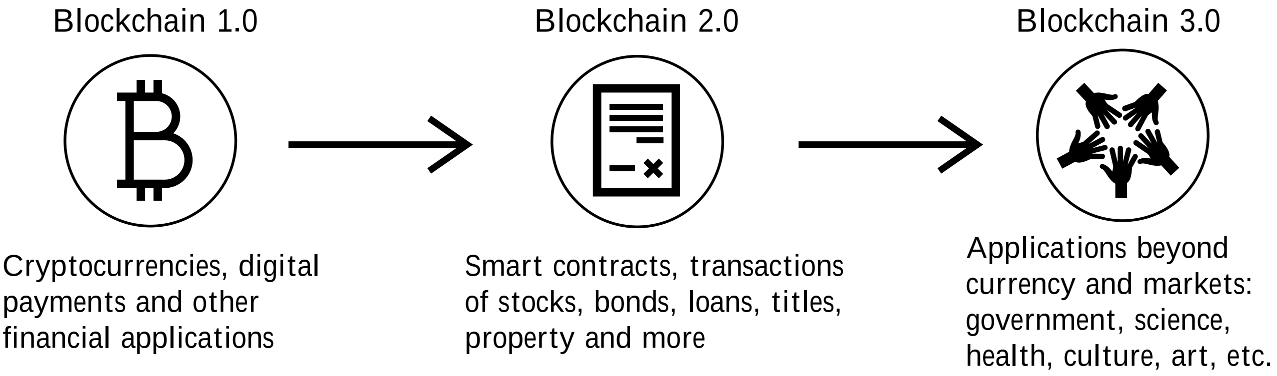

FIGURE 3.3: *The main focus of each blockchain generation (Gatteschi et al., 2018; Swan, 2015).*

- **Nonce**: also known as a “number used only once”; a random numeric value that is used to create a hash that will be accepted by the blockchain.
- **Timestamp**: the time at which the block was generated.
- **Merkle tree root hash**: the final hash value or in simpler terms, the digital identity of data in the current block, which is created using the Merkle tree function.

The body of a block contains the main data that is stored on the blockchain, which may include transaction records, contracts, IoT data, tracking records, etc., depending on the blockchain’s use (I.-C. Lin and T.-C. Liao, 2017).

The main components of blockchain technology

Although it may seem like a brand-new technology, the novelty of blockchain lies in the combination of technologies it encompasses (Pawczuk, Massey, and Schatsky, 2018; Allen et al., 2019). The

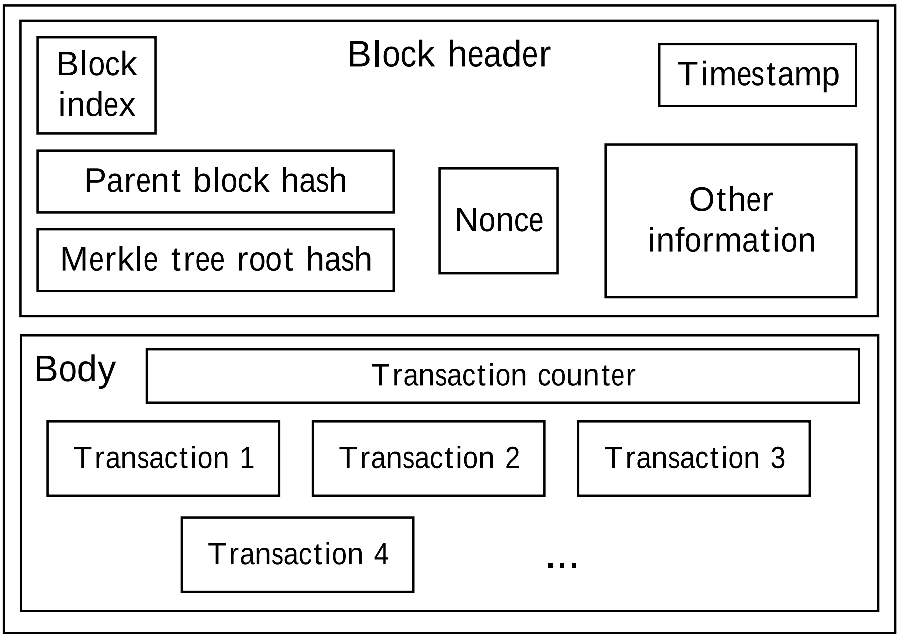

FIGURE 3.4: *Structure of a generic block in the blockchain (based on Zheng, S. Xie, H. Dai, et al., 2017; I.-C. Lin and T.-C. Liao, 2017; Y. Wang, Singgih, et al., 2019; Bunduchi, 2019).*

technologies discussed below, are the main components that play a key part in blockchain technology. They include DLT, public and private key cryptography, P2P networks, consensus mechanisms, and smart contracts.

Distributed ledger technology. As mentioned earlier, blockchain is a type of distributed ledger. This means that it is a ledger that records information in a chronological order and distributes it across a network of computers, where a copy of the ledger is held by each participant (Mohan, Berg, and Poblet, 2020; Divey, Hekimoğlu, and Ravichandran, 2019). In other words, data is not stored in a single location, so data will not be lost if one of the computers on the network fails. The distributed nature of the ledger also enables it to be updated by any user, meaning no centralised authority has full control over the data.

Public key cryptography. Cryptographic technologies and principles are used to secure information stored on the blockchain (Mohan, Berg, and Poblet, 2020). Each user receives a pair of keys that are used to encrypt and decrypt transactions (Korpela, Hallikas, and Dahlberg, 2017). A private key represents the user's digital identity and is kept secret, allowing the user to stay anonymous (El Ioini and Pahl, 2018). The private key is used to authenticate the user, while the public key, that is visible to everyone on the network, is part of the user's public address that is distributed across the network along with the transaction that they wish to make (Yli-Huumo et al., 2016).

Cryptographic hashing functions and pointers. Other types of cryptographic tools that are also used by blockchain technology are hashing functions, such as the commonly used SHA-256 hash function, and hash pointers. The former encrypts data by converting passwords, files or other inputs into a unique, unforgeable string of characters, known as a hash. The latter records where information is stored and points at its location (Hewett, Lehmacher, and Y. Wang, 2019). Any change in the contents of a block will lead to a new hash value, meaning all subsequent blocks are invalidated (Dinh et al., 2018). Consequently, the change will be rejected by the consensus mechanism.

Peer-to-peer networks. This type of network spans between a number of interconnected computers

– called peers or nodes, depending on the context – that shares resources such as central processing unit (CPU) power. This is done without relying on a central server in contrary to centralised networks, where the central server controls and coordinates every node (Bunduchi, 2019). Each node stores information, that is shared and received directly from other nodes, meaning every computer on the P2P network is interconnected (O. Petersen and Jansson, 2017). Blockchain uses this technology to scale up the network, to avoid a single point of failure and to prevent a small group of players from taking over the network (El Ioini and Pahl, 2018).

Consensus mechanisms. Since the blockchain is replicated on various nodes in the network, it can only be updated when a majority of members agree to it to ensure the data is valid (Dinh et al., 2018; Verhoeven, Sinn, and Herden, 2018). A consensus protocol allows all network nodes that do not trust one another to agree on the single version of the truth – which blocks are added to the chain in the case of blockchain – without relying on a trusted third party (El Ioini and Pahl, 2018). Once a transaction is confirmed by the majority nodes, it is added to the blockchain where it becomes a permanent part of the database (Tian, 2017). Two commonly used consensus protocols include Proof of Work (PoW) and Proof of Stake (PoS), although there are many others that cater better to specific needs. These consensus models are compared later in this section.

Smart contracts. As briefly mentioned earlier, smart contracts are computer protocols running on the blockchain that automate the facilitation, verification or enforcement of the terms of contracts. The novelty lies in the ability to enable credible transactions without requiring a trusted intermediary (Cole, Stevenson, and Aitken, 2019). These pieces of code that contain certain rules and penalties are automatically executed when a predefined set of conditions are met (H. M. Kim and Laskowski, 2018). The main goals of smart contracts are to fulfil common contractual conditions, minimise both malicious and accidental exceptions and to reduce the need for trusted third parties (Korpela, Hallikas, and Dahlberg, 2017).

How blockchain works

Now that the main components of blockchain are known, it is easier to understand how it works. There are four main steps in the transaction process (Ganne, 2018):

1. **Submission**. Firstly, the sender generates a mathematically linked public-private key pair – of which the public key is made available to the receiver. Secondly, the data that is to be sent is used to create a string of alphanumeric characters using the hashing algorithm, which is then encrypted using the sender's private key (Divey, Hekimoğlu, and Ravichandran, 2019), thus forming the digital signature of the data, which ensures the data's integrity. Since the transaction will be visible to all users of the network, the data itself may also be encrypted so that only the receiver can decrypt it (Ganne, 2018).

2. **Transmission**. The data, along with its digital signature is transmitted to the receiver(s) over the network by sending it to the receiver's public key (H. M. Kim and Laskowski, 2018). Additionally, the transaction is also transmitted to every other node in the network. Next, the transaction is added to a pool of transactions that need to be validated, known as a "block". The Merkle Tree function is used to create a final hash value for the block, based on the hash values of the transactions in the block (I.-C. Lin and T.-C. Liao, 2017).

3. **Validation**. The other receiving nodes of the network then validate the block – this is the "mining" process in the case of a PoW consensus algorithm. These nodes calculate multiple hash values by applying the same hashing algorithm on the data of the transaction until they find the nonce that generates a hash value that corresponds to block's hash. If the block's hash value matches the calculated hash value, the block is validated (Ganne, 2018). The first node to

find matching hash values receives a financial reward in the form of a transaction fee and then broadcasts the updated blockchain across the network to be validated by the remaining nodes.

4. **Addition**. Once consensus on the validity of the new version of the blockchain is reached by the remaining nodes, the new block receives a timestamp and is linked to the previous block in the chain using a hash pointer. The new version of the blockchain is then saved at each of the nodes, creating a new immutable addition to the chain.

3.2.2 The features of the blockchain

Blockchain has various features that, individually, are not necessarily unique to blockchain, but in combination differentiates blockchain from alternative systems and technologies that are currently in use. One of these features is decentralisation, which means that no single party controls the data or information on the blockchain – the network is entirely run by its members (Iansiti and Lakhani, 2017). The main enabler is the use of a P2P network, where peers can communicate directly with one another without needing to go through a central node, such as a bank to facilitate transactions (Zheng, S. Xie, H.-N. Dai, et al., 2018).

Additionally, each participant keeps a complete copy of the ledger of transactions this is simultaneously updated in a decentralised manner (Kouhizadeh and Sarkis, 2018) using another enabler of decentralisation: the consensus mechanism. Users of the system validate transactions directly with incentives to keep participants in the system honest, which replaces the trusted third-party intermediary that usually validates transactions (Zile and Strazdiņa, 2018). The decentralised nature of blockchain is one of the features that allow parties who do not necessarily trust each other to transact with a high degree of confidence (Francisco and Swanson, 2018). In short, "Blockchain technology's decentralised model of trustless peer-to-peer transactions means [...] intermediary-free transactions" (Swan, 2015).

Another major feature of blockchain is data integrity, security and user privacy. The use of cryptographic hashing methods to link blocks in the blockchain is the main enabler of data integrity (Yli-Huumo et al., 2016). Once a block is added to the chain, it becomes immutable, meaning it is next to impossible to change its contents (Q. Lu and X. Xu, 2017), or as Nakamoto (2008) puts it, "computationally impractical to reverse". Even if a block's contents are manipulated, such a change will invalidate every block that follows in the chain, since they are cryptographically linked using hash functions and pointers (Zile and Strazdiņa, 2018; H. Wu et al., 2017). Thus, one would need to alter every succeeding block in the chain as well, including blocks that are currently being added by other nodes (O. Petersen and Jansson, 2017). The consensus mechanism also plays a role in the data's integrity. Any change to the blockchain would need to be verified by other members of the network through the consensus algorithm, meaning dishonest alterations will be rejected due to the incentive mechanism that aligns each node's interest with those of its peers (Hackius and M. Petersen, 2017).

In terms of security, blockchain does not have a single point of failure due to its decentralised architecture. This, along with its distributed and encrypted nature makes blockchain highly resilient to cyberattacks or crashes compared to traditional databases (Kouhizadeh and Sarkis, 2018; Ganne, 2018), while also increasing the trustworthiness of its data (Block and Marcussen, 2020). Finally, blockchain also provides a degree of anonymity – rather pseudonymity – to its users by allowing them to generate multiple public addresses, while keeping their private keys secret (O. Petersen and Jansson, 2017). No central party keeps these users' private information (Zheng, S. Xie, H.-N. Dai, et al., 2018) and since their private keys are encrypted, their real-world identities are protected (Scott et al., 2018).

The third major feature of blockchain is the increased transparency that it provides. The fact that blockchain is a distributed database shared over a P2P network means that the data – encrypted or not

– is visible to anyone with access to the system, since each member has an updated copy of the ledger (Iansiti and Lakhani, 2017). Thus, each member has access to the same data, ensuring a single point of the truth (Hackius and M. Petersen, 2017). The immutability of data on the blockchain enables improved auditability and traceability, as each block is validated and timestamped, and the entire transaction history can be accessed (Zheng, S. Xie, H.-N. Dai, et al., 2018; Kouhizadeh and Sarkis, 2018). Further adding to the transparency is that each transaction contains the digital signatures of parties involved, while protecting the actual identities of these parties through cryptography, thus providing both transparency and privacy (Scott et al., 2018; Saberi et al., 2019).

Computational logic in blockchain means that algorithms and rules can be programmed to automatically trigger transactions between nodes (Iansiti and Lakhani, 2017). A major enabler of this computational logic, along with the digital nature of blockchain, is the smart contract, which checks predetermined conditions and automatically executes certain actions without the need for a third party to initiate it (Gatteschi et al., 2018; Kouhizadeh and Sarkis, 2018). As a consequence, various processes can be automated, leading to improved efficiency (Ganne, 2018; Hewett, Lehmacher, and Y. Wang, 2019).

A final benefit associated with blockchain is its ability to reduce various costs in the long term (Pawczuk, Massey, and Schatsky, 2018). Blockchain offers the cost-effective transmission of transactions by removing the need for a trusted third party to facilitate and verify these transactions, which usually incurs various costs (Korpela, Hallikas, and Dahlberg, 2017). Thus, blockchain offers reduced administrative work due to the disintermediation, which also leads to fewer human errors and an increase in processing speed and quality (Verhoeven, Sinn, and Herden, 2018; Kouhizadeh and Sarkis, 2018).

The different types of blockchains

Next, it is important to discuss the different types of blockchain architectures that exist, as each has its own benefits and drawbacks, which plays a massive role in the success of a blockchain implementation. The purpose of the blockchain will influence what type is selected. Blockchain platforms can be classified into three general classes according to membership, i.e. who has access to the ledger and who is allowed to execute the consensus protocol: public, consortium and private (Cole, Stevenson, and Aitken, 2019; I.-C. Lin and T.-C. Liao, 2017; Divey, Hekimoğlu, and Ravichandran, 2019). Public blockchains are freely accessible and controlled by no-one, consortium blockchains are only accessible by a group of companies and private blockchains are only accessible by a single organisation (Y. Wang, Han, and Beynon-Davies, 2019; Sternberg and Baruffaldi, 2018). A comparison of these types are presented in Table 3.2 according to the following points:

- **Management**. The entity or entities that control the system.
- **Read permission**. Who can access and view data stored on the blockchain.
- **Write permission**. Who can perform transactions and write new data to the blockchain.
- **Consensus participation**. Which nodes are allowed to participate in the process of validating transactions and updating the blockchain.
- **Efficiency**. The speed at which new data can be added to the blockchain.
- **Data integrity**. How safe data is from being changed or tampered with.
- **Decentralisation**. The degree to which the blockchain is not controlled by a central party.

TABLE 3.2: *Comparison of different types of blockchains (based on Mohan, Berg, and Poblet, 2020; Zheng, S. Xie, H.-N. Dai, et al., 2018; Ganne, 2018; Hewett, Lehmacher, and Y. Wang, 2019)*

	Public	**Consortium**	**Private**
Management	No centralised party	Multiple organisations	Single organisation
Read permission	Anyone	Public or restricted to authorised nodes	Public or restricted to authorised nodes
Write permission	All nodes	Restricted to authorised nodes	Network operator only
Consensus participation	All nodes	All or subset of authorised nodes	Network operator only
Efficiency	Low	High	High
Data integrity	Very high	High	Lower
Decentralisation	Decentralised	Partially decentralised	Centralised
Examples	Bitcoin, Ethereum	Hyperledger, Corda	Multichain

Consensus Mechanisms

Proof of work (PoW) is the consensus protocol used by Bitcoin and many other cryptocurrencies (Ganne, 2018), therefore it is common in public permissionless blockchains. To add a block of transactions to the blockchain, each node in the network has to calculate a hash value by using different nonces, until the calculated value is less than or equal to a certain number, known as the network's difficulty level (Kouhizadeh and Sarkis, 2018). The process of calculating a hash value is known as *mining* and each node is called a *miner*. As incentive for investing computing power to mine the token, the first miner to find the correct hash value receives a monetary reward (Ganne, 2018). Unfortunately, energy consumed by nodes that do not find the winning hash is wasted with PoW. Since each node in a network using the PoW protocol must participate in the consensus process, public blockchains that use PoW tend to be less scalable, i.e. they handle growing amounts of work poorly.

Proof of stake (PoS) solves the energy wastefulness problem by replacing the mining process with one where a node must prove ownership of the virtual currency or assets on the blockchain, i.e. their stake in the network. Thus, nodes that own more currency, are more powerful. This model assumes that nodes with larger stakes in the network are less likely to attack it (Zheng, S. Xie, H.-N. Dai, et al., 2018). Since PoS is much more energy efficient than PoW, it is useful for organisations that have less computing power (Ganne, 2018). Often, blockchains initially use a PoW consensus algorithm, which is eventually replaced by a PoS algorithm as the network grows more mature (Zheng, S. Xie, H.-N. Dai, et al., 2018).

Proof of elapsed time (PoET) is the consensus protocol of the Hyperledger Sawtooth project and uses a random leader election or lottery-based model, where a new leader that will finalise the next block is randomly selected (Ganne, 2018). Each potential validator is assigned a waiting time by the algorithm during which each node must sleep, therefore conserving power. The node with the shortest waiting time wakes up first and is therefore the leader that can now validate the block and add it to the chain after proving that it had the shortest waiting time and that it actually waited for the time to elapse before starting the mining process (Baliga, 2017).

Byzantine fault tolerance (BFT) and its variants are used in permissioned blockchains where all participants are known and their identities are registered and verified. The Practical BFT (PBFT) algorithm employs the concept of replicated state machines and a voting system based on the current state of the system using a majority rule (Baliga, 2017). The primary node orders transactions sequentially, which is then broadcasted to each of the secondary nodes to sign. Once enough identical

Table 3.3: *Comparison of common consensus protocols (based on Brody et al., 2019; Zheng, S. Xie, H.-N. Dai, et al., 2018; Baliga, 2017; Ganne, 2018).*

	PoW	**PoS**	**PoET**	**BFT**	**FBA**
Main idea	Cryptographic puzzle	Virtual asset ownership	Random validator selection	Identical responses from trusted nodes	BFT with anonymous participants
Blockchain type	Permissionless	Both	Both	Permissioned	Permissionless
Transaction rate	Low	High	Medium	High	High
Scalability	Low	High	High	Low	High
Trust model	Untrusted	Untrusted	Untrusted	Semi-trusted	Semi-trusted
Cost of participation	Processing power	Virtual assets	None	None	None

responses have been received (i.e. $3f+1$ responses, where f is the maximum number of faulty nodes), the transaction is approved and added to the blockchain (Ganne, 2018). Finally, a federated byzantine agreement (FBA) is a variation of BFT used for financial applications and payments by making the model open-ended with regards to node participation, i.e. users can stay anonymous (Baliga, 2017). A brief comparison of the algorithms discussed above can be found in Table 3.3.

It is thus necessary to look at the size of the network, relationships between participants, and performance and confidentiality requirements before selecting the type of blockchain and consensus protocol.

3.2.3 The challenges associated with blockchain

As with any emerging technology there are various challenges associated with implementing blockchain. A recurring problem mentioned in literature is the scalability of blockchain systems (El Ioini and Pahl, 2018; Zile and Strazdiņa, 2018; Pawczuk, Massey, and Schatsky, 2018). Block size, i.e. the number of transactions in a single block, is predetermined and cannot be changed after the fact (Ganne, 2018), which limits the throughput of the blockchain. A larger block size would increase throughput, but introduces other issues such as size and bloat (Swan, 2015). To put this problem into perspective, the Bitcoin blockchain typically handles three to seven transactions per second (TPS), while VISA can handle 2000 to more than 10000 TPS (Swan, 2015; O. Petersen and Jansson, 2017). Latency is also part of the scalability issue. The Bitcoin blockchain takes around 10 minutes to add a new block, while VISA takes mere seconds (Tian, 2017). Capacity is another scalability problem. Since the blockchain is an append-only ledger, it continuously grows in size as new transactions are added. Consequently, it becomes harder to load and store the blockchain and updating it takes longer (I.-C. Lin and T.-C. Liao, 2017).

Power consumption is another frequently cited problem associated with blockchains, although this is mostly limited to public blockchains that use a computationally intensive consensus protocol, like PoW (Gatteschi et al., 2018; Brody et al., 2019). Each miner competes against others for a reward by consuming resources to be the first to solve the proof-of-work. Since only the winning node's efforts are rewarded, the power consumed by all other nodes are wasted, thus making blockchains with a PoW consensus protocol highly wasteful in terms of electricity consumption (Q. Lu and X. Xu, 2017). This leads to unnecessary costs; another problem of blockchain. The infrastructure required is expensive and results in massive upfront hardware costs (Gatteschi et al., 2018; Brody et al., 2019). Thus, while blockchain may reduce certain costs in the long run, it leads to greater costs in the short run.

Even though the blockchain itself is extremely secure, the applications, exchanges, user interfaces and smart contracts that access or run on it make the blockchain system vulnerable to security flaws (Scott et al., 2018; Ganne, 2018; Calle et al., 2019). Supporting technologies and infrastructure may thus be problematic. A major security concern – once again for blockchains that use a PoW consensus mechanism – is the 51% attack, where one network node or a group of malicious nodes collectively holds a majority of the processing power and takes control of the network, thus enabling them to decide which blocks to confirm (Zile and Strazdiņa, 2018; Swan, 2015; Yli-Huumo et al., 2016). This problem, however, is solved by other consensus protocols that do not rely on computing power for consensus. Another possible threat is the Sybil attack, where a malicious node creates several fake nodes that it controls to influence the consensus process (Baliga, 2017). This is where the PoW consensus protocol is resistant, since the fake nodes have no processing power and thus can't participate in the consensus process (Zile and Strazdiņa, 2018).

Regulatory issues are seen as major barriers to blockchain investments. A novel technology like blockchain requires new laws and regulatory frameworks to recognise the legal validity of blockchain transactions, to clarify applicable law and liabilities and to regulate the way in which data is accessed and used (Ganne, 2018). Furthermore, blockchain will need to prove its compliance in heavily regulated industries, such as healthcare and pharmaceutics, which may slow down its adoption (Scott et al., 2018). The decentralised nature of blockchain makes it hard for governments and lawmakers to control, which may further slow down its adoption (I.-C. Lin and T.-C. Liao, 2017). Conflicting international laws can cause complications, where some laws regulate where and what type of data can be stored. Since the blockchain's data is stored on multiple nodes, possibly in different countries, this may be problematic when data may not be stored outside country borders (Scott et al., 2018).

Interoperability, the ability for different systems to effectively communicate with one another, is a key challenge for blockchain, that stems from the lack of standardisation (Korpela, Hallikas, and Dahlberg, 2017). A common interpretation of data is required for information stored in a database (such as a blockchain) that is distributed across multiple organisations. This can be achieved by the development of common data standards through the collaboration of industry managers with blockchain practitioners, cryptography specialists and international standards organisations (H. M. Kim and Laskowski, 2018; Zile and Strazdiņa, 2018; Ganne, 2018).

A final challenge faced by blockchain is the levels of hype surrounding it, with a number of blockchain advocates making bold claims about blockchain and trying to present it as a solution to all problems. Coupled with a lack of clear understanding of blockchain's uses, benefits and drawbacks, many companies adopt blockchain for the wrong reasons, which hurts its reputation when their problems are not solved (Zile and Strazdiņa, 2018). It is vital that enough research is done to determine whether blockchain is truly the best solution to the problem and that the goals of the organisation adopting the technology are aligned to those of blockchain.

3.2.4 The applications of blockchain

Generic blockchain applications discussed in this section are split into two categories: financial applications and non-financial applications. Different types of assets that can be stored on the blockchain are listed in Table 3.4. Since blockchain was created with the idea of enabling online P2P transactions between parties without going through a financial institution, it makes sense that most existing and the more mature applications of the technology are present in the financial sector (Cole, Stevenson, and Aitken, 2019).

Cryptocurrencies like Bitcoin are used for more secure digital transactions between parties without the need for a third-party intermediary (Pawczuk, Massey, and Schatsky, 2018; Swan, 2015). Blockchain supports crowdfunding by enabling platforms where start-ups can create their own digital currencies, whose tokens they sell as shares to early backers to receive funding (Swan, 2015; Zile and Strazdiņa, 2018). Insurance also benefits from blockchain, as ownership of any asset that is registered on the blockchain can be verified and whose transaction history can easily be traced and audited (Gatteschi et al., 2018; Crosby et al., 2016). Finally, blockchain also has applications in the investment world. Information regarding stocks, private equity, bonds, annuities and pensions are stored on the blockchain where it is extremely hard to tamper with (Swan, 2015).

The number of non-financial uses for blockchain is increasing as more possible applications are identified in various sectors. Governmental uses include gathering election votes in a transparent and publicly verifiable way, while guaranteeing anonymity and immutability, as well as personalised governance systems where citizens only pay for the services they use (Gatteschi et al., 2018). Blockchain supports personal data management and can allow users to verify their identity with a certified organisation once without subsequently having to share their IDs and other personal information in the future when their identities must be validated elsewhere (Gatteschi et al., 2018). Data verification including document notarisation, academic certification and work history verification is also supported by blockchain (Zile and Strazdiņa, 2018). Furthermore, data privacy and security applications are also increasing in popularity (Zheng, S. Xie, H.-N. Dai, et al., 2018).

According to Deloitte (2018), blockchain has use cases in the media and entertainment industry for tracking and monetising content, addressing piracy and managing digital assets from its creator to its consumer. Intellectual property (IP) can be tracked on the blockchain (Cole, Stevenson, and Aitken, 2019) and used to prove its existence and authorship, which can then be used for ensuring royalties are paid out the right recipients (Gatteschi et al., 2018; Crosby et al., 2016). In the healthcare sector, blockchain supports data collection and storage of health records and the recording of genomic data whose access is forbidden in certain countries, while also ensuring the authenticity of pharmaceuticals and medical equipment. The education sector can use blockchain for transparently recording students' achievements or automatically executing certain actions when a student successfully passes a module (Gatteschi et al., 2018).

The next section takes a closer look at the supply chain sector and discusses the implementation of blockchain in the context of supply chains, while including the benefits and drawbacks, as well as specific use cases of the technology in the supply chain.

3.3 Blockchain and its Role in Supply Chains

To date, nearly all systems used to manage information in supply chains are centralised: information is mostly provided from a single source and made available on an as-needed basis, thus leading to asymmetric and opaque information sharing, which could easily lead to trust problems and the inability to quickly respond to unexpected events (Tian, 2017; H. Wu et al., 2017). Existing enterprise resource planning (ERP) systems – used to coordinate information and manage business processes on a company-wide scale using a centralised database – have limitations in their ability to extend beyond organisational borders (Cole, Stevenson, and Aitken, 2019). Supply chains are growing evermore complex, extended and harder to manage as the number of stakeholders from across the world increases, among various other factors.

Ensuring real-time visibility of the global supply chain by providing adequate flow of timely and trustworthy information between all relevant parties by using such centralised systems is becoming nearly impossible. Besides, centralised systems are not only vulnerable to a single point of failure in the event of an error, hack or fraud, but also require more intermediaries as the number of parties in

Table 3.4: *Blockchain applications grouped by the type of asset that is transacted (based on Gatteschi et al., 2018; Zile and Strazdiņa, 2018; Swan, 2015).*

Category	**Application**
General	Escrow transactions; multiparty signature transactions; bonded contracts
Financial transactions	Currencies; P2P transactions; stocks; equities; crowdfunding; insurance; bonds; annuities; pensions; donations
Public records	Property titles; business licenses; birth, marriage and death certificates; vehicle registrations, criminal, court and government records
Semi-public records	Degrees, certifications and grades; human resources, medical and delivery records; genome data
Private records	Loans; contracts; signatures; wills; trusts
Identification	Identity documents; passports; driver's licenses; voter registrations; identity verification
Attestation	Proof of insurance, ownership and origin; notarised documents
Physical asset keys	Digital keys for physical assets including cars, homes, hotel rooms, lockers, etc.
Intangible assets	Licences; trademarks; patents; domain names; proof of authorship or authenticity
Other applications	Gaming; reviews and endorsements

the supply chain increases, which incurs additional costs and risks and further decreases transparency (Saberi et al., 2019). Additionally, companies need high levels of trust in intermediaries to handle sensitive information in a secure way, which can be devastating when the intermediary is compromised or dishonest. Furthermore, centralised systems mean that each organisation has their own version of the truth about a product's journey through the supply chain. A solution to easily integrate the information systems from various organisations is required to present a single version of the truth (Hewett, Lehmacher, and Y. Wang, 2019).

This section looks at blockchain as a solution to some of the problems caused by centralised systems in supply chains and discusses the benefits and challenges of blockchain, specifically in the supply chain, as well as practical use cases, current implementations and finally, considerations for implementing blockchain in the supply chain.

3.3.1 The benefits of blockchain that are most applicable to supply chains

As previously discussed, blockchain provides many benefits to its users in general. When specifically looking at supply chains, even more benefits can be realised.

Blockchain is a useful tool for creating transparency in supply chains, as shown by Dietrich, Turgut, et al. (2020) when they created a smart contract-based blockchain solution to dynamically map changes in complex supply chains. Overall transparency in the supply chain can increase significantly thanks to the high levels of data integrity and auditability provided by blockchain (Q. Lu and X. Xu, 2017). Blockchain will allow companies to track and trace product origins and processes more easily, allowing them to quickly find and resolve issues, increase product safety and improve service levels (Cole, Stevenson, and Aitken, 2019). Transparency ensures that companies are held accountable for their actions. Since information on the blockchain is immutable and available to all users, firms are automatically more transparent with the information they share with others, thus ensuring ethical production practices in terms of human rights, food integrity and environmental sustainability (Francisco and

Swanson, 2018).

Transparency among supply chain stakeholders extends visibility throughout the entire network, as each party has access to more information and thus have greater awareness of what is going on in the supply chain. Since information regarding the location, condition and movement of goods is more freely available when required, companies can track items through the supply chain and make data-driven decisions which enable them to quickly respond to unexpected events and thus prevent disruptions in the supply chain (Y. Chang, Iakovou, and Shi, 2020; Shirani, 2018).

The security blockchain provides is mostly related to data and information integrity and the fact that once it is stored on the blockchain, it is nearly impossible to change. Y. Wang, Han, and Beynon-Davies (2019) state that decentralisation is a unique data security mechanism of blockchain. Combining this feature with cryptography and the consensus mechanism ensures immutability of data stored on the blockchain. Furthermore, the distributed architecture of blockchain means that it is protected against single points of failure (Deng, 2020). Supply chain stakeholders can thus be sure that the data they send and receive has not been tampered with since it was added to the blockchain. This leads to lower supply chain risk, as secure and reliable data will support more informed and data-driven decisions (Pawczuk, Massey, and Schatsky, 2018).

Linked to the previous point is the trust that blockchain creates – or rather the reduced *need* for trust. Enhanced data security, as well as increased transparency and greater visibility solves the problems of accountability between parties that do not necessarily have aligned interests (Cole, Stevenson, and Aitken, 2019), as information is available in real-time and is guaranteed to be unchanged since the time it was uploaded to the blockchain. Furthermore, transacting parties do not need to place their trust in an intermediary to facilitate and validate transactions (Civelek and Özalp, 2018). A major benefit is thus the high levels of trust between supply chain stakeholders that is embedded in blockchain (Y. Wang, Singgih, et al., 2019).

Blockchain is expected to provide much greater speed and efficiency compared to existing systems in supply chains – especially those that are still highly paper-based (Shirani, 2018). Blockchain's computational logic and the implementation of smart contracts will allow various processes to be automated, thus reducing the need for double-checking and guesswork, consequently improving speed and reducing human errors throughout the supply chain (Cole, Stevenson, and Aitken, 2019; Y. Wang, Singgih, et al., 2019). Greater efficiency and increased processing speeds, along with enhanced security and transparency will generate significant time-savings and cut various costs such as those due to intermediaries, regulatory compliance, documentation errors, delays, and more general operational and transaction costs (Cole, Stevenson, and Aitken, 2019; Saberi et al., 2019; Ganne, 2018).

Blockchain brings new levels of integration to the supply chain. Disintermediation, the removal of the third party, allows supply chain parties to directly interact with one another, thus integrating previously disparate stakeholders (Q. Lu and X. Xu, 2017). Blockchain provides a cross-company and even cross-industry platform, thus allowing information systems to transcend the borders of a single organisation and integrate actors from different companies and industries (Block and Marcussen, 2020). Various databases, existing information systems, processes, machines and other entities are integrated through the use of blockchain, which allows easier communication and increased information flows (Y. Wang, Han, and Beynon-Davies, 2019; Korpela, Hallikas, and Dahlberg, 2017).

3.3.2 The challenges that blockchain faces in supply chains

The emerging and novel nature of blockchain lends the technology to various challenges that need to be overcome for it to gain mainstream adoption in global supply chains. According to unrelated surveys by Deloitte (2018) and Hackius and M. Petersen (2017), regulatory issues are one of the greatest organisational barriers to greater investment in blockchain technology. The general lack of regulation and laws is slowing the adoption of blockchain, as it causes high levels of uncertainty (Pawczuk, Massey, and Schatsky, 2018; Divey, Hekimoğlu, and Ravichandran, 2019). One specific issue is deciding which laws to follow and which courts have the power to make decisions regarding the technology, since the blockchain will be subject to various jurisdictions due to its distributed nature (Y. Chang, Iakovou, and Shi, 2020; Y. Wang, Han, and Beynon-Davies, 2019).

A related issue is the legal recognition of blockchain-based information because governments have different domestic regulation compliance requirements (Allen et al., 2019). Block and Marcussen (2020) state that existing legislation is still focussed on paper-based processes. Blockchain requires an entire regulatory framework that accounts for electronic versions of signatures, documents and transactions, one that recognises the authority of different government entities and one that also ensures interoperability of various networks (Ganne, 2018).

The lack of standards regarding the information stored on the blockchain is another major challenge that must be overcome. The absence of consistent standardisation means that users are not aware of how to use the technology efficiently (Block and Marcussen, 2020). A standardised format for data entering the blockchain and other relevant semantics are required for participants to have a similar understanding of the data, as this will improve interoperability and consistency of information from various stakeholders (Ganne, 2018). A challenge with the creation of standards is compliance to the various domestic requirements of different applicable countries or regions (Allen et al., 2019).

One of the reasons for the importance of blockchain standards is the interoperability that it enables. The ability to easily share information and operate between different systems is vital for blockchain, as it is meant to smoothly cooperate with existing systems and other blockchains belonging to different companies and sectors (Y. Chang, Iakovou, and Shi, 2020).

For large, complex cross-border supply chains the scalability of blockchain is a major challenge due to throughput, latency and capacity limitations (Tian, 2017). The blockchain must be spread across industry sectors and users for it to be effective, but what makes this challenging is the distributed architecture and consensus mechanism of blockchain that limits the speed at which transactions can be processed (Y. Chang, Iakovou, and Shi, 2020). Large volumes of data and the high-speed flow of information that is necessary in global supply chains are thus not yet completely possible with blockchain (Deng, 2020). Scalability in terms of the number of transactions is a larger issue for public blockchains with lower levels of trust than for consortium or private blockchains, where completely different and more efficient consensus algorithms are often used (Ganne, 2018).

Confidentiality is another concern regarding blockchain – specifically due to the transparency it provides. Many stakeholders in the supply chain fear a competitive disadvantage when sharing information on the blockchain, as this will be accessible to more parties – some of which may be competitors (Block and Marcussen, 2020). Botton (2018) describe transparency as a double-edged sword: it improves efficiency, but opens a company's practices to criticism and possible loss of competitive advantage. Fortunately, there are some solutions to these problems, including off-chain storage of private or sensitive data or using more advanced cryptographic methods to encrypt the data (Hewett, Ogée, and Furuya, 2019).

Blockchain's novelty and the fact that it consists of various technologies mean that it requires significant infrastructure. Consequently, most companies and supply chains need to make large initial investments in the technology to address the digital gap that many organisations are facing (Ganne, 2018; Block and Marcussen, 2020). Such investments are thus not high priority for top management if the benefits of the technology are not clear, which leads to the next challenge faced by blockchain in the supply chain.

As was the case with many previously emerging technologies, unrealistic levels of hype surrounding the technology result in its publicly pressured adoption in areas where it is a poor fit compared to other technologies, which leads to disappointing results and consequently damages the reputation of the emerging technology (Verhoeven, Sinn, and Herden, 2018; Hewett, Lehmacher, and Y. Wang, 2019). This is no different for blockchain. Various other factors contribute to scepticism towards the technology: lack of suitable use cases in certain areas (Divey, Hekimoğlu, and Ravichandran, 2019), unclear benefits in some industries (Hackius and M. Petersen, 2017), lack of clear return on investment (ROI) (Y. Chang, Iakovou, and Shi, 2020), misunderstanding of blockchain technicalities and functions (Y. Wang, Singgih, et al., 2019), and finally misconceptions due to reputational issues with cryptocurrencies that are associated with blockchain (Block and Marcussen, 2020; Pawczuk, Massey, and Schatsky, 2018).

3.3.3 Practical use cases of blockchain in supply chains

As more research regarding blockchain technology in supply chains is performed, the number of identified use cases increase. Dietrich, Mehmedovic, et al. (2021) looked at different use cases that combine blockchain with supply chain management and developed a classification model for the feasibility of moving the associated supply chain events to the blockchain. Their model can be useful for evaluating the use cases discussed below. The literature shows uses for cross-border dispute resolution since records are easily retrievable, to facilitate compliance to a vast number of requirements thanks to the visibility it provides (Y. Chang, Iakovou, and Shi, 2020) and IP management, including proof of creation, ownership and existence, and rights registration and enforcement (Ganne, 2018). More popular use cases for blockchain are discussed below.

A frequently mentioned use case in literature is the use of blockchain to support supply chain and trade digitalisation and automation (Ganne, 2018). This is done by digitising the tons of paper-based documentation that are abundant in cross-border supply chains and storing these digital documents on the blockchain (Calle et al., 2019; Hewett, Lehmacher, and Y. Wang, 2019), which can greatly reduce costs associated with paperwork processing and improve efficiency related to the flow of information between parties in different parts of the world (Hackius and M. Petersen, 2017).

Another use case with massive potential in supply chains is tracking and tracing – previously close to impossible due to the high complexity of goods and limited visibility in supply chains (H. M. Kim and Laskowski, 2018). Information regarding products, e.g. its nature, quality, quantity, location and ownership is recorded on the blockchain and accessible by all its users (Saberi et al., 2019), thus allowing these products to be tracked through the supply chain and traced back to its origins (Hackius and M. Petersen, 2017). Each transaction between parties is recorded, meaning any instance of counterfeiting, theft or corruption can be traced back to the party responsible for the crime (Francisco and Swanson, 2018). This allows for greater transparency into supply chain practices, allowing environmental, health and safety issues to be unearthed along with any human rights abuse or unethical practices (Saberi et al., 2019). By investigating 43 publications in various industries, Dietrich, Ge, et al. (2021) identified increasing transparency in supply chains as the main objective of recent blockchain projects in the context of supply chain management.

Blockchain can serve as a more reliable solution than existing centralised internet servers to integrate, connect, manage and store the large amounts of data generated by IoT devices in supply chains (Hackius and M. Petersen, 2017). Blockchain in combination with IoT may be especially useful for tracking and tracing applications, as such information is usually recorded by IoT, GPS and RFID sensors and devices (Allen et al., 2019; Ganne, 2018). Blockchain also has the ability to integrate various disparate ERP systems belonging to different organisations in the supply chain, allowing them to communicate through the blockchain, rather than individually (Cole, Stevenson, and Aitken, 2019; Francisco and Swanson, 2018).

Finally, similar to the tracking and tracing of products, assets can be managed and tracked using blockchain by assigning each asset with a unique digital identity and using this to track them between different parties. Furthermore, thanks to blockchain, assets can be used as collateral, thus opening new ways of supply chain financing (Hewett, Lehmacher, and Y. Wang, 2019). A summary of blockchain's use cases in supply chains is provided in Table 3.5.

3.3.4 Current implementations of blockchain in supply chains

As of 2022, there are and have been many blockchain implementations and pilots in supply chains across the world. The names of investment banking companies such as UBS, Goldman Sachs and JP Morgan, financial services companies like Citi and Barclays, and other major companies including Samsung, Amazon, eBay, Unilever and Accenture are frequently mentioned in literature regarding blockchain implementations in supply chains (Crosby et al., 2016). The rest of this section discusses some of the larger blockchain pilots in industry by companies of various sizes – whether start-ups or industry giants.

In 2014, the Danish shipping company, Maersk, tracked a shipment of perishable goods from Kenya to the Netherlands with the goal of understanding the physical processes and documents associated with each shipment (Ganne, 2018). They found that a single shipment requires input from up to 30 actors, involvement from more than 100 people and includes over 200 interactions (Scott et al., 2018). The shipment was completed in 34 days, 10 of which were spent waiting for documents to be processed (Ganne, 2018). Following this, Maersk partnered with International Business Machines Corporation (IBM) and the Dutch government to apply blockchain to this process in the form of a proof of concept (POC), which was successfully conducted from 2016 to 2017 to showcase the ability of blockchain to streamline the approval workflow of certificates (Scott et al., 2018). The POC's subject is the shipping of flowers from Mombasa, Kenya to Rotterdam in the Netherlands – a process that requires six documents that describe the origin, chemical treatment, quality and customs duties which must be signed by three different companies (Ganne, 2018).

The farmer in Kenya uploads a packing list to the permissioned blockchain making use of the Linux Foundation's Hyperledger Fabric platform (Y. Wang, Han, and Beynon-Davies, 2019). This triggers a smart contract that simultaneously requests authorisation from each of the three participating government agencies, while also communicating other information from the flowers' inspection to customs approval to the outgoing Port of Mombasa for them to prepare the shipping container (Y. Chang, Iakovou, and Shi, 2020). All information on the blockchain is updated and available in real-time to all authorised participants, allowing for greater transparency and efficiency. It shows who submitted which documents and when, as well as the flowers' location, the current owner and the remaining steps that need to be taken.

After a successful round of pilots was completed in early 2017, IBM and Maersk developed TradeLens, a blockchain-based global trade platform that aims to integrate all maritime supply chain process into one platform (Civelek and Özalp, 2018) by connecting the various participants and digitalising the supply chain to make information sharing easier and more efficient (Ganne, 2018). This allows all authorised participants to view and track a container from its origin to destination with an immutable record stored on the blockchain (McDaniel and Norberg, 2019). The project shows how blockchain can simplify various time-consuming processes and reduce the workload associated with verifying and securing transactions (Botton, 2018).

TABLE 3.5: *Blockchain use cases in supply chains.*

Main category	**Use case**	**Authors**
Digitisation and automation	Customs declaration	Y. Chang, Iakovou, and Shi (2020); Ganne (2018); Calle et al. (2019)
	Document and information sharing	Gatteschi et al. (2018); Swan (2015); Crosby et al. (2016); Hackius and M. Petersen (2017); Y. Wang, Singgih, et al. (2019); Ganne (2018); Calle et al. (2019); Hewett, Lehmacher, and Y. Wang (2019); Y. Chang, Iakovou, and Shi (2020)
	Secure and efficient operations	Zile and Strazdiņa (2018); Crosby et al. (2016); Zheng, S. Xie, H.-N. Dai, et al. (2018); Cole, Stevenson, and Aitken (2019); Hewett, Lehmacher, and Y. Wang (2019)
	Decentralised P2P marketplace	Gatteschi et al. (2018); Zile and Strazdiņa (2018); Zheng, S. Xie, H.-N. Dai, et al. (2018); I.-C. Lin and T.-C. Liao (2017)
	Insurance	Gatteschi et al. (2018); Zile and Strazdiņa (2018); Swan (2015); Crosby et al. (2016); Dinh et al. (2018); Ganne (2018)
Tracking and tracing	Fraud detection and prevention	Gatteschi et al. (2018); Pawczuk, Massey, and Schatsky (2018); Hackius and M. Petersen (2017); Cole, Stevenson, and Aitken (2019); Y. Wang, Han, and Beynon-Davies (2019); Hewett, Lehmacher, and Y. Wang (2019)
	Real-time tracking and analytics	Scott et al. (2018); Sternberg and Baruffaldi (2018); Saberi et al. (2019); Pundir et al. (2019); Shirani (2018); Allen et al. (2019); McDaniel and Norberg (2019); Calle et al. (2019)
	Proof of ownership	Gatteschi et al. (2018); Swan (2015); Crosby et al. (2016); Ganne (2018); Calle et al. (2019)
	Provenance tracking	Zile and Strazdiņa (2018); Brody et al. (2019); I.-C. Lin and T.-C. Liao (2017); Hackius and M. Petersen (2017); Verhoeven, Sinn, and Herden (2018); Francisco and Swanson (2018); H. Wu et al. (2017); H. M. Kim and Laskowski (2018); Kouhizadeh and Sarkis (2018); Saberi et al. (2019); Shirani (2018)
	Product quality and safety verification	Gatteschi et al. (2018); H. Wu et al. (2017); Scott et al. (2018); Saberi et al. (2019)
Trade finance and payments	Supply chain finance processes	Ganne (2018); Calle et al. (2019); Hewett, Lehmacher, and Y. Wang (2019)
	Cross-border payments	Gatteschi et al. (2018); Pawczuk, Massey, and Schatsky (2018); Divey, Hekimoğlu, and Ravichandran (2019)
	Blockchain-based contracts	Zile and Strazdiņa (2018); Swan (2015); Verhoeven, Sinn, and Herden (2018); Cole, Stevenson, and Aitken (2019); Pundir et al. (2019); Y. Wang, Singgih, et al. (2019)

Another major player that looked at blockchain in its supply chain is Walmart, the American multinational retailer. In collaboration with IBM they worked on blockchain pilots in 2016 and 2017 to enhance transparency and improve the tracking of products in their supply chain, similarly to IBM's collaboration with Maersk (Verhoeven, Sinn, and Herden, 2018). Two pilot projects were conducted. The first involved tracking fresh produce from Mexico to the United States and received input from 24 different actors, including farms, packing houses, brokers, import warehouses and a processing facility (Y. Chang, Iakovou, and Shi, 2020). They were able to identify and track products significantly faster than before (six days compared to two seconds) and were able to quickly remove recalled items from their shelves (Verhoeven, Sinn, and Herden, 2018).

For the second pilot project Walmart collaborated with IBM, JD.com, the online Chinese marketplace, and Tsinghua University in Beijing to track different pork products from farms to stores within China (Y. Chang, Iakovou, and Shi, 2020; Ganne, 2018; Scott et al., 2018). These two projects showed the benefits associated with more transparent and accurate records describing the movement of food: companies are able to quickly and precisely find all tainted products when a recall is necessary, food safety in general is increased, fresher products are available to customers and consumer trust will increase. Based on the success of the pilot projects, Walmart and IBM formed a consortium in 2018 powered by the IBM Food Trust blockchain platform with the aim of setting new standards for the industry and increasing consumer trust (Y. Chang, Iakovou, and Shi, 2020; Ganne, 2018). Members include Driscoll's, Nestlé, McCormick and Company, Kroger and Unilever among others (Y. Wang, Han, and Beynon-Davies, 2019).

A frequently occurring name in literature is that of the London-based start-up, called *Everledger*, who partnered with Barclays to track diamonds through the supply chain to ensure its authenticity and ethical sourcing from conflict-free regions (Francisco and Swanson, 2018; Scott et al., 2018; Y. Wang, Han, and Beynon-Davies, 2019). Various uniquely identifiable features of a diamond are recorded on the blockchain, along with a digital ID for each diamond, all of which act as digital certification, thus ensuring that the diamond is actually owned by the seller and was not mined under unethical conditions (Francisco and Swanson, 2018; Hackius and M. Petersen, 2017; Scott et al., 2018). Since its inception, Everledger has extended its fraud protection system to other luxury items, including wine and art (Hackius and M. Petersen, 2017; Francisco and Swanson, 2018).

Another UK-based start-up that focusses on blockchain for track and trace within supply chains, is fittingly named *Provenance* and has the objectives of increasing the integrity of certifications and to ensure food provenance and fair payment (Y. Wang, Han, and Beynon-Davies, 2019). Their first pilot project in 2016, in collaboration with the World Wildlife Fund (WWF), tracked tuna from the sea to the plate through supply chains in Southeast Asia to ensure sustainably sourced and slavery-free products (Scott et al., 2018; Cole, Stevenson, and Aitken, 2019). For their second pilot project in 2017 the company partnered with UK retailer Co-op to track the journey of fresh foods through its supply chain in real-time and making such information available for customers to access via an application on their smartphones (Scott et al., 2018; Y. Wang, Han, and Beynon-Davies, 2019). Other Provenance projects include tracking alpaca fleece from the farm to the final product and tracking coconuts from Southeast Asia to Europe (Ganne, 2018).

T-Mining is a start-up based in Antwerp, Belgium that has created a blockchain solution for the port's container release operations. Information required for releasing a container is recorded on the blockchain and made available to authorised participants. This ensures that only those that are involved in the transaction can claim a container and that ownership can easily be determined and transferred (Y. Chang, Iakovou, and Shi, 2020). The Port of Antwerp and T-Mining successfully implemented a POC in 2018 for a specific apple trade between the Port of Napier in New Zealand and the Port of Antwerp. The main objective was to automate and secure the flow of documents by using blockchain technology and smart contracts to create a digitised phytosanitary certificate that is distributed over the blockchain network (De Cauwer, 2018).

Other blockchain implementations from smaller companies are also present in supply chains. Along with its banking partners, CGI, the trade finance platform, implemented a successful POC in 2017, which showed how banks can provide digital trade finance services to customers who transact on B2B blockchain platforms. This was done by integrating CGI's trade finance platform, CGI Trade360, with the blockchain-based platform, Skuchain (Y. Wang, Han, and Beynon-Davies, 2019; Divey, Hekimoğlu, and Ravichandran, 2019). 300Cubits improves accountability in the maritime industry and focusses on the booking process with the aim of enforcing closed agreements. The customer and shipping liner both wager a digital token as deposit into an escrow account, which acts as a contract between them and is stored on a blockchain. If one party fails to fulfil its part of the agreement, they lose their token, which goes to the other party, consequently reducing the number of no-shows and overbookings – events that previously had little consequences for the perpetrator (Verhoeven, Sinn, and Herden, 2018).

BanQu addresses a social sustainability issue and offers unbanked people, i.e. those that do not have bank accounts or use banking institutions at all, the opportunity to access global supply chains. Not having some sort of bank account makes it nearly impossible for people to participate in the global economy. BanQu's solution helps unbanked farmers record their financial transactions on a blockchain to create a trustworthy credit history and provides access to financial services on the platform. Unbanked farmers are the weakest suppliers in many supply chains and this solution allows them to be more competitive in global supply chains (Verhoeven, Sinn, and Herden, 2018).

Bext360, a Denver-based start-up, also addresses a social sustainability issue in a global supply chain: fairness towards coffee bean farmers with regards to payments. Robots are used to automate the quality evaluation and weight measurement of coffee beans and subsequently assign a fair price which is then stored on the blockchain in the form of a digital token. This offers complete traceability of each bag of coffee beans and ensures fair payment for coffee bean farmers and other intermediaries (Verhoeven, Sinn, and Herden, 2018; Scott et al., 2018).

Kouvola Innovation aims to use blockchain to improve information flows in supply chains by addressing the inefficient movement of cargo units through inter-organisational supply chains due to limiting communications infrastructure (Verhoeven, Sinn, and Herden, 2018). The idea is to use blockchain to facilitate the process of bidding for the right to move a certain load of cargo through the supply chain. Using smart contracts, the bidder that best meets the shipper's price and requirements is automatically awarded the job. This information is stored on the blockchain and allows the job and location of the shipment to be tracked (Cole, Stevenson, and Aitken, 2019).

A paper by R3 (2019) discusses various projects that make use of their Corda blockchain platform. Project Voltron introduces an efficient process for sharing and verifying trade documents. Project Marco Polo supports deep tier financing by providing greater transparency in the supply chain, thus allowing more tiers of the supply chain to be visible to financiers, allowing them to provide help further upstream. Evernym shows how documents that have been verified by a government or trusted third party can be used to prove identity during customs processes by linking Corda with Sovrin, an identity network where users can prove their identities.

3.3.5 Considerations of blockchain implementation

Before pursuing blockchain as a solution to a problem, there are various considerations that must be taken into account. This includes determining whether blockchain is actually the best suited technology for addressing the problem when compared to other similar technologies. In many cases blockchain is hyped up to be the answer to problems that it cannot yet solve or, in most cases, issues where other technologies are more appropriate – resulting in expectations that exceed reality (Zile and Strazdiņa, 2018). Besides, blockchain requires significant infrastructure – something that many companies do not have. Various factors influence the adoption of blockchain technology, and this must be taken into account when pursuing such a project. Blockchain is still an emerging technology that has limitations and faces various challenges that it needs to overcome, and must thus be approached in an open-minded way.

Blockchain has high value in situations where automation and trust is important (see Figure 3.5). Niche blockchain applications are for areas where the value of trust is high, but automation is not important, given that it is financially feasible (Ganeriwalla et al., 2018). Where automation is important, but the value of trust is low, other technologies may be more suitable than blockchain. Cole, Stevenson, and Aitken (2019) go on to explain that blockchain may also be beneficial where social sustainability is a major concern, as the extended visibility provided by blockchain can increase transparency in the supply chain, thus unearthing unethical practices. They also state that longer, more extended supply chains may benefit more from the technology than smaller local supply chains that are less complex. Thus, such a technology may not be worth the investment required for small supply chains.

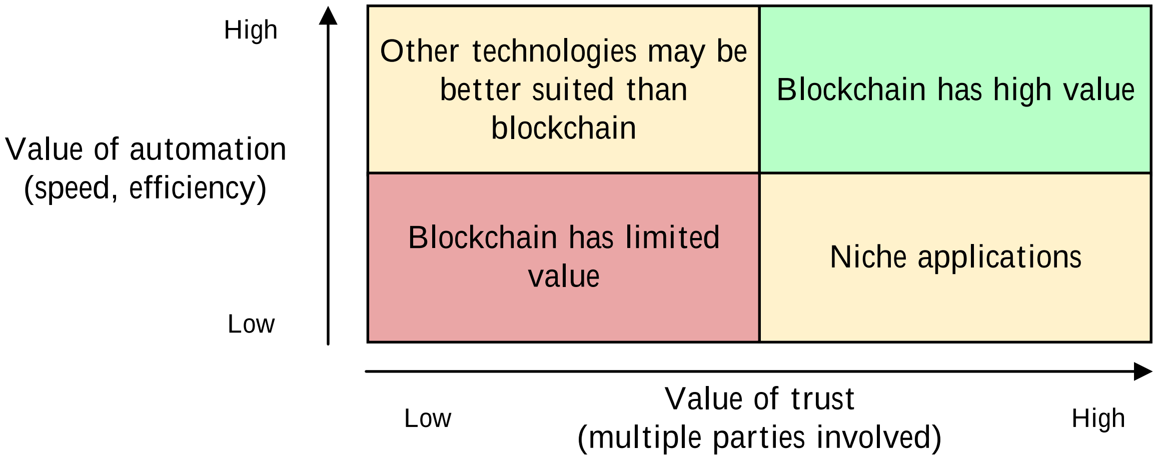

FIGURE 3.5: *The suitability of blockchain with regards to automation and trust requirements (Ganeriwalla et al., 2018; Cole, Stevenson, and Aitken, 2019).*

According to Allen et al. (2019), blockchain is useful in supply chains dealing goods that have high information costs, such as agriculture, manufacturing and pharmaceuticals – all areas in which various blockchain use cases have been explored. Ganne (2018) identifies areas where trust and transparency are required by parties involved in transactions, as areas where blockchain works best.

As mentioned before, blockchain is not always the best solution to a problem. It is important to weigh the cost of blockchain against its benefits. In many cases a more mature and less expensive technology may be a more cost effective solution that still meets the requirements. Therefore, it is important to compare blockchain to other similar and more traditional information management technologies (Divey, Hekimoğlu, and Ravichandran, 2019). Some of these include solutions that make use of RFID, ERP, electronic data interchange (EDI) and wireless sensor network (WSN) technologies or a combination of them (Cole, Stevenson, and Aitken, 2019; Tian, 2017), although many of these technologies may complement blockchain when used in conjunction with it. The WEF (2019) mentions that more traditional databases, such as an SQL or a similar database may be an overall better solution where the unique features of blockchain is not necessarily helpful.

Various existing technologies used in supply chains may be improved by integrating it with blockchain. For example, ERP systems usually operate on a business level, but thanks to blockchain, they are able to communicate on a network level across companies in the supply chain (Cole, Stevenson, and Aitken, 2019). Furthermore, blockchain can improve the tracking and tracing systems that make use of RFID and IoT devices by allowing them to communicate directly with one another through the blockchain without needing to route their data through a centralised system or intermediary, which is the case for most exiting traceability systems (Divey, Hekimoğlu, and Ravichandran, 2019; Pundir et al., 2019).

Infrastructure also plays a massive role in blockchain projects. Blockchain guarantees that data stored on it has not been corrupted or tampered with *since the time it was added to the blockchain*, but it does not prevent inaccurate information from entering the system (McDaniel and Norberg, 2019; Hewett, Lehmacher, and Y. Wang, 2019). False or incorrect information may be added to the blockchain if the infrastructure for recording data in the first place is inadequate or unreliable. This highlights the importance of input data quality and accuracy (Sternberg and Baruffaldi, 2018). By connecting IoT devices and sensors directly to the blockchain, this problem may potentially be solved (Allen et al., 2019). The user interfaces (UIs) such as web portals used for accessing the blockchain are infrastructure that is targeted during many cyberattacks, since they are less secure and often outdated. Many of these cyberattacks on blockchain are possible due to insecure vendors or bugs in the programs that run on the blockchain. The problem thus lies not with blockchain itself, but its supporting infrastructure (Calle et al., 2019; Hewett, Ogée, and Furuya, 2019).

A blockchain solution also has security and privacy considerations that may cause additional legal risk. Other than compliance to the General Data Protection Regulation (GDPR) in the European Union and similar data protection laws in other regions that regulate the transfer of personal data (Calle et al., 2019), a company must also decide how visible their data should be. For example, they may choose to store their data directly on the blockchain, visible to all participants, or they may choose to store the data off-chain with a hash of the data stored on-chain (Hewett, Hanebeck, and McKay, 2019). This way, only data that needs to be shared with others are kept on the blockchain, while sensitive and private data is stored elsewhere, while still being linked to the blockchain (Hewett, Flanagan, et al., 2019).

The literature contains many factors that influence blockchain adoption, many of which also apply to technology adoption in general. Cole, Stevenson, and Aitken (2019) mention organisational needs, such as job relevance and performance gaps, perceived factors, such as benefits and cost savings, and organisational readiness, such as availability of financial resources and technological knowledge as such factors. Additionally, widespread connectivity and digital literacy, along with participation from each actor in the supply chain are also important factors to consider (Divey, Hekimoğlu, and Ravichandran, 2019). Collaboration from all parties are vital, as even the largest players cannot succeed alone, since an industry-wide blockchain project will affect all members of the supply chain (Ganne, 2018). Through a conceptual model they developed, Francisco and Swanson (2018) identified the following factors that influence blockchain adoption:

- Performance expectancy: the more performance increases when blockchain is used, the more likely the user is to keep on using it.
- Effort expectancy: the easier it is to use blockchain, the more likely it is to be used.
- Social influence: blockchain is more likely to be used if others find it important.
- Facilitating conditions: the greater a firm's infrastructure and technical resources, the more likely they may be to use blockchain.
- Technology trust: greater trust in the security provided by blockchain will make it more likely to be used.

- Inter-organisational trust: trust between companies influence information sharing and technology acceptance.

Various frameworks for determining whether a blockchain is the right solution exist in literature, such as those by Wüst and Gervais (2018) and Maull et al. (2017). Although the frameworks are not identical, they perform the same function at their core. These frameworks ask the user a series of questions and, depending on the answers, suggests the best type of solution. The framework by Wüst and Gervais (2018) is presented in Figure 3.6.

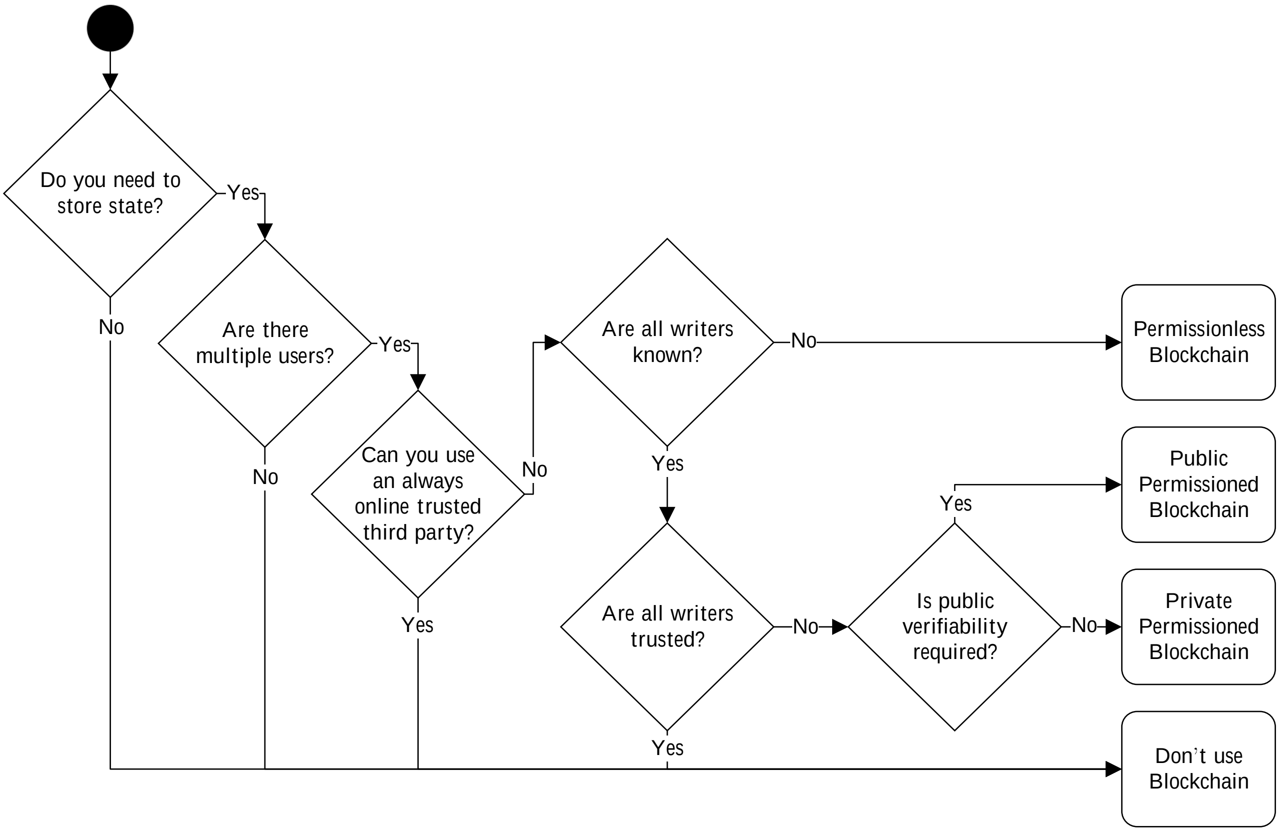

FIGURE 3.6: *Framework for determining whether blockchain is the most appropriate solution to a given problem (Wüst and Gervais, 2018).*

The first question is whether data must be stored. If not, neither a blockchain, nor a different storage solution is required. The second question to answer is whether there are multiple users. A blockchain solution is not required if there is only one user. If a trusted third party is desired and is always online, then a blockchain solution is not required because the third party can verify transactions. If all writers are not known, it is better to use a permissionless blockchain where all users can read and write to the blockchain. If all writers are known, but not trusted, it is better to use a permissioned blockchain where only certain individuals may read and/or write to the blockchain. The requirement for publicly verifiable information determines whether a public (anyone can read, but only certain users can write) or private (only certain users can read and write) permissioned blockchain should be used (Wüst and Gervais, 2018).

Blockchain type and consensus protocol selection

After blockchain has been determined as the best solution to the problem, new considerations are introduced. When pursuing a blockchain project two important choices are the type of blockchain that will be used and the consensus protocol that will validate transactions. Consensus in literature is that permissioned private or consortium blockchains are best suited for supply chain applications in most cases (Saberi et al., 2019; Y. Wang, Singgih, et al., 2019), since they are more effective at managing the consistency and integrity of data stored on the blockchain (Y. Wang, Han, and Beynon-Davies, 2019). These types of blockchains allow for a much higher throughput of transactions. Permissionless public blockchains on the other hand, are more secure against malicious parties, while sacrificing throughput (Baliga, 2017). Alternatively, organisations can look to hybrid blockchains, which combine the best of public and private blockchains, although these types of projects tend to be more complex (Hewett, Hanebeck, and McKay, 2019). When selecting what type of blockchain to use, the WEF (2019) identified the following considerations:

- Data access: who can read, write and update the ledger.
- System performance: the speed at which transactions are added to the blockchain.
- Data integrity, availability and security: safety of data from manipulation or corruption and timely flow of information between relevant parties.
- Interoperability and standards: public blockchains tend to be more interoperable due to the larger number of parties involved that work to create standards
- Total cost of ownership: private blockchains have high upfront investment costs, but low transactions costs, while public blockchains tend to be the opposite.
- Security: private blockchains have restricted access, but may be more vulnerable when participants are dishonest, while public blockchains are more resistant in that aspect due to its consensus protocol.
- Personal data protection: the fewer participants there are, the easier it is to conform to data protection laws such as the GDPR.
- Governance: public blockchains are governed by all, while private blockchains give greater control to participants and are more closely aligned to their objectives.

3.4 Chapter Summary

Key findings from the second part of the literature review can be summarised as follows. Digitalisation is vital for supply chains to survive the 4IR. As supply chains expand worldwide, visibility and transparency problems grow. The solution to obtaining end-to-end visibility, according to literature, is digitalisation. It leads to increased communication and collaboration; the real-time flow of information; and new business models and product offerings. The major challenges of digitalisation include its disruptive nature, data security concerns due to increased information flows, shortage of relevant skills, and the investment required. Firms need to have the correct digital strategy and must be open to collaboration and change.

Blockchain is an emerging technology developed to solve the double-spending problem with digital currencies. In general it is extremely useful for storing and sharing information in a secure and reliable way, which is why it shows great potential for use in supply chains. A private permissioned blockchain seems to be the best type of blockchain in cross-border supply chains. The three features of blockchain that make it such a promising solution in supply chains are immutability, security and decentralisation. Blockchain currently faces standardisation and regulatory issues, suffers from limited interoperability, and has scalability issues depending on the type of blockchain used. It has various potential use cases in supply chains, of which the digitisation and the automated flow of cross-border trade documentation is a promising direction. Blockchain is surrounded by high levels of hype, so careful consideration must be made when deciding what solution to use for a certain problem.

The second chapter of the literature study reviewed two main topics. Section 3.1 focussed on supply chain digitalisation. It started off with a discussion of the importance of digitalisation in supply chains, followed by the benefits, challenges and the desired state of future supply chains. Next, the role of technology in digital supply chains were emphasised, which was then succeeded by a discussion on paperless supply chain systems and finally concluded with recommendations for pursuing digitalisation.

Section 3.2 looked at blockchain technology and provided a background to the topic, as well as a discussion of the basic building blocks, various features, challenges and generic applications of the technology. Section 3.3 explored blockchain in the context of supply chains. Context-specific benefits and challenges were discussed. This was followed by practical use cases of the technology in supply chains, as well as specific existing implementations. Finally, the section ended with a brief discussion of various considerations that must be kept in mind when pursuing a blockchain project.

Chapter 4 looks at centralised and decentralised alternatives to blockchain technology. Centralised alternatives include relational and non-relational databases, while decentralised alternatives are other types of distributed ledgers.

CHAPTER 4

Databases and Alternatives to Blockchain

Data can be stored and transmitted in a multitude of ways – blockchain is just one type of database and has a rather unique data structure. This chapter looks at database alternatives to blockchain for storing data that will be shared between various parties. It starts off by providing a brief overview of databases in general and their more common types. There are two main categories of alternatives: more conventional *centralised databases* and newer, more decentralised *distributed databases*. For centralised databases, this chapter takes a closer look at relational and non-relational databases. For decentralised alternatives, other types of DLTs are briefly examined.

4.1 A Brief Background on Databases

A database is a collection of large volumes of data that describes various related aspects of an environment and is stored on one or more computers, while being accessible in many ways (Jatana et al., 2012; Harrington, 2009). Databases can quickly become very complex, since not only the data, but also information that explains the relationships between the data (known as metadata) need to be stored there. The idea behind a database is that the user does not need to know how the data is physically stored on the storage drive of the computer. To facilitate this, a piece of software known as a database management system (DBMS) is used to create and manage databases. It provides functionalities such as creating the structure for a database (known as its *schema*), ways to enter, modify and delete data (thus interacting with the data), a way to retrieve data, and finally methods for restricting access to data (Harrington, 2009).

Databases come in various types, depending on the data that it stores. Some of the more common database architectures include (Austerberry, 2006; Jatana et al., 2012):

- **Flat file**: an extremely basic database where data is stored in a plain-text file, with each line representing one record and commas or tabs are used as delimiters to separate fields. A good example is a comma separated values (CSV) file.

- **Hierarchical**: an older type of database that resembles a tree structure, where a number of data elements (children) are linked to a single primary record (parent), therefore supporting only one-to-many relationships. Such databases are static, meaning that data is inserted into fixed locations. Thus, the reference of each data record is fixed.

- **Network**: a type of hierarchical database that supports many-to-many relationships and can be visualised as an upside-down tree structure. Children nodes can thus have more than one parent node, meaning that this type of database allows the relationships between records to be more naturally modelled than traditional hierarchical databases.

- **Relational**: the most commonly used database where structured data is stored in two-dimensional tables. The rows and columns of different tables are related to one another through keys. Structured Query Language (SQL) is commonly used to access and modify these types of databases.
- **Non-relational**: a relatively new database that does not use relations or tables as its storage structure. It is useful for storing large amounts of unstructured data, thus making it highly applicable to modern-day applications where data is generated at high speeds. Non-relational databases are also referred to as Not Only SQL (NoSQL) databases.
- **Object-oriented**: a type of non-relational database where data is stored in objects. An object belongs to a class, which is a high level category that describes similar objects. An object also has attributes that describe its relationships to other objects. This type of database can easily handle more complex many-to-many relationships.
- **Text-based**: also a type of non-relational database that uses the extensible markup language (XML) or an alternative standard like JSON to store unstructured information, such as that of a text document, in an XML or JSON formatted document. The format is both human- and machine-readable.

Relational databases are currently most commonly used and are known to provide high levels of reliability, flexibility and scalability. Modern applications use massive amounts of data that is generally unstructured – something that relational databases cannot store. Therefore, non-relational databases are seeing increasing applications (Jatana et al., 2012). These two broad types of databases are classified as the more conventional and centralised alternatives to blockchain technology, while other types of DLTs are proposed as decentralised alternatives. The preceding sections discuss these alternatives in more detail.

Before this discussion, it is important to clearly differentiate between centralised, distributed and decentralised systems. A fully centralised database has a single master copy that is stored at a single location and controlled by a single entity (Barge et al., 2020). A distributed database is *divided* into parts and stored across multiple servers or nodes, but may still rely on a central party for authority. A decentralised database is *replicated* across multiple servers or nodes that are controlled by different parties. It is fully decentralised if an arbitrary number of entities can be feasibly ignored without compromising the entire system (Rauchs et al., 2018).

4.2 Conventional Centralised Databases

This section focusses on the more conventional and centralised databases that are currently being used in most situations, in other words, those that are stored in a single location and controlled by a single party (or company in the context of this research). It looks at the broad categories of relational and non-relational databases and provides a description of each type, main benefits and drawbacks, and a few examples of real-world implementations of such databases.

As briefly mentioned in the previous section, centralised databases have one master copy of the data that is usually stored at a single location. There exists a distinct entity or group of entities with which an actor must interact to be able to access the data (Rauchs et al., 2018). These databases are thus centralised both in terms of location and control. It should be noted that the databases described in this section can be implemented in a distributed fashion (thus decentralised storage). However, this section focusses on centralised implementations.

Databases that have a centralised architecture offer various benefits compared to decentralised solutions (Rauchs et al., 2018; Barge et al., 2020; Raikwar, Gligoroski, and Velinov, 2020):

- Low latency means that the database responds quickly to read or write requests.
- High throughput capacity and speed due to fewer decision makers in the governance process means that the database can be updated in a very short time.
- Low computing overhead due to centralised control means that fewer resources are consumed when performing certain tasks. For example, in a client-server setup, only the server and the client that made the request consume resources.
- Efficient use of resources due to a single master copy of the database that needs to be maintained. Any changes to the database need to be confirmed only by the administrator.
- Control and high levels of confidentiality, since it easy for administrator to manage the system and control the parties that have read and write access.

There are, of course, many drawbacks to such an architecture as well, many of which go hand-in-hand with certain benefits (Rauchs et al., 2018; Barge et al., 2020; Raikwar, Gligoroski, and Velinov, 2020):

- Low censorship resistance means that the single administrator of the database can easily censor certain data and revoke the privileges of specific users.
- High trust requirement in third party intermediaries, i.e. the system administrators. Massive amounts of trust is put in them to manage and secure the database.
- Possible collision of owner and user incentives, which also adds to the problem of a third party administrator.
- Single point of failure, as the entire database may be compromised if the administrator is bypassed or if the master copy of the database is corrupted. A single failure can affect the whole system, thus leaving it vulnerable and less robust to attacks and failures.

4.2.1 Relational databases

Relational databases have been around since the 1970s and are currently the most used databases in the world (Karaarslan and Konacaklı, 2020). The main idea is that related sets of information is stored in various tables, where each row represents a record and each column an attribute that describes the record. Since the locations where data is stored are not fixed and therefore have no fixed reference, a unique field, known as a private key, is assigned to each record to make it identifiable (Austerberry, 2006). Most relational database management systems (RDBMS) use SQL to access and modify data stored in the database (Jatana et al., 2012). SQL was developed as a standard language to access, store, manipulate and retrieve data in relational databases. Consequently, "SQL" or "sequence databases" are used in reference to relational databases.

To maintain the integrity of data in a relational database, transactions must have certain properties, collectively called *ACID* (Austerberry, 2006; Jatana et al., 2012; Karaarslan and Konacaklı, 2020):

- *Atomicity.* Transactions must either be fully completed or aborted. If any part of the transaction is incomplete, the entire transaction must fail (all or nothing).
- *Consistency.* A database must be stable at a valid state before and after any transaction. A valid state is defined by certain rules of the database. In the case of any invalid state, the previous valid state must be restored.

- *Isolation.* Transactions may not be influenced by others, thus a transaction is only available to other transactions once it has been committed. To ensure this, transactions that are executed at the same time are serialised, meaning they are executed one after the other.
- *Durability.* Once a transaction has been committed to the database, it must remain in that state. In other words, a transaction and a record of any changes made to it must be permanently stored in the database, regardless of any failures such as a system crash or power loss.

Benefits and drawbacks of relational databases

Relational databases offer additional benefits over centralised databases in general. Firstly, they are well structured and follow a strict schema, meaning the database is predictable and leaves little room for errors. Adding, updating or deleting data can be done by the database administrator with ease. A major benefit is that this type of database has been around for many decades during which it has matured and improved extensively. Therefore, even though they are not state-of-the-art technologies, relational databases can be a safe and reliable way to store certain data. Another benefit is the general ease of scalability – they are able to handle relatively high volumes of smaller structured data well and the database can be expanded to accommodate more data with ease (i.e. vertical scalability). Finally, due to its maturity, there are many capable people that have the knowledge to correctly administer relational databases (Austerberry, 2006; Jatana et al., 2012).

Drawbacks of relational databases are of course also present and growing ever more prominent as the technology ages. Relational databases handle big data very poorly due to its meticulous nature, strict schemas and constraints. This makes it incapable of handling the massive amounts of data generated by applications in the modern-day world, such as cloud and web services (Bhat and Jadhav, 2010). Relational databases are only scalable up to a certain point, after which it must be partitioned and stored across multiple servers, thus becoming a distributed database (Jatana et al., 2012). The table structure may lead to high complexity when data cannot be easily stored in a table, i.e. when data is unstructured. SQL is also very complex when working with unstructured data. Thus, relational databases handle unstructured data poorly (Karaarslan and Konacaklı, 2020). Finally, data must be formatted, normalised and interlinked with foreign keys before it can be stored in a relational database, which dramatically reduces flexibility (Chitti, Murkin, and Chitchyan, 2019).

Real-world uses of relational databases

ERP systems have been used by firms around the world since the 1990s with the goal of integrating various business processes. It uses internet technologies to integrate various information flows from internal business functions, customers and suppliers. Naturally, such systems require a DBMS and in most cases a relational database is used along with a client/server network architecture (Yusuf, Gunasekaran, and Abthorpe, 2004). This is also the case for most asset-management products (Austerberry, 2006). Typical RDBMSs include Oracle Database by Oracle Corporation, Amazon Relational Database Service (RDS) by Amazon, the DB2 family of data management products by IBM and the Microsoft SQL Server by Microsoft (Austerberry, 2006). Some RDBMSs are open-source and include MySQL with a focus on cloud-based applications, PostgreSQL, an object relational database system, and MariaDB, a derivative of MySQL (Raikwar, Gligoroski, and Velinov, 2020).

4.2.2 Non-relational databases

One of the solutions to the problem of ageing relational databases that struggle to keep up with the massive amounts of unstructured data produced in the Internet Age, is non-relational databases.

Apart from SQL, it also uses other query languages and is therefore known as "NoSQL" (i.e. "Not Only SQL") or "non-sequence" databases. As seen in its name, these types of databases do not use the table/key storage structure of relational databases. Instead, data is stored in the form of documents in various different formats, depending on the type of non-relational database. This type of data structure provides much greater flexibility and allows massive amounts of unstructured or semi-structured data to be stored (Jatana et al., 2012). Some of the most common non-relational database types include key-value stores, document stores, graph databases, column databases, object-oriented databases and XML databases.

Most non-relational databases violate the "consistency" property of ACID, so instead, BASE properties are used to ensure data integrity in non-relational databases (Jatana et al., 2012):

1. *Basically Available.* The data must be mostly available, meaning the database appears to be working most of the time.
2. *Soft-state.* The state of the system may change at any time, even without input due to the third BASE property:
3. *Eventual consistency.* The system will eventually become consistent, given that it does not receive any new inputs. This contrasts with the "consistency" property of ACID, as consistency takes time to be reached in this case.

Benefits and drawbacks of non-relational databases

Non-relational databases offer significant benefits (Bhat and Jadhav, 2010; Jatana et al., 2012) – many of which make up for the deficiencies of relational databases. They are extremely scalable due to the relaxed structure compared to relational databases, which makes them capable of handling massive amounts of unstructured data. High availability and reliability – even on hardware that is prone to failure – is another benefit of non-relational databases, but this requires data to be stored on multiple nodes or machines, thus making the storage distributed instead of centralised. A final benefit is that non-relational databases are schema-free, meaning no schema has to be defined before writing data to the database. For example, documents stored in the same database are independent and do not need to contain the same fields. The schema-free nature further improves scalability and provides developers with much greater flexibility when developing applications. This also means that the entire database does not need to be updated when a new field is added, as is the case with relational databases.

Unfortunately, there are also drawbacks (Jatana et al., 2012; Bhat and Jadhav, 2010). Although non-relational databases have increased performance, this is done at the cost of consistency (thus, why ACID properties are not ensured). Lower reliability is a consequence of not ensuring consistency. This means that developers will have to create additional functionality to ensure greater reliability, which increases complexity. Finally, the non-relational database is a much newer concept than relational databases and have not had much time to mature. Developers are thus not extremely familiar with the technology, meaning it is less stable and lacks certain functionalities.

Real-world implementations of non-relational databases

Non-relational databases are used for newer generations of applications that use unstructured or semi-structured data or require elastic scalability. Many of these applications operate in environments with massive workloads, such as web or cloud services. As mentioned earlier, there are many different types of non-relational databases, of which many are open-source (Jatana et al., 2012; Bhat and Jadhav, 2010; Raikwar, Gligoroski, and Velinov, 2020). Popular document-oriented non-relational databases include MongoDB and CouchDB. Some well-known key-value databases include Apache Cassandra and Amazon SimpleDB. Another database by Apache is HBase, which is column-oriented.

4.3 Decentralised Alternatives to Blockchain

Distributed ledger technology is more than just blockchain – there are various types of DLTs, of which blockchain is the most widely-used one of these (Galanis and Habermacher, 2019). Other DLT designs were developed to address certain limitations of blockchain (Schueffel, 2017). This section compares other DLTs not only to blockchain, but also the previously mentioned centralised alternatives.

4.3.1 A brief background to DLT

A broad definition of DLT, provided by Rauchs et al. (2018), is that it is an umbrella term for multi-party systems that operate in an environment with no central authority where participants may be unreliable or malicious. Kannengießer et al. (2020) provide a more specific definition by defining it as an "... append-only database (a distributed ledger) that is maintained by physically distributed storage and computing devices (referred to as nodes) in an untrustworthy environment."

In other words, DLTs are databases where identical copies of the database are locally stored on different geographically-spread nodes (i.e. distributed) belonging to the various participants of the P2P network. The database is synchronised through a consensus protocol that requires approval from multiple nodes (i.e. decentralised) before any changes are made. Therefore, it is a database without a central administrator or centralised storage (Born, 2018), which is one of the factors differentiating it from a regular distributed database. Although this description seems extremely similar to that of blockchain, the main difference is the cryptographically linked block structure used by blockchain. Different data structures can be used in other types of DLT, as described later in this section.

The CAP theorem for databases and its alternative for blockchains

The CAP theorem applies certain logic to database systems by stating that any database system, whether its control is centralised or decentralised, can only have two of the following three desired characteristics (Raikwar, Gligoroski, and Velinov, 2020; Kannengießer et al., 2020):

- *Consistency*: a read from any node provides the latest write to the database.
- *Availability*: any request receives a response from the system at any point in time, regardless of whether it is the newest write.
- *Partition tolerance*: even if one or more nodes stop working or lose connection to the system, the system should still continue to function.

Centralised databases are not partitioned and distributed across various nodes, so they do not support partition tolerance, thus making them CA systems that have the properties of Consistency and Availability. Since distributed systems must be partition tolerant in order to function correctly, the remaining choice for them, and thus a trade-off, lies between Consistency and Availability. AP systems, those that have the properties of Availability and Partition tolerance, do not guarantee that any reads are up to date. CP systems, those that have the properties of Consistency and Partition tolerance, are not available when new information in being written to the system, which can then disrupt the consensus process.

Blockchain is an exception to the CAP theorem, as it provides consistency, availability and partition tolerance. Consistency, however, only occurs later due to the consensus mechanism and blockchain's decentralised nature. Therefore it provides *eventual consistency*. To account for this, the DCS theorem is proposed for blockchain systems. Any blockchain system can only have two of the following three desired characteristics (Raikwar, Gligoroski, and Velinov, 2020):

- *Decentralisation*: no central entity controls the network, thus there is no single point of failure.
- *Consistency*: a read from any node provides the latest write to the database.
- *Scalability*: the performance of the system increases as the number of peers and computational resources increase.

DC (decentralised and consistent) systems, such as Bitcoin and other cryptocurrencies compromise on scalability and are not able to handle a growing number of users or transactions well. CS (consistent and scalable) systems are mostly private and permissioned blockchains that are not completely decentralised. Finally, DS (decentralised and scalable) systems, like the Interplanetary File System (IPFS), compromise on consistency. Figure 4.1 visualises the CAP and DCS theorems and classifies certain real-world databases according to the characteristics they prioritise.

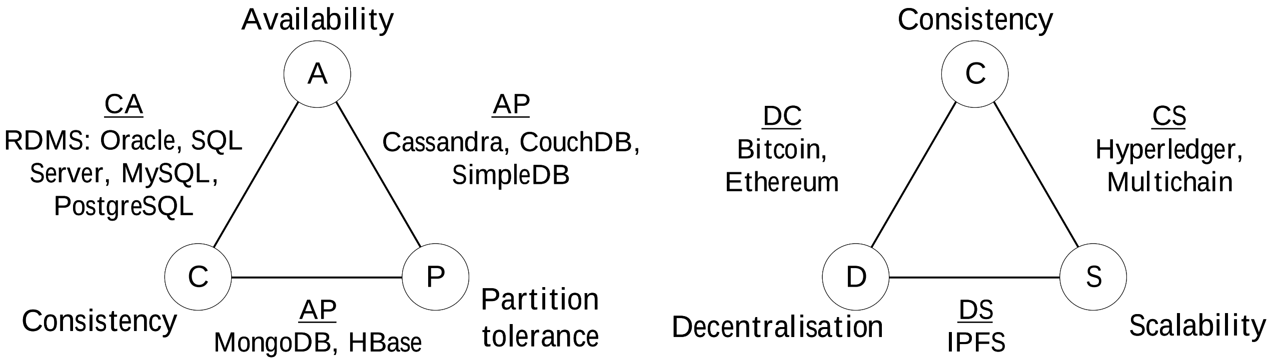

FIGURE 4.1: *CAP triangle (left) for traditional databases and DCS triangle (right) for blockchain systems (Raikwar, Gligoroski, and Velinov, 2020).*

4.3.2 Benefits and drawbacks of DLT systems

DLT systems have various benefits compared to centralised databases. They have a high resistance to collusion and the abuse of power because no central authority controls the database (Rauchs et al., 2018; Born, 2018). This also stems from the transparency and auditability provided by the technology, which further reduces opportunities for fraud and tampering (Natarajan, Krause, and Gradstein, 2019). The decentralised nature of DLT systems give the users more power by removing the need for a central administrator, thus eliminating the need for trust. This makes DLTs extremely useful in areas where high levels of trust are required (Rauchs et al., 2018).

Another major benefit are the built-in security mechanisms. DLT systems are much more resilient to outside attacks than centralised systems in general. If one node of the network is compromised, the entire system will not fail, which is the case with centralised systems where there is only one node and thus a single point of failure (Galanis and Habermacher, 2019; Harrington, 2009). Cryptography and consensus mechanisms in DLT systems ensure that stored data is immutable, unlike with most centralised systems where the administrator can change any data they wish.

Compared to blockchain, other DLT designs offer fewer additional benefits, since most of the alternatives were developed to overcome the limitations of blockchain. These benefits vary from design to design, so they are discussed along with the different designs later in this section.

Some drawbacks that other DLT designs share with blockchain compared to centralised databases are longer transaction confirmation times, lower throughput capacity, higher overheads and less efficient use of resources in general (Rauchs et al., 2018). Scalability and transaction speeds remain issues for most DLT designs (Chowdhury et al., 2019; Romero Ugarte, 2018), however some are able to scale well as the cost of some other attribute (see discussion on existing implementations below). Additional costs are also a drawback to DLT designs. While certain costs are reduced or eliminated, new costs are introduced. An example is the cost of parallelisation, where the data must be written to each existing copy of the database, i.e. each node (Born, 2018). This leads to higher maintenance cost and physical space requirements.

The issue of governance is mentioned quite often in literature (Natarajan, Krause, and Gradstein, 2019; Romero Ugarte, 2018). The lack of a central authority raises the question of how the infrastructure will be governed to ensure that applicable laws and regulations are followed and that misbehaving nodes are disciplined. A final issue present in all DLTs is their lack of maturity (Natarajan, Krause, and Gradstein, 2019; Romero Ugarte, 2018). Existing implementations are limited in scale and functionality. One of the consequences is the lack of standards, which further leads to problems with interoperability and integration with other systems.

Finally, compared to blockchain, other DLT designs are often overshadowed by its hype. These alternatives are more niche than blockchain, so issues like lack of maturity, standardisation and interoperability are even more severe for other DLTs. As with the benefits compared to blockchain, drawbacks are often specific to the DLT design, so this is further discussed in the next part of the section.

4.3.3 Real-world implementations of DLT systems

This section looks at alternative DLT designs to blockchain. Examples of more common implementations are discussed and briefly compared to one another.

Some DLT designs address the scalability problem of blockchain by using the directed-acyclic graph (DAG) data structure. Refer to figure 4.2 for a visual representation of the blockchain data structure compared to others discussed in this section. For the DAG, each node represents a transaction and each line between two nodes is a validation of the transaction (El Ioini and Pahl, 2018). This type of data structure is used by two well-known DLT implementations: IOTA and Hashgraph.

IOTA is a competitive alternative to blockchain that was designed with IoT in mind. Instead of a PoW type of consensus algorithm, IOTA uses Tangle, whose data structure is based on a DAG (Chowdhury et al., 2019). Transactions are validated by requiring the sender of a new transaction to validate two other transactions; thus combining the processes of creating transactions and reaching consensus on their validity. This eliminates the need for miners and thus also the cost associated with transaction fees (El Ioini and Pahl, 2018). Consequently, designs that use the DAG data structure are fast (for each new transaction, two others are validated), free of cost (no transaction fees due to no miners) and extremely scalable (each new user helps to validate transactions).

Another DLT design that makes use of DAG is Hedera's Hashgraph. In reference to figure 4.2, each column represents a user, each vertex an event and each line between vertices an indication of gossip. The main difference between blockchain and Hashgraph is its consensus mechanism: a combination of the gossip protocol and virtual voting (Kahn, 2019). Each user randomly selects a neighbouring user to share all their information with. That user repeats the process with their new knowledge, thus spreading the information throughout the system through "gossip". This reduces bandwidth, as a new transaction does not have to be shared with the entire system at once, but rather a single node (El Ioini and Pahl, 2018). Since each user has a copy of the database and knows who else has received the information they have, they can calculate whether other nodes will accept or reject a given transaction. This is known as virtual voting where every node knows each other's decision without casting a ballot. Hashgraph provides much greater speeds and scalability than blockchain.

Unfortunately, the technology is patented and has only been tested in private environments (Schueffel, 2017).

The concept of a sidechain is a novel approach to overcome the limitations of traditional blockchain security, privacy and performance (El Ioini and Pahl, 2018). The main idea is to have a primary ledger (the mainchain) that manages requests from all users and a set of smaller, independent ledgers running in parallel to the mainchain (the sidechains) that are used to process local transactions. An example is to have a primary consortium blockchain among companies, where each company or a smaller group of companies have their own private blockchain. The mainchain contains all information that is shared with other members of the consortium, while the sidechains contain private information and validate only the applicable transactions. Thus, no processing or validation of transactions occur on the mainchain, but rather on the applicable sidechains. This leads to massive improvements in scalability (each node validates fewer transactions), privacy (sensitive data can stay private on the sidechain) and security (sidechains are independent from the mainchain) (Karaarslan and Konacaklı, 2020).

Holochain also implements the gossip protocol, but unlike Tangle, uses a distributed hash table (DHT) data structure. DHT maps the whole network of nodes by key values that act as a node's ID (Karaarslan and Konacaklı, 2020). Each node runs its own ledger and therefore only has to validate its own transactions, which means that Holochain offers limitless scalability and no transaction fees (Anwar, 2018). Data is shared with other peers via the gossip protocol, as previously explained. Since the transaction occurs between two parties in the network, any false information is detected and consequently rejected (Kahn, 2019).

Figure 4.2 shows the difference in structure between blockchain, Tangle, Hashgraph and sidechains. The DLT designs discussed above are compared in Table 4.1. Entries marked with * depend on the specific implementation of the DLT design. For example, in the case of blockchain, there are massive differences in performance between public and private blockchain implementations, so the TPS varies greatly.

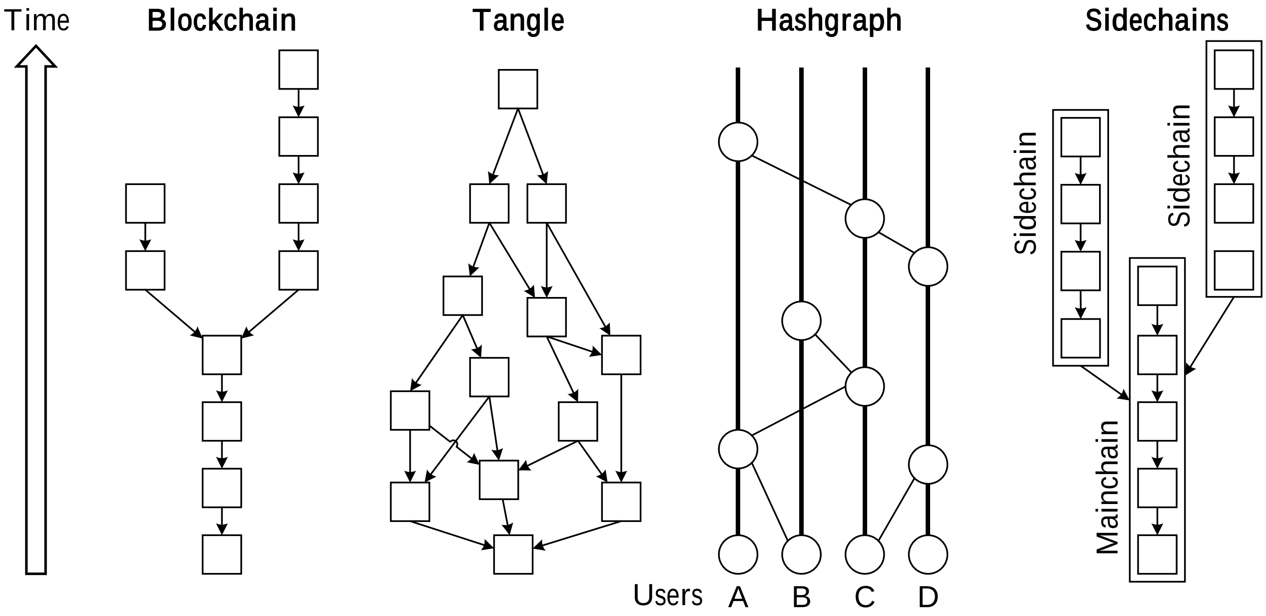

FIGURE 4.2: *Differences in structure of some well-known DLT designs (El Ioini and Pahl, 2018).*

TABLE 4.1: *Comparison of well-known DLT designs (adapted from Karaarslan and Konacaklı, 2020; El Ioini and Pahl, 2018).*

	Blockchain	**Tangle**	**Hashgraph**	**Sidechains**	**Holochain**
Data structure	Linked list	DAG	DAG	List of linked lists	DHT
Platform	Bitcoin, etc.	IOTA	Hedera	Plasma, etc.	Holo
Transaction fee	Yes *	No	No	Only for main-chain	No
TPS	7-20,000 *	500-800	>200,000	>billions	>millions
Licence	Open source	Open source	Patented	Open source	Open source
Maturity	More mature	Experimental	Experimental	Experimental	Experimental
Initial release	2008	2016	2017	2017 *	2018

4.4 Chapter Summary

In summary, centralised relational databases have had more time to mature compared to non-relational databases and distributed ledgers. This leads to benefits such as being more reliable, having fewer unresolved issues, and having more experts capable on managing such solutions. They are, however, unable to adequately deal with the massive amounts of unstructured data generated today, are less flexible due to their strict schemas, and suffer from security issues associated with centralisation, such as having a single point of failure. Blockchain is the most well known distributed ledger implementation. Therefore, most DLTs have similar benefits to blockchain (e.g. increased transparency, decentralisation, and no need for a third party intermediary), but also suffer from many of its drawbacks (e.g. slower speeds in some cases, governance issues, increased investment costs and a lack of maturity). Some DLTs are better solutions to certain problems when compared to blockchains, which must be accounted for when selecting a solution to a problem.

This chapter provided a brief background on alternative centralised and decentralised databases to blockchain in Section 4.1. Relational and non-relational databases were discussed in Section 4.2, along with their benefits, drawbacks and a few real-world examples. The same was done in Section 4.3 for DLT designs other than blockchain. Chapter 5 discussed a case study of a company in a cross-border supply chain that was used to collect more information on trade documents and issues experienced in global trade.

CHAPTER 5

A Case Study in a Cross-border Supply Chain

This chapter discusses the general operations related to the international trading process in a cross-border supply chain. Firstly, background is provided on the case company of the supply chain, as well as why this specific company was selected to be the subject of this case study. Secondly, the identification of critical stakeholders in the supply chain and their roles are described. Thirdly, critical trade documents along with their contents are discussed. Fourthly, the mapping of the flow of goods, documents and other types of information throughout the supply chain is described. The fifth part is a discussion on the issues that are often experienced in the supply chain related to the flow of information and physical documents. The interview guide and questions that were discussed in the interviews can be found in Appendix A.

5.1 Background to the Case Study

The focus of the case study is a fresh fruit exporting company headquartered in the Western Cape province of South Africa. For the sake of privacy, "the Company" will be used in reference to the case company. An interview with the Chief Operating Officer (COO) of the company's fruit division was conducted to gain insight into their supply chain and the challenges they experience regarding information flows. The major commodities in their supply chain are citrus (43%), grapes (34%), pome fruit (16%), i.e. apples and pears, and other fruit (7%). The company sources these fruit from their own farms in South Africa and Namibia, as well as from suppliers in Brazil, Chile, Costa Rica, India, Mexico, Peru and Spain. Around 55% of their volume is sourced from South Africa, while 45% is sourced globally. Products are exported to major markets in North America, Europe and Asia (The Company, 2021). Figure 5.1 visualises the globally spread nature of the supply chain by showing the areas from which fruit are sourced and in which areas they are sold.

This supply chain is a good example of a complex cross-border supply chain with stakeholders spread across the world where physical documents have a significant presence and play a large role in the daily operations. Various protocols, processes and systems are in place to protect the industry from issues, including but not limited to pests, spoiled fruit, fraud, and forgery. A consequence of this, along with strict rules and regulations in the industry, is that many documents are required to be physically stamped, signed and transported between various role players to ensure tight control. The physical nature of these documents leads to multiple issues that are discussed in Section 5.5. To limit the scope of the thesis, the case study focussed on citrus exports, since this fruit category requires tighter control than others and document-related issues are often associated with it (Anonymous, 2021a).

5.2 Critical Stakeholders in the Supply Chain

Important stakeholders in the exporting part of the supply chain are listed and their main responsibilities are discussed below. More information on the documents that are shared between stakeholders

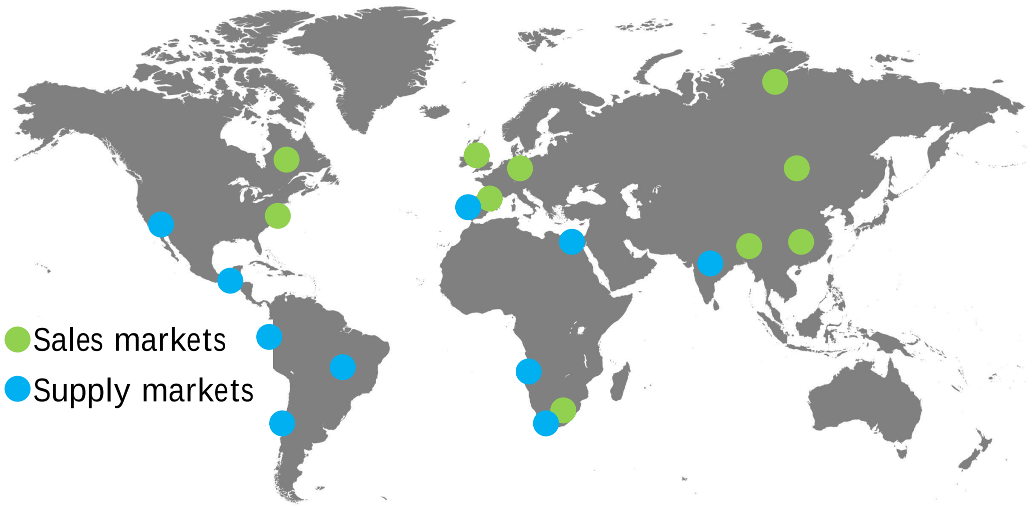

FIGURE 5.1: *Sales and supply areas of the company (The Company, 2021).*

and who they interact with are discussed in later sections.

- **Farmers and producers**. The suppliers of the products that are sold. They grow the fruit, send their supply information to the exporter, receive orders from the exporter and send the fruit further downstream to packhouses or cold stores.

- **Exporter/seller**. Plays a vital role in organising the export of fruit and acts as the seller in the transaction. Handles nearly all the trade documents and ensures that orders are correctly fulfilled and paid for.

- **Government- and related authorities (e.g. PPECB, DALRRD)**. There are various types with different functions, e.g. some perform inspections and issue trade documents. They ensure that the relevant standards and regulations are adhered to.

- **Freight forwarder/shipper**. Handles important trade documents and is intermediary between exporter and ocean carrier. Organises transport for products between ports.

- **Shipping line/ocean carrier**. Transports products from the port of load (POL) to the Port of Destination (POD). Usually works with many different freight forwarders.

- **Third-party logistics (3PL)**. Transport the products and their containers between locations such as the packhouses, depots, cold stores and ports

- **Notify party/consignee**. Submits the shipping documents at the customs authorities in the POD for customs clearance. Can be consignee who represents buyer and takes ownership of shipment after discharge in POD.

- **Customer/buyer/consignee**. Ultimate receiver of the bulk products. Is consignee when notify party is not the consignee.

- **Customs authorities**. Control the import and export of goods across the world. They check shipping documents to ensure adherence to regulations, and discharge shipment to consignee.

5.3 Critical Trade Documents in the Supply Chain

Cross-border trade documents can be grouped into five groups: commercial documents, official documents, insurance documents, transport documents, and financing documents (DAFF, 2014; Karabulut, 2020; ExportHelp, 2021). The rest of this section describes the documents in each of these categories.

5.3.1 Commercial documents

The *proforma invoice* is used by the exporter to provide information regarding the goods and the conditions of their sale to the importer with no financial obligation, in other words, a quotation in invoice format. It contains the terms of sale, such as the price, delivery and payment terms (DAFF, 2014). Once the proforma invoice is accepted by the importer, the exporter prepares the *commercial invoice*. This document contains information such as the names and addresses of both the importer and exporter, the name of the vessel, an invoice date and number, the type, quantity, unit price and total price of goods, packaging information, total weight of the goods, loading and unloading addresses, delivery method, payment method, bank details and the origin of the products (ExportHelp, 2021). A consular invoice is used to approve information on the commercial invoice, such as the price and origin of goods and is issued by the consulate of the importing country in the exporting country. Finally, a freight invoice is issued by the logistics company that is transporting the goods between origin and destination, and contains a description of the freight, name of the freight forwarder, origin, weight, and the number of charges (Karabulut, 2020).

The *packing list* provides details on all the products that are loaded into the container for the shipment (Anonymous, 2021a), which must match what is on the commercial invoice. Important details on the packing list include the date, shipper (freight forwarder), exporter and consignee contact information, origin and destination of cargo, total number of packages in the shipment, a detailed description of each package, volume and weight of each package, as well as the entire shipment and the commercial invoice number (FreightRight, 2021). According to the case company, the packing list also includes a seal number, container number and a serial number of the temperature monitoring device in the container (Anonymous, 2021a).

5.3.2 Official documents

The *export certificate* is a document that is issued by the relevant authority after goods that are designated for export passes inspection (DAFF, 2014). In South Africa, this authority is the Perishable Products Export Control Board (PPECB). The export certificate contains the following information: the date on which it was issued, a serial number, the name and address of the exporter, the country of origin and destination, means of transport, name of the vessel, container number, the weight of the cargo, as well as the number and types of packages (Hanief, 2018).

The *phytosanitary certificate* shows the origin of the shipment and also confirms that the goods were inspected in the country of origin by a member of the importing country's National Plant Protection Organisation (DAFF, 2014). A phytosanitary certificate is required as proof that the exported products contain no diseases or harmful substances. This document applies to regulated plant products, while a health certificate is required for regulated animal products (Karabulut, 2020). Typical information on such documents include the name, address and contact details of both the freight forwarder and the consignee, origin and destination, transport means, declared point of entry, import permit number, shipment details such as container numbers, number of packages, type of product, treatment details, and a stamp from the relevant authority (B. Thompson, 2019).

The main purpose of the *certificate of origin* is to certify the country from which the exported goods originated (DAFF, 2014). It describes the type, quantity and total weight of the goods, as well as the names and addresses of the exporter and importer, where it was loaded and, of course, where it was produced (Karabulut, 2020). The certificate is accompanied by a stamp of the relevant authority and the date on which it was issued.

Customs declaration forms, such as the SAD 500, are required for customs clearance when goods are exported to ensure that goods are properly declared with the exporting country's revenue service. There are various customs declaration forms, but common information include the name of the consignee, the port of load, means of transportation, and the estimated date of departure (ExportHelp, 2021).

5.3.3 Insurance documents

The *insurance certificate*, issued by an insurance company, acts as proof that the exporter has procured marine insurance for the shipment (DAFF, 2014). Marine insurance is vital due to the massive number of risks involved with international trade. The term describes insurance that covers the risks involved with all forms of transport, including sea, road, rail, and air (ExportHelp, 2021).

The certificate of insurance only acts as proof of insurance, but does not set out the terms and conditions of the insurance. The document that contains this information is the *insurance policy*, which specifies the rights and responsibilities of each party involved in the insurance process (Karabulut, 2020).

5.3.4 Transport documents

The *bill of lading* (BoL) is a legal document that acts as a receipt to confirm that goods were received by the shipping line. It is also described as a contract between the shipping line and freight forwarder that states the terms and conditions of the shipment (ICE Cargo, 2019). A third function is that it expresses who currently has the property rights on the goods (Karabulut, 2020). The bill of lading protects the shipping line by ensuring that the cargo cannot be released to the customer before the freight forwarder releases the bill of lading to the consignee (Anonymous, 2021a). Information on the BoL include the name and title of the carrier (shipping line), name of the captain, name and nationality of the vessel, name of the shipper (freight forwarder), name of the consignee, port of load, port of destination, cargo information (type, quantity, weight, etc.), container type, date and place, and freight terms (Karabulut, 2020). An *air waybill* is used for airfreight, while a *road waybill* is used for road transport (DAFF, 2014).

5.3.5 Financial and financing documents

The documents that fall into this category depend on the payment method for the shipment. In many cases, the *letter of credit* is used (DAFF, 2014). It is a financial document that is issued by a bank and guarantees payment from a buyer (importer) to a seller (exporter) (Pritchard, 2020). Many of the documents discussed in this section are required as various types of proof before a letter of credit can be issued (Credit Guru Inc, 2021).

Although there are other documents involved in the cross-border trade process, the ones discussed above are the most important and usually the most demanding documents in terms of effort, time and money.

5.4 Mapping the Supply Chain

Information flows pertaining to the exporting and importing processes in the supply chain are mapped and visualised in this chapter. The cross-border trading process has various important documents, three of which that were focussed on: the phytosanitary certificate (referred to as "phyto" from here on), the export certificate, and the bill of lading. The importance of these documents were emphasised in the interview (Anonymous, 2021a) and is consistent with the literature (Civelek and Özalp, 2018; Karabulut, 2020; Australian DFAT and Chinese MofCom, 2001). For a summarising mapping of the information flow of the trade process, refer to Figure A.1 in Appendix A, which provides an overview of the general documentation flows in the supply chain. The rest of this section focusses on the products and the critical documents that were identified in the interview and their flows.

Product flows

Fruits are harvested on their respective farms. From there, it is either packed into boxes on the farm and then sent to a cold store, or the raw product is transported to a packhouse where it is packed into boxes. From the packhouse, the boxed fruit are palletised and either placed into containers and moved directly to the POL where the containers are stacked, or they are transported to a cold store. The pallets of fruit are kept in the cold store until it is ready for export, after which it is placed into containers and transported to the POL, where the containers are stacked.

From the stack, containers are loaded onto a ship and transported to the POD, where it is discharged, unloaded from the ship and stacked. From there, the containers are either collected and inspected by the customer, or are moved to a cold store, where the goods are inspected and the pallets are removed from the containers. Goods are repackaged into smaller sizes if necessary and then handed over to the customer. Refer to Figure 5.2 for a visual representation of the product flows.

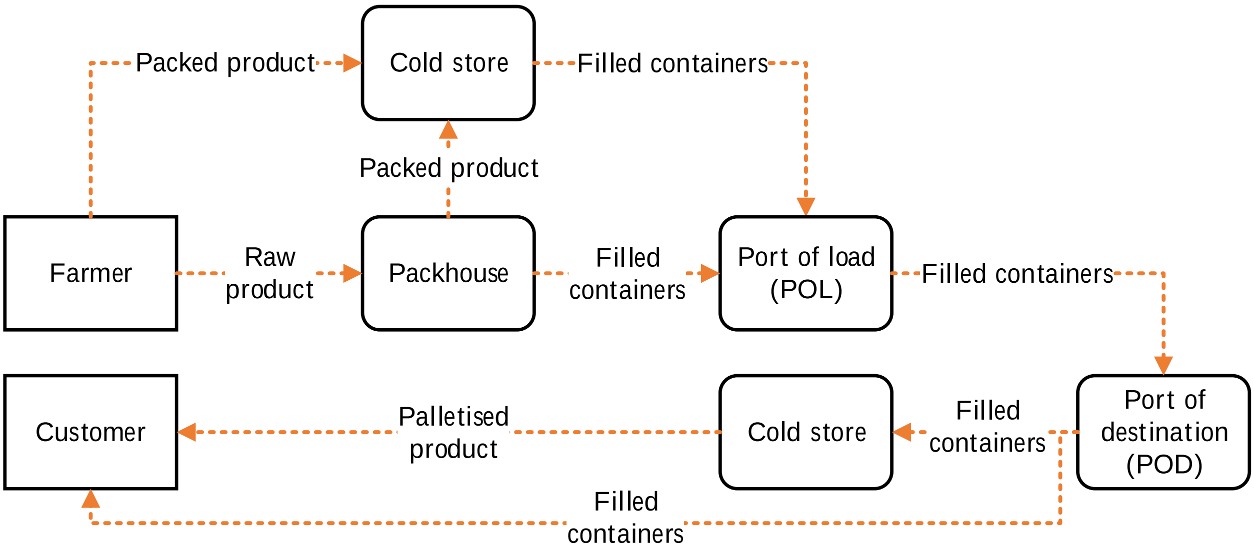

Figure 5.2: *Product flows in the case supply chain (Anonymous, 2021a).*

Phytosanitary- and export certificate flows

Phytos are required when exporting plants, plant products and other regulated commodities (B. Thompson, 2019). In South Africa, the Department of Agriculture, Land Reform and Rural Development (DALRRD), previously known as the Department of Agriculture, Forestry and Fisheries (DAFF) issues phytos to the relevant parties. The packhouse sends the intake documents to the exporter, who forwards it, along with an addendum, to the freight forwarder. The freight forwarder applies for an export certificate by sending the intake documents and its addendum to the PPECB, who signs the addendum and sends it back to the freight forwarder, along with an export certificate. The freight forwarder then submits the export certificate and the signed addendum to DALRRD, who issues them a phyto in return. Finally, as part of a package of shipping documents, the phyto is sent by the freight forwarder via courier to the notify party or consignee in the destination country who uses it to discharge the goods in the POD by submitting these documents to customs authorities. Figure 5.3 visualises the flow of phytos. The flow of the export certificate is indicated by a yellow line, while the flow of the phyto is a green line.

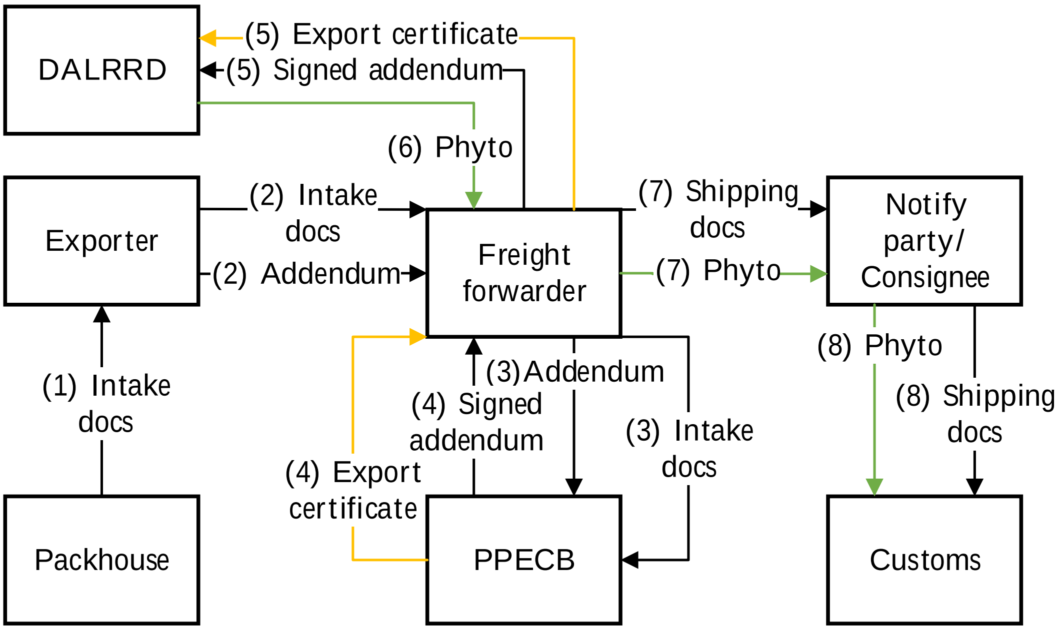

FIGURE 5.3: *Phyto and export certificate flows in the case supply chain (Anonymous, 2021a).*

Bill of lading flows

Upon receipt of the goods that are to be transported, the shipping line generates the BoL and sends it to the freight forwarder. Next, the BoL is forwarded to the customer who checks it against their purchase order and then submits it to customs in order to release their shipment from the POD. Figure 5.4 shows how this document flows through the supply chain.

5.5 Prevalent Issues Experienced in the Supply Chain

The process of trading fruit – especially citrus fruit – requires many trade documents because of strict control over pesticides to prevent pests, such as the false codling moth and the citrus black spot from spreading from South Africa to Europe, and other parts of the world. Strict rules, protocols and regulations are put in place by the Citrus Growers Association (CGA) in South Africa to protect the country's citrus industry. Being banned in Europe is catastrophic because it is a major market. Additionally, each orchard – not just the farm – must be registered with DALRRD to be able to export to a certain country. Furthermore, the fruit exporter also requires an export certificate and a phytosanitary certificate to export fruit to most countries (Anonymous, 2021a).

The current state of digitalisation and automation in the supply chain

Information flow in the supply chain is still highly manual with relatively low levels of digitalisation. Most information from packhouses and cold stores are automatically recorded via EDI onto the Company's systems. Some information (e.g. the customer profile) used to be shared over the cloud file

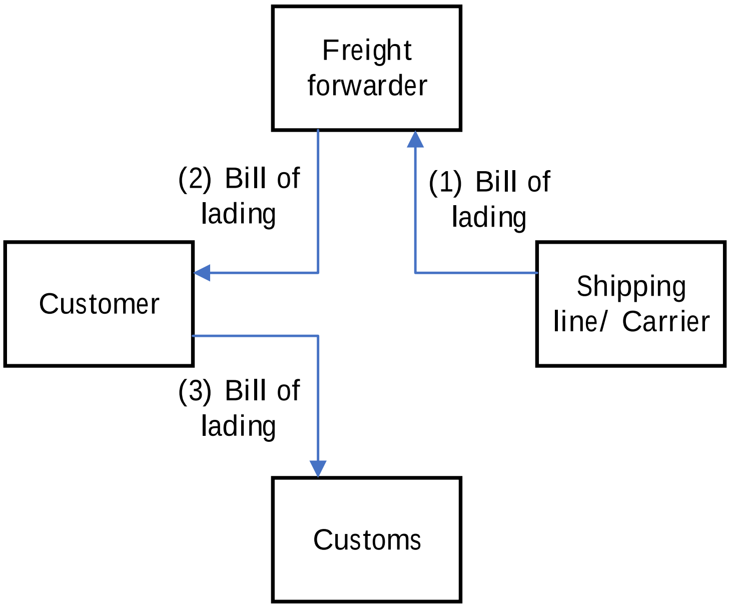

FIGURE 5.4: *Bill of lading flows in the case supply chain (Anonymous, 2021b).*

hosting service, Dropbox, but is now done via the web-based collaborative platform, Microsoft SharePoint, because it is more secure with better access control and a clearer audit trail. The Company is working with other companies to electronically pull invoice information to their systems via EDI. Invoicing is currently very manual and cumbersome, because each invoice must be checked against rate sheets, the container number must be verified, the invoice must be sent for approval, etc. All communication related to this process occurs via email, which leads to a large amount of effort and email traffic. Furthermore, massive amounts of information that flow between the company and freight forwarder are highly manual and occur via email.

The industry is mostly automated for information flows between packhouses, cold stores and exporters (such as the Company), thus, further upstream in the supply chain. This, however, is not the case for other parties further down the supply chain, such as freight forwarders, shipping lines and customs authorities. Formal documents, such as intake and outtake files are automated. Furthermore, the PPECB is working on applications and platforms that eliminate the need for physical documents. An example is eCert, an online platform created to facilitate the receiving, verifying, processing and delivering of certification documentation to trading partners involved with agricultural export products. Another initiative in the more formal markets (such as the UK and Europe) is the development of an e-phyto, where the phytosanitary certificate is electronically communicated with customs authorities. In other words, the need for a physical phyto is eliminated.

The Company has multiple systems for managing their data: DIPA as their general information system, Microsoft Dynamics for their finances, Microsoft SharePoint for sharing sensitive documents with other parties, shared network drives for many different types of information storage and many specialised applications to fulfil certain functions – especially for their finances.

A major issue throughout the supply chain is the recapturing of information, which consumes a lot of time and resources and is prone to mistakes. Information must be captured correctly at the source, but due to the vast number of stakeholders and different types of information, this process is extremely complex. Furthermore, the scope of automation and EDI implementation efforts is not generic enough, but rather very specific to the client and therefore not standardised. In general, there are not enough industry-driven automation and digitalisation initiatives.

Issues with intra-company flows

A problem within the Company itself is that too much information is handled by email – data is unstructured, often duplicated, irrelevant people are carbon copied to an email and emails are often not prioritised correctly (there tends to be a focus on newer emails at the top of the inbox). This is extremely inefficient and wastes valuable time. Invoices are problematic as well because they are handled manually. The Company's accounts department receives an invoice, checks it against the rate sheet and sends it for approval by email – all of which takes time since it is not automated. Furthermore, unexpected events that lead to costs also wastes time. If such a cost is noted, its record must be found and whether it was approved by someone at the Company. Depending on whether such proof can be found, this process leads to an inefficient back-and-forth until the cost is eventually approved.

Issues with inter-company flows

Upstream in the supply chain, data from suppliers are mostly electronic and flows are automated. Checks are built into the Company's information system to automatically identify common mistakes, which makes it easier to fix. Information flows downstream in the supply chain are more problematic. Communication with the freight forwarder is highly manual with email being the main medium of communication. Documents shared via email include the load instruction, Q67 and packing list. The freight forwarder communicates with the shipping line via email as well, so lots of information is copied and pasted which must be recorded in the systems of each party and is thus prone to errors. Figure A.1 in Appendix A shows the number of important information flows between the exporter, freight forwarder and shipping line. The fact that these flows are inefficient and highly manual presents a major problem for the supply chain.

General industry-wide issues

Incomplete or incorrect paperwork is a major problem. Due to the massive impact an incorrect document can have, the Company has worked hard to reduce the frequency of such problems. Delayed paperwork can prevent shipments from being discharged. This incurs massive storage costs and may potentially lead to spoiled fruit as well. Various levels of standardisation are present throughout the supply chain, depending on the document that is in question. Standardised templates are used for the important documents such as the load instruction and Q67. Invoices, however, are not standardised at all. Most invoices are manually sent via email and uses different sizes and formats.

Many role players in the industry are hesitant to adopt new technologies because there are so many systems and technologies available that other companies are trying to sell – all of which cost a lot of money but does not necessarily address the specific problem that a buyer has. According to the COO of the Company, a better understanding of the technology will help companies make educated purchase decisions and will also help the development of relevant and generic standards.

A final industry-wide issue is limited visibility in the supply chain. Visibility only stretches, at most, to tier 1 neighbours, i.e. the exporter's direct neighbours. Once the products have been loaded onto trucks, the Company gets fairly regular updates from the freight forwarder. When the products are loaded onto a ship, they can see when it has been loaded and what the estimated time of arrival (ETA) is, although this is not always accurate and visibility between departure and arrival is extremely limited. A major problem they experience is real-time visibility with the ability of exception management. An example is when a transshipment is supposed to take place where the container must be loaded onto another ship in a different port. If the transshipment is missed, the issue will only be picked up by the Company once the shipping line finds the issue and updates the ETA they initially provided.

5.6 Chapter Summary

This chapter provided an overview of a complex supply chain that operates in the global trade environment. The case company was introduced as background to the case study. Next, the most important stakeholders in their supply chain were identified, followed by the critical trade documents required for successful trades. Based on the literature review and information from an interview with a professional at the case company, information flows in the supply chain were mapped, with a focus on the three most important documents. The last part of the chapter discussed the major issues that the company and other stakeholders in their supply chain experience. Chapter 6 discusses the development of two models that describe the flow of documents in cross-border supply chains – the first one based on a centralised relational database system and the second one based on more decentralised blockchain technology.

CHAPTER 6

Conceptual Model Design

The main purpose of this chapter is to showcase the two different models that were developed for sharing digital information between actors in a global supply chain with the goal of replacing physical documents. It describes two different conceptual models: a model based on centralised architecture that makes use of relational database technology (referred to as the RDB model) and a model based on decentralised architecture that makes use of blockchain technology (referred to as the BC model). In Section 6.1 various generic and specific model requirements that were identified are briefly discussed. Section 6.2 describes the centralised RDB model, while Section 6.3 describes the decentralised blockchain-based model.

An important decision to make is deciding whether to develop the database solution from scratch or to make use of a service offering like database-as-a-service (DBaaS) or PaaS offerings provided by companies such as IBM, Oracle, Amazon, Microsoft and Google. Each choice offers its own benefits and drawbacks. Developing a solution in-house provides greater control over the database and its data, but such projects require massive investments and additional expertise. A fully-managed DBaaS, on the other hand, offers less control and independence, but have much lower costs and effort, and much higher flexibility and scalability (Norris, 2017). Since fully-managed databases are services offered by a different company, they handle the setup, maintenance and security of the system, while also providing expertise and other value-added services. For the context of companies in a globally spread supply chain with many different stakeholders, outsourcing such an endeavour makes more sense (Anonymous, 2021b). Therefore, the two models described below are based on fully-managed DBaaS offerings.

6.1 Requirements Identification

This section briefly discusses various practical aspects of databases that these models needed to describe in order to provide at least a basic idea of what the solutions entail. Firstly, requirements that applied to both models are briefly discussed, followed by more specific requirements for each model. This list was compiled with basic practical aspects that should depict what using technology based on such a model is like without going into detail on all the technical aspects. The following general requirements were identified for each model:

- **Database storage**. Refers to the physical location where the database will be stored. Relational databases are often stored in a central location on a single node. For a blockchain solution, ledgers are stored on multiple nodes, each one usually located at the premises of the different users of the network. By using DBaaS, this decision is made by the service provider and depends on the specific service that is used.
- **Access control** is vital for databases in this environment to prevent sensitive data from being accessed by unauthorised individuals. Each model must describe how access to the database

can be granted to specific users, as well as who the party is that will facilitate the authorisation process. For DBaaS, the service provider will have a process in place for this.

- **Accessing the database**. After permission to access the database has been granted to a user, they will need a way to access it. The models must describe how users are authenticated, what devices can be used to access the database, and how that device is connected to the database.
- **Writing to the database**. The models should address how data will be written to the database, i.e. how documents are uploaded for example. Adding data to the database may only be done by users with write permissions, so the models must also specify how this control will be ensured.
- **Data encryption and decryption**. To ensure the privacy and security of sensitive information, data added to the database will be encrypted. The specific encryption algorithm and process must be described by the models. This also includes the decryption process by the receiving party.
- **Reading from the database**. Much like writing data to the database, users must be able to read data as well. Only those with read permissions may access the data. Therefore, the models must describe how data is accessed by individuals with read permission, and also how this control is ensured.
- **Error and mistake correction**. Mistakes and different types of errors are a common occurrence with databases. The models must describe how such errors and mistakes can be corrected when they occur.
- **Maintenance**. The database and its infrastructure must be maintained over its lifetime. This includes physical maintenance and software updates, among other tasks. Each model needs to specify who is responsible for such maintenance and how it will be performed.

The RDB model had certain requirements that did not apply to the BC model. The specific database of the DBaaS provider and its type must be specified. This determines the query language that is used to interact with the database. Making use of a fully managed database service eliminates the need for identifying the specific components of DBMSs, e.g. the hardware, software, procedures, etc.

Similarly, the BC model had its own specific requirements. Firstly, the type of blockchain (public, consortium, or private) that it is based on must be specified. Another vital requirement is the consensus algorithm that is used to update the ledger. The third requirement is whether on-chain or off-chain storage is used. The latter requires additional databases to be maintained, the specifics of which must be described by the model.

6.2 A Conceptual Model for Relational Databases

The relational database is a tried and tested technology, thus making it a potentially safer option with many companies offering it as a DBaaS. The model described in this section is based on one such offering. The reason for selecting a relational database as the focus of this model was because of its wide variety of uses in supply chains, the high availability of such services, as well as its benefits: reliability, flexibility and vertical scalability (Jatana et al., 2012). The relational database can also be expanded to store structured data for other business-related operations that are not the focus of this research. This model, however, also makes use of a non-relational database – details of which are discussed in Section 6.2.2.

The following DBaaS offerings were considered: IBM's Db2 on Cloud, Amazon's Relational Database Service (RDS) for MySQL, Oracle's MySQL Database Service, Microsoft's Azure Database for MySQL, and Google's Cloud SQL. IBM and Oracle have been offering relational databases for decades since its origin in the 1970s with their DB2 and Oracle Database products respectively being cited as "typical relational database products" (Austerberry, 2006; Christopher and Asagba, 2021). The other three companies are major players in the cloud computing domain with massive catalogues of cloud-based services that include top-tier relational DBaaS offerings (Mateljan, Čišić, and Ogrizović, 2010; Iancu and Georgescu, 2018). Furthermore, the selected products were among the most popular and highly rated fully-managed DBaaS offerings at the time that were rated by commercial verified users on websites such as Gartner (2021b), the global research and advisory company, and G2 (2021b), a dedicated business software and services review website.

The comparison of these five offerings is discussed in the next section and the service that was deemed most applicable to the cross-border trading environment's documentation flows was consequently selected for the model.

6.2.1 Comparison of RDBMS alternatives

Databases have hundreds of aspects that can be compared – only some of which are more relevant to cross-border supply chains. The previously mentioned DBaaS offerings were compared with one another using the following criteria (G2, 2021a; Gartner, Inc., 2021a; Capterra, 2021):

- **High availability (HA)**. This means that cloud databases will still be available in the event that a database component fails (N. Verma, 2020). DBaaS providers offer the ability to replicate the database on multiple nodes in different availability zones (AZ). The guaranteed availability is specified in the provider's service-level agreement (SLA).
- **Security**. This criterion considers the availability of tools that can be used to secure the database. It includes support for encryption, user authentication and verification, credential management, auditing, backups and application security.
- **Scalability** refers to how easily throughput can be adapted under varying loads, i.e. changing the number of virtual processors, memory and storage allocated to the database.
- **Portability/interoperability**. Standardised data formats allow one to easily use data in different systems that support the same format and also allows data to be migrated from one system to another. This criterion takes into account how interoperable the database is with other systems that may need to use the data.
- **Performance** refers to how quickly the DBMS supplies information to its users. Performance in general is considered, including the ability to handle high workloads, latency, throughput and optimisation. This is influenced by the number of virtual central processing units (vCPU) and allocated memory.
- **Cost and pricing** is a vital criterion that looks at the general cost of running a database. It takes into account the variety of plans offered by the provider, additional costs (such as paying extra for better support), licensing costs, etc.
- **Ease of use** encompasses the general user experience of the product. Simplicity, intuitive design, accessibility (i.e. variety of ways in which the service can be accessed) and the level of control that an administrator has is also measured by this criterion.
- **Ease of setup and deployment**. Refers to how easy it is for the administrator to setup the service for use in their organisation and to eventually deploy it. The amount of training required and integration with existing systems also play a role here.

- **Support** is mainly focussed on the quality of the customer service provided by the DBaaS provider. Quality of the support documentation, availability of support staff, ease of finding help on the internet, as well as the cost of support are considered here.

A decision matrix is a relatively quick and easy way to compare alternatives. Firstly, the options were rated by the researcher according to each criterion (refer to Table 6.1). Secondly, weights were assigned by the researcher to each criterion to show its importance, where a weight of 1 is less important and a weight of 5 is very important. The ratings of alternatives and weights of criteria were based on user reviews of the alternatives (G2, 2021a; Gartner, Inc., 2021a; Capterra, 2021). Thirdly, the rankings were multiplied by the weights to determine the scores per criterion (refer to Table 6.2). The scores for each product were then summed to find the total score, the largest of which indicates the optimal decision. Thus, the product with the largest score was selected for the model. In this case, the RDB model was based on Amazon RDS for MySQL with a score of 103, compared to IBM Db2 on Cloud with a score of 90, Oracle MySQL Database Service with 93, Microsoft Azure Database for MySQL with 99 and Google Cloud SQL with a score of 98.

TABLE 6.1: *Ratings per DBaaS product according to each criterion.*

	IBM	Amazon	Oracle	Microsoft	Google
Rating (1-5)	Db2 on Cloud	RDS for MySQL	MySQL DB Service	Azure DB for MySQL	Cloud SQL
High Availability	3	4	3	4	3
Security	3	4	4	4	4
Scalability	5	4	3	4	4
Portability/ interoperability	3	3	3	4	4
Performance	4	4	4	3	3
Cost and pricing	2	3	3	2	3
Ease of use	3	3	2	4	3
Ease of setup/ deployment	3	4	3	3	4
Support	3	3	4	3	3

TABLE 6.2: *Scores per DBaaS product according to each criterion and its respective weight.*

		IBM	Amazon	Oracle	Microsoft	Google
Score	Weight	Db2 on Cloud	RDS for MySQL	MySQL DB Service	Azure DB for MySQL	Cloud SQL
High Availability	4	12	16	12	16	12
Security	5	15	20	20	20	20
Scalability	3	15	12	9	12	12
Portability/ interoperability	1	3	3	3	4	4
Performance	2	8	8	8	6	6
Cost and pricing	5	10	15	15	10	15
Ease of use	4	12	12	8	16	12
Ease of setup/ deployment	2	6	8	6	6	8
Support	3	9	9	12	9	9
Total		90	103	93	99	98

6.2.2 Amazon Relational Database Service for MySQL

This section describes the RDB model based on Amazon RDS for MySQL with the discussion following the previously identified requirements. The method for selecting this DBaaS product and service provider was discussed in the previous section. The service is used by major companies including the likes of Unilever, Airbnb and General Electric (AWS, 2021n).

Database storage

Amazon cloud computing resources are hosted in multiple locations across the world, referred to as regions. Each region comprises of AZs that are independent, isolated locations where physical servers are kept (AWS, 2021l). For high availability and failover support, a Multi-AZ deployment was selected. This means that a synchronous standby replica of the database is kept at a different AZ for automatic failover in the event of an outage at the primary AZ. Decisions regarding the specific availability zone and storage and backup storage capacity are made when selecting a specific plan.

Storing document files directly in a relational database is generally not recommended, as it quickly increases the size of the database. Relational databases are made to store structured data, whereas files are typically unstructured, which makes the process of storing them more complicated. Files have greater storage requirements, so the large number of complex cross-border trade documents that would be stored in the database would significantly slow down any operations of the database. Therefore, the document's metadata is stored in the database itself, while the actual document is kept on a dedicated shared file server (Karwin, 2010). Since database workloads for this scenario are not input/output (I/O) intensive, i.e. won't read or write massive amounts of data at a time, general purpose solid state drives (SSDs) were selected as the storage type.

Access control

Amazon RDS for MySQL comes bundled with the Amazon Web Services (AWS) Identity and Access Management (IAM) service, which allows the administrator to create and manage AWS users and groups and to control access to AWS resources. An IAM administrator is in charge of creating and managing users and groups. This individual creates a new user (representing a person or an application) by assigning them credentials, such as a username and password, or a set of access keys (AWS, 2021h). Users are authorised to access certain functions by giving them specific permissions or rights to those functions.

Users can belong to groups, which allows the administrator to easily manage the permissions of multiple users. For increased security, multi-factor authentication (MFA) can be implemented. This requires users to enter an additional temporary numeric code along with their username and password as part of the authentication process. The basic process for creating a user and authorising them to perform certain tasks is as follows (AWS, 2021t):

1. Create a user using one of the following tools: AWS Management Console, the AWS command-line interface (CLI), Tools for Windows PowerShell, or through an AWS application programming interface (API). Each user is assigned a unique ID that does not change when the user's name is changed.

2. Create credentials for the user (i.e. a password or access keys).

3. Give the user their required permissions – either individually or adding them to a group with the relevant permissions.

4. Configure MFA for the user to require them to provide a one-time code every time they sign into the AWS Management Console.
5. Give users permission to manage their credentials, i.e. change their own passwords.

In a cross-border supply chain, each company would have a service administrator (i.e. an employee or group of employees of their IT department) that manages its company's users, i.e. employees that use the database. All services and resources are accessible by the AWS account root user; the identity that was used to create the AWS account. This account is extremely valuable and according to best practices it is recommended that it should only be used for tasks where the root user is required, such as creating the first IAM admin user or closing the AWS account (AWS, 2021u). The root user credentials must be securely locked away, as unauthorised access to the root user account can have devastating consequences.

Accessing the database

The AWS RDS can be managed in three ways: through the AWS Management Console, the AWS CLI or through simple API calls (AWS, 2021n). The AWS Management Console is a web-based application that can be accessed from any device with an internet connection and a web browser (AWS, 2021s). It is also available as an application for Android and iOS devices. The Management Console is the more user-friendly access method and allows for interaction with the system through an intuitive graphical user interface (GUI).

The AWS CLI allows interaction with AWS services by running commands from a device's local terminal session command-shell line. This method is much less user-friendly and requires a better understanding of the commands, but various tasks are less time-consuming this way. Common shell programs can be used to run commands in Linux or MacOS, while Windows command prompt or PowerShell is used for devices with the Windows operating system (AWS, 2021r). This access method allows for services to be automated with powerful scripts that are run through the command line.

A third method for accessing the database is using the Amazon RDS API – specifically the Query API (AWS, 2021c). This allows applications to access data, business logic or functionality from back-end services on the AWS platform. While the Management Console is better suited for people, APIs are made for applications, databases and devices to programmatically exchange data with one another.

The three methods discussed above are for managing the database service. To view and manipulate the data itself, an appropriate client application or utility, such as the MySQL Workbench, must be connected to the database and used to view it (AWS, 2021d).

Writing to the database

A storage space is required to store the actual file that is being sent from one party to another. Amazon offers various cloud storage services, of which the Simple Storage Service (S3), an object storage service, allows for easier integration with the RDS MySQL database (AWS, 2021q). With S3, objects – files, in this case – are stored in "buckets"; the equivalent of top-level folders in traditional file storage systems. A service that is used to automate the interaction between S3 and RDS is AWS Lambda, a serverless compute service that allows code to be virtually run with no administration required from the user.

The sender uploads the file that they wish to share via the AWS Management Console to the relevant bucket that was created by an administrator in the S3 storage. AWS Lambda automatically runs code to extract the file's metadata, e.g. filename, date and time of creation, author, etc. to an

Extensible Metadata Platform (XMP) file. Additional information, e.g. name of uploader, storage path, timestamp, etc. is added to the XMP file. The metadata and additional information are automatically transferred via a pipeline that has been setup by an administrator to the applicable table in the RDS MySQL database (AWS, 2021q). On the receiving end, the receiver downloads the file from S3. AWS Lambda then runs code to add further information, i.e. name of the downloader, timestamps, etc. to the RDS MySQL database. Any change in the document's status automatically triggers an update to the information stored in the MySQL database.

Data encryption and decryption

Encryption of database instances is possible with RDS, but this must be done when creating the instance, as it cannot be done afterwards. AWS supports the Federal Information Processing Standard (FIPS) 140-2 for encrypting sensitive information for increased protection (AWS, 2021f). Data at rest, i.e. data stored in the database, including its backups, read replicas and snapshots, are encrypted using the industry standard Advanced Encryption Standard (AES)-256 encryption algorithm. Each database instance is encrypted using a unique data key. The data keys are further encrypted using the customer master key (CMK) and managed with the AWS Key Management Service (KMS). After encryption, access authentication and decryption are all managed by RDS (AWS, 2021g).

Connections to the database engine can also be encrypted. Data in transit are encrypted using Secure Sockets Layer (SSL) or Transport Layer Security (TLS) protocols. RDS creates an SSL certificate, which it installs on the database instance when it is provisioned. The MySQL client application has a specific parameter, *–ssl-ca*, that specifies where the SSL connection certificate can be found. To establish a secure connection between the database and the MySQL client, the client must be launched with the parameter referencing the public key of the server (AWS, 2021m).

AWS is also certified for compliance with ISO[1]/IEC[2] 27001, 27017, 27018, and ISO/IEC 9001, as well as CSA[3] STAR[4] CCM[5] v3.0.1 (AWS, 2021v). There are thus various data security measures in place to ensure that data in this model is secure.

Reading from the database

Viewing the MySQL database's tables and the data stored in them is done using the appropriate client, not the AWS Management Console. In this case, the freely available MySQL Workbench is used for this function. After connecting the client to the database, the user will be able to view and manage the tables and their data (AWS, 2021e). The process of downloading a file is done in the AWS Management Console. A user with applicable permissions logs into the console and navigates to the S3 console, where they select the bucket that contains the file they wish to download (AWS, 2021o). As mentioned earlier, downloading the file triggers the Lambda service, which runs code that updates the table in the MySQL database to show when and by whom the file was downloaded, among other information.

Error and mistake correction

Administrators with the right permissions will be able to correct any mistakes related to files and their metadata simply by editing the tables using the MySQL Workbench. It is, however, important that strict control is maintained over who has permissions to change or delete existing data. Therefore, the

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[1] International Organization for Standardization

[2] International Electrotechnical Commission

[3] Cloud Security Alliance

[4] Security, Trust, Assurance, and Risk

[5] Cloud Controls Matrix

RDS for MySQL database instance uses the MariaDB Audit Plugin to record database activities such a users logging on, running queries, etc. (AWS, 2021j). Similar event logging for the S3 database is possible by enabling CloudTrail data events in the AWS Management Console (AWS, 2021p).

The MariaDB audit plugin will, for example, show each connection and query in the RDS database (AWS, 2021j), which can indicate when a document was uploaded for the first time, when it was signed and consequently updated by a different party and finally downloaded by the receiving party. CloudTrail will show events related to objects (or documents, in more general terms), thus also providing logs for any changes to documents (AWS, 2021p). This creates a record of any changes, so any unauthorised changes will be picked up in the audit trail. To ensure a secure audit trail, access to the event log files must be strictly controlled and be limited to a small group of users.

Maintenance

Amazon RDS is a fully managed DBaaS. Therefore, backups, software patching, automatic failure detection, recovery and updates to underlying hardware, the operating system (OS), or the database engine are all performed by Amazon RDS (AWS, 2021k). Some maintenance requires the database instance to be offline while it occurs. These types of maintenance are performed during a maintenance window, which is a 30-minute scheduled time frame during which any system changes are applied. In a multi-AZ deployment downtime is greatly reduced, since the standby instance is simply promoted to the primary instance, while maintenance is performed on the old primary (AWS, 2021i).

6.3 A Conceptual Model for Blockchains

This section describes a model based on blockchain technology. As with the RDB model, a solution was not developed from scratch. Rather, the services provided by other companies were considered and incorporated into the model.

6.3.1 Alternative blockchain solutions

Compared to relational databases, blockchain is a much younger technology that is still in its emergence phase. The technology also has a wider range of applications, so service offerings by companies that specialise in the technology for certain applications are not widely available. A platform that was specifically designed with the digitisation of supply chains in mind with the goal of increasing efficiency and promoting global trade, is TradeLens. It is an open and neutral digital supply chain platform underpinned by blockchain technology that was developed in 2018 in a collaborative effort between IBM and GTD Solution, a subsidiary of A.P. Moller-Maersk (IBM and GTD Solution, 2019). It is based on Hyperledger Fabric, a well-known platform in the blockchain community (Y. Wang, Han, and Beynon-Davies, 2019) that is commonly used for developing industrial blockchain solutions (Compigneaux et al., 2020).

TradeLens integrates supply chain parties by connecting them via a single and secure platform that allows them to easily share information with one another and collaborate with ease. The emphasis is on the diverse types of information that can be shared in real-time and includes shipping milestones, cargo details, trade documents, sensor readings, etc. (IBM and GTD Solution, 2019). Thus, TradeLens not only provides an efficient way to share trade documents, but also provides much greater supply chain visibility, and tracking and tracing abilities – all on a cryptographically secured platform. Ocean carriers such as APL, CMA CGM, Hamburg-Süd, Hapag-Lloyd and MSC, as well as some government authorities and various terminal operators are participants of the platform (TradeLens, 2021g).

The shipping industry has similar initiatives, but most of these are either less mature, are still in their pilot stages, or have been discontinued. The Global Shipping Business Network (GSBN), developed by CargoSmart (2019), aims to facilitate shipping network expansion and provide real-time transparency on the status of shipments. The platform enables users to share trusted first-party logistics data and documents securely and in real-time. Its shareholders – some that are also part of the TradeLens platform – include major global carriers and terminal operators such as CMA CGM, Cosco, Hapag-Lloyd, Evergreen Marine, OOCL and PSA International (Hakirevic, 2021; PixelPlex, 2021).

HMM (formerly known as Hyundai Merchant Marine) and Samsung SDS conducted a pilot to test the use of blockchain in shipping and logistics (MI News Network, 2018). A consortium comprising of AB InBev, Accenture, APL and Kuehne + Nagel also tested a solution for sharing documents using blockchain technology and found positive results (Brett, 2018). Another pilot was performed by Abu Dhabi Port in partnership with shipping giant MSC to test blockchain's ability to facilitate the process of exchanging, identifying, and acknowledging cargo documents and certificates between Abu Dhabi Ports and other port operators (MSC, 2018). Unfortunately, these pilots have not led to commercially available services such as TradeLens.

A start-up with a promising product that focusses on the sharing of trade documents is CargoX. Much like TradeLens, participants of the network can securely share trade documents in a quick and secure manner using blockchain technology (PixelPlex, 2021). Although initially focussing on the bill of lading, the platform is adding support for many other types of trade documents, including the sea waybill, export certificate, phytosanitary certificate and the packing list. A differentiating factor is that the platform is built on top of Ethereum and is thus based on a public blockchain, making it completely neutral (CargoX, 2021). While there are benefits to using a public blockchain, this platform also suffers from the drawbacks of public blockchains, e.g. the lack of governance that is required in a complex environment such as supply chains, possible scalability issues, and transaction costs.

When creating a conceptual model that is based on a certain product, it is beneficial when a large amount of information of that product is available. Being the more mature offering of those that were discussed above, TradeLens had more information available that enabled a more detailed model to be created than when basing it on the other alternatives. Its maturity also meant that it is supported and used by more companies and authorities than its alternatives, with nearly 200 members that are currently on the platform or in the process of connecting to it (TradeLens, 2021g). Another point that set TradeLens apart from competitors is the additional functionality that it provides over and above document-sharing – discussed in more detail below.

6.3.2 TradeLens: a digital supply chain platform underpinned by blockchain

TradeLens has three major components, all of which combined makes it such a fitting solution with massive potential (IBM and GTD Solution, 2019):

1. **The Ecosystem**. The entire network of shippers, freight forwarders and 3PL, port and terminal operators, ocean carriers, government authorities, customs brokers, financial services, etc. make up the ecosystem. The platform handles more than 700 million events and 6 million documents a year; an indication of its growing user base (TradeLens, 2021g).

2. **The Platform**. TradeLens is based on the Hyperledger Fabric blockchain and hosted on IBM Cloud. The platform provides access to the various services and digital tools offered. Furthermore, it is accessible via open APIs and uses the Supply Chain Reference Data Model from the United Nations Centre for Trade Facilitation and Electronic Business (UN/CEFACT) to ensure interoperability with other platforms.

3. **The Marketplace**. Applications and smart contracts developed by TradeLens and third parties are housed in the Marketplace. These applications and smart contracts interact with the platform

> and its data to provide additional functionality. Thus, whenever a specific feature is required, it can simply be added via a smart contract on the Marketplace. TradeLens Core, for example, offers digital tools for facilitating trade document collaboration, among various other features that support true end-to-end visibility and effective collaboration.

The blockchain-based model is described below according to the previously identified requirements.

Database storage

A major decision to make when considering blockchain storage is whether to store data on-chain (on the blockchain itself) or off-chain (in a different database with only a reference of the data on the blockchain itself). TradeLens stores the documents off-chain on the IBM Cloud, while the document's hash is stored on-chain. Specifically, document hashes, document actions and metadata, and internal object references are the only types of data stored on the blockchain (TradeLens, 2021c). Due to the immutable nature of blockchain, any data that is stored or transactions that are recorded to the ledger are retained indefinitely. This is one of the reasons that documents are stored off-chain, as any personal information contained in the documents cannot be removed if it is stored on-chain, which would violate various privacy laws, such as the GDPR.

TradeLens uses a combination of object storage, document databases, relational databases and blockchain for storing data, depending on the type of information and how it is accessed (TradeLens, 2021f). The main formats in which documents are stored are thus either in a structured JavaScript Object Notation (JSON) format, or in unstructured portable document format (PDF) or image formats – all of which are common in the supply chain environment (TradeLens, 2021d). The product also makes use of PaaS and DBaaS components for greater efficiencies and economies of scale, for example, by providing cloud storage on IBM Cloud.

Blockchain nodes, each with its own platform components and dedicated document storage, are hosted and managed by TradeLens and ocean carriers. A channel is created for each ocean carrier, which connects the nodes that need to share information and ensures parties in other channels can't access the sensitive information. For increased security and privacy, documents are only stored on a single node and only accessible by other nodes on the same channel, given that their permissions allow for access (TradeLens, 2021f).

Access control

TradeLens is built on a permissioned consortium blockchain, meaning that only authorised users from participating organisations can join, view and publish data on the blockchain. All users on the TradeLens platform are added and managed by administrators with the User Management UI. Authentication, though, is facilitated by the IBM Cloud IAM Service. Therefore, a user needs to be registered both with IBM Cloud IAM and on the TradeLens platform. There are two types of IDs: user IDs and service IDs. Regular and administrative users are identified by their IBMid, SoftLayer or AppID. A username and password are linked to this identity and are used to sign into IBM Cloud IAM, which then redirects them to the Solution Manager identity service, which links the user to their organisation on TradeLens (IBM, 2021c).

System users are services and applications that need access to IBM Cloud services and are identified by a service ID, which enables access without requiring individual user credentials. Instead, the system user has a single API key that it uses to obtain an access token from Cloud IAM. The access token allows the system user to obtain a bearer token from the Solution Manager to sign into the TradeLens platform (TradeLens, 2021b).

Users and service IDs that require similar permissions can be organised into access groups, which allows permissions to be managed for multiple users at once. Permissions can easily be granted via policies that provides users, service IDs and groups different levels of access to certain resources (IBM, 2021c). Permissions are largely based on the organisation that the user belongs to, the participant type (e.g. 3PL agent, ocean carrier, truck operator, customs authority, etc.) and their roles (e.g. buyer, importer, consignee, transport service provider, etc.) (TradeLens, 2020). Users can only access data specifically related to them and their organisation.

Accessing the database

The main interface with which the end user interacts with the TradeLens platform is the Shipment Manager, a web-based UI that is accessible through a web browser. The Shipment Manager allows the user to view and visualise trade objects (shipments, consignments and transport equipment), manage users for their organisation, manage subscriptions, i.e. notifications for certain events, manage their organisation and its relationships on the platform, and upload, view and download trade documents (TradeLens, 2021e). Similar to the Shipment Manager, the IBM Cloud IAM service also has a web UI that is accessible via a web browser.

Another way of accessing the platform is through applications and services that are connected to it via open APIs using the previously described service IDs (TradeLens, 2021a). TradeLens supports the use of APIs that follow the representational state transfer (REST) architectural style, one of the most common API architectures. Further standardisation is ensured by using Swagger, a common open-source framework for designing, developing, documenting and testing REST APIs (TradeLens, 2021a). This allows companies to integrate their in-house systems with those of TradeLens. The following sets of APIs are currently used on the platform: Actionable Flows, Business Partners, Document Sharing, Event Publish, Event Subscription, Notifications & Alerts, Platform Constants, Trade Object, and User Preferences. Each has its own set of functions; for example, the Event Publish API enables users to record and send notifications for various events, such as a new shipping document being issued or a container being ready for pickup.

Writing to the database

TradeLens allows trade parties to easily and securely share trade documents. Depending on their permissions, users can upload, download, edit and view documents related to them. Documents – structured in JSON format or unstructured in PDF or image formats – are either uploaded via the Shipment Manager or through API (TradeLens, 2021d). Only users with write permissions can upload documents to the platform. The document itself is stored in the IBM Blockchain Document Store hosted on a blockchain node in the IBM Cloud, while its encrypted hash is recorded on the blockchain itself (Biazetti, 2019a).

As is the case with blockchains, the database is updated via a consensus protocol – in this case, using an ordering service, which is common with permissioned blockchains. Hyperledger Fabric 2.x deprecates the Apache Kafka method, which uses a "leader and follower" model, and replaces it with a similar but simpler and more understandable method, known as Raft (Hyperledger, 2020). Raft dynamically elects a leader node among a set of ordering nodes for each channel. The leader receives the transactions and replicates it to its followers, who update their own logs with the new information. The voting process that Raft uses ensures a candidate can only be elected as leader if its log contains all the committed entries. Therefore, this ensures that each copy of the ledger is updated with new information, thus filling in the gaps where some transactions may be missing in certain logs (Ongaro and Ousterhout, 2014).

Consensus is reached only among the nodes that are part of the channel in which the transaction is made, so only the relevant parties can participate in the consensus process (Biazetti, 2019b). Any actions taken on documents are recorded and automatically triggers an event that shows what action was taken. An example is when the BoL is uploaded. This will trigger the event “Bill of Lading submitted”. Furthermore, the different versions of a document are tracked. The version is incremented whenever a document with the same reference ID is uploaded or when changes to a structured document is saved (TradeLens, 2021d).

Data encryption and decryption

The blockchain architecture on which TradeLens is based means that cryptography plays a large role in the platform’s security. All communication and all data sent to and from the IBM Blockchain Platform is done through Hypertext Transfer Protocol Secure (HTTPS), which includes TLS v1.2 encryption (Biazetti, 2019a). This means that communication between nodes, but also between nodes and applications are encrypted using TLS, which prevents data to be intercepted while in transit (IBM, 2021a). Data in rest, e.g. the documents in the document store, are encrypted with AES-256 encryption. Any keys that are used for encryption and decryption are managed by TradeLens, so the user may not even be aware of the encryption-decryption process that is happening behind the scenes (IBM, 2021b).

The blocks that form the chain are cryptographically linked using the SHA-256 hash function, which generates a hash value based on the contents of the specific block (Hyperledger, 2021). This hash is stored on the next block in the chain, thus cryptographically linking the current block with the next one. Furthermore, a data model and access control scheme are used that are aligned with the UN/CEFACT data standard (IBM and GTD Solution, 2019). In terms of data standards, TradeLens is ISO27K certified, which means that they follow certain information security standards that are even stricter than required by the GDPR. These include ISO/IEC 27001, 27002, 27017, and 27018 standards (Biazetti, 2019a).

Reading from the database

To view and download the relevant trade documents and events, users can simply log into the Shipment Manager or call it via API. Only users with read permissions will be able to view and download documents. The blockchain network topology further ensures that data belonging to other parties cannot be accessed by others to whom it is not applicable (TradeLens, 2021f).

An authorised user can access and download all versions of a document using the Shipment Manager. When a document is selected, a consistency check is performed to verify it on the blockchain. This is done by retrieving the document from the Blockchain Document Store and comparing the stored hash with a newly generated one. If this check is successful, the document has been verified on the blockchain as authentic and immutable and has thus not been tampered with (TradeLens, 2021d).

Error and mistake correction

Mistakes are often still present on trade documents. Since TradeLens runs on a blockchain, fixing a mistake by completely removing the faulty entry is not feasible. Therefore, a new entry is simply made to overwrite the faulty one. In the case of trade documents, a new document is uploaded and the version is incremented. Evidence of the mistake will still be visible in the audit trail, as this activity will be recorded on the blockchain.

Maintenance

TradeLens is a completely managed service, so any forms of maintenance, whether it is physical or software, is performed by TradeLens during dedicated maintenance windows. During this time, there may be downtime (depending on the type of maintenance), during which the platform is not available for use until maintenance has concluded (TradeLens, 2021h).

6.4 Chapter Summary

This chapter described two conceptual models for facilitating the flow of trading documents in cross-border supply chains. Before the models were discussed, various requirements that each had to describe were identified and briefly discussed. The first model makes use of a more traditional relational database. Various database service offerings in this category are available, so it was first necessary to compare various relational DBaaS offers to find one that is more applicable to documents in the cross-border supply chain environment. AWS RDS was selected as the relational database on which the model is based. After the comparison, the model was described in terms of various the requirements that were previously identified.

The second model is based on blockchain architecture. Due to the young age of the technology, service offerings are relatively immature. TradeLens is a more mature solution that was specifically built for trade facilitation in cross-border supply chains. Therefore, along with other reasons as discussed, TradeLens was selected as the base for this model. Similar to the RDB model, the BC model was described in terms of the previously identified requirements.

CHAPTER 7

A Cost-Benefit Analysis for Blockchain in Supply Chains

The case study further emphasises that the efficient flow of information and trade documents is a serious shortcoming that is experienced in supply chains around the world. A major driver of this problem is the general lack of digitisation and automation. As possible solutions to this problem, two models were created and their characteristics discussed in Chapter 6. The first model is based on the more conventional relational database, while the second model is built upon the newer, more hyped technology that is blockchain. What is still required, however, is a detailed comparison between the two that looks at the relative costs and benefits of each. This chapter aims to quantify the impact that a modern digital solution for sharing trade documents and related information can have on supply chains. The analysis took multiple scenarios into consideration to make it more representative of how the costs differ between the two models. Each scenario accounts for supply chains of different sizes in terms of their shipping volumes.

The comparison of the two models is in the form of a type of cost-benefit analysis (CBA), which is roughly based on the process visualised in Figure 7.1. The business goals (what the solution must achieve) and architectural strategies (how the solutions work) have been addressed in previous chapters. Firstly, the financial cost drivers for the models were identified, their values were calculated and their implications were discussed, along with the financial benefits. The second section combines two scientific methods for multi-criteria decision making, which makes up the non-financial analysis. Finally, the chapter concludes with a preliminary recommendation based on the literature review, case study and analysis.

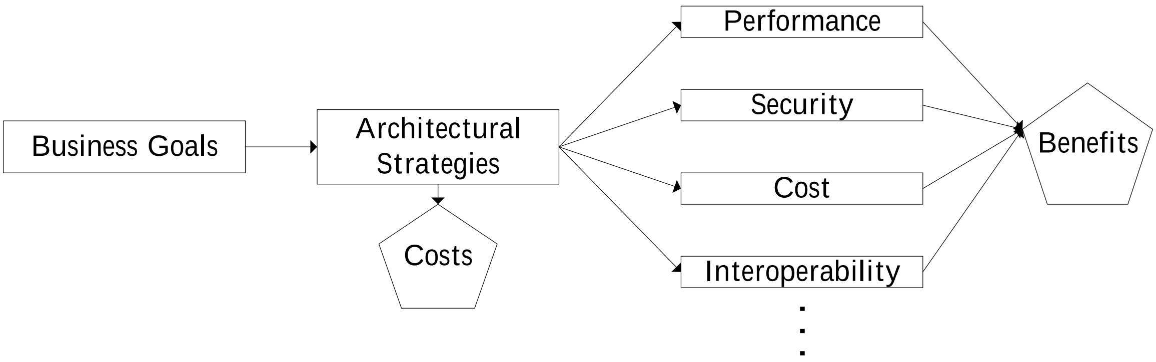


FIGURE 7.1: *The process of a cost-benefit analysis (Kazman, Asundi, and Klien, 2002).*

7.1 Financial Analysis

The financial analysis in this research looks at costs and benefits, and then creates a comparison to show the net financial benefit expected from each solution. To collect information that is required for analysing the blockchain model that is not freely available, a semi-structured interview was conducted with a TradeLens employee (Anonymous, 2021c).

7.1.1 Financial costs

The costs discussed in this section were identified as the most prevalent costs associated with projects of this nature. As is the case with outsourcing, it is less expensive in terms of financial costs to use the service provided by another company than it is to develop a solution in-house (Gopalakrishnan, Hall, and Behdad, 2021).

It should be noted that the costs discussed in this section are relative – these costs are simply to show how a solution based on blockchain technology would differ from one based on more traditional databases. Therefore, other costs that are associated with adopting a new solution are not discussed because they are associated with both solutions. The two major cost drivers and their reasons for being excluded are:

- API costs: both models support open APIs that need to implemented.
- Data usage costs: the same number of documents and data will be uploaded and downloaded, so the data usage between the models are expected to be negligible.

The analysis makes use of three different scenarios for various trade volumes: low, medium, and high. This was done to create a clearer image of how the costs and benefits differ between models depending on the size of the trades. Furthermore, the period of analysis, i.e. the length of the project, was taken to be five years (Odell and Fadzeyeva, 2018).

Cost drivers for both models

The main cost drivers of this cost-benefit analysis were identified and are described below, with more model-specific detail following in subsequent sections. Some cost drivers are applicable to both models and were estimated to be roughly equal in size. These cost drivers are therefore not included in this cost-benefit analysis, as this comparison is *relative* and its goal is to see how the costs *differ* between solutions. Cost drivers that are applicable to both models, but have different sizes are discussed here, as well as cost drivers that are unique to each model. Where costs are recurring, an annual value was calculated. Costs for the relational database and its respective services were calculated using the AWS platform's estimate calculator (AWS, 2021a).

The cost driver that lies at the core of this analysis is the **usage cost** of the service or product on which the model is based. It is the basic cost that a user pays to use the solution. In most cases this cost will be recurring (e.g. a monthly fee that is common for a service), or it may be a once-off cost (usually paid when acquiring a product). In this analysis an annual usage fee was used in the calculations, since the models are based on services, i.e. AWS RDS for MySQL and TradeLens.

Data storage is another notable cost driver in this analysis. This refers to the cost paid to the cloud storage service provider for having access to their remote storage infrastructure. Even though both solutions require roughly the same amount of data to be stored, the type of storage required differs. The specific solution on which the model is based will also influence the storage cost. For example, TradeLens stores data on the IBM Cloud in the short term – the cost of which is included in the usage cost (Anonymous, 2021c). Long-term storage costs are not included in usage cost, so the blockchain model makes use of AWS S3 for long-term storage. The basic usage cost of the relational database model only includes data storage for the relational data (document metadata in this case). Therefore, data storage costs are incurred for storing the actual documents on AWS S3.

Labour is the largest cost driver of this analysis and consists of two parts. Onboarding labour, i.e. the employees required to get the solution up and running, is associated with the pilot and implementation phases of the project. Ongoing labour, i.e. the employees that manage the solution during its life cycle, is associated with the costs incurred during the everyday use of the service. The first category of labour include IT professionals, software developers and engineers who work on the technical side to ensure the systems are working correctly. This includes setting up the service, implementing APIs, creating users and their permissions, and ensuring the desired level of security measures are in place. The second category of labour is legal employees, business owners and IT management who are involved in the governance aspects of the solutions. They will work on a governance model that describes how each relevant party will be held accountable. These employees will also work on establishing models for describing how the costs of the solution will be carried by the stakeholders, how data privacy will be ensured, standards and other policies that will be followed and other governance-related aspects.

The costs described above are also relevant to alternative solutions where the services of another company are used, which makes it generally applicable to the global trade environment. Some cost drivers are only associated with a certain model. These drivers are discussed in the sections below.

Cost drivers of a blockchain-based solution

In the case of TradeLens, the **usage cost** depends on two factors: the selected package and the number of containers that the user wants to track using the platform. TradeLens Core currently has three packages: Essential, Visibility, and Collaboration (Anonymous, 2021c). Since the aim of this solution is to facilitate the flow of documents in global supply chains, the Collaboration package was selected for this model. With Collaboration, the user has access to all the features that TradeLens has to offer. It offers transport insights and continuous data improvement that are part of Essential, notifications and dashboards from the Visibility package and finally, document sharing that is unique to Collaboration (Anonymous, 2021c). Table 7.1 shows the usage cost for a blockchain solution based on TradeLens that uses its Collaboration package.

TABLE 7.1: *Usage cost paid to the service provider for the blockchain model*

Cost Driver	**Unit**	**Low**	**Medium**	**High**
Base Usage	$/container/period	$22	$22	$22
Number of containers	containers	1 000	3 000	9 000
Discount	%	12%	27%	48%
TradeLens Usage	$	*$19 360.00*	*$48 180.00*	*$102 960.00*
	$/year	**$3 872.00**	**$9 636.00**	**$20 592.00**

The base usage and discount values were given (Anonymous, 2021c). With TradeLens, the amount of discount received increases as the number of containers committed increases, starting at one percent discount when committing 55 containers to the platform. The number of containers committed in each scenario were determined using data from interviews with industry professionals (Anonymous, 2021b; Anonymous, 2021c).

At the time of the interview, TradeLens stores documents and data that are transmitted via the platform for 220 days. After that period, the user is responsible for organising **data storage** (Anonymous, 2021c). For this model, Amazon S3 was selected as the storage solution for the documents after 220 days. Not only is it also the relational database model's storage solution for documents – which makes it easier to compare – but it also has one of the least expensive per-gigabyte costs when compared to other popular cloud storage solutions from Google, Microsoft and IBM. The specific S3 option for this model is S3 Infrequent Access, since documents typically do not need to be accessed after their associated trades have been completed (Anonymous, 2021b). As time passes, more documents will need to be stored. Therefore, the storage capacities are revised annually, which means that the cost also changes year-over-year.

The additional data storage costs are shown in Table 7.2. It only shows the data for the Medium scenario, as this allows more information to be included. The values for the Low and High scenarios, along with other data used to calculate these values can be found in Appendix B. This is also the case for other tables and figures in this chapter where only the Medium scenario is shown. Calculations for the Medium scenario are based the following figures: 3 000 containers, each with around 15 documents associated with it that amount to around 45 000 documents per year with an average file size of 2.25 MB per document (Anonymous, 2021b). This leads to around 8.44 GB of data that is added per month. The storage capacities are revised on an annual basis, so this is increased by 42.19 GB each year. On top of that, it also includes a buffer capacity of around 10 GB to account for any unexpected storage requirements.

TABLE 7.2: *Cost of additional data storage for the blockchain model (Medium scenario)*

		Year				
Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	53	154	255	356	458
Monthly cost	$/month	2.77	4.46	6.11	7.76	9.42
Additional storage	**$/year**	**33.18**	**53.46**	**73.26**	**93.06**	**113.04**

Onboarding labour costs were calculated based on information from a study by Odell and Fadzeyeva (2018) on the IBM Blockchain, as well as salaries from Glassdoor (2021) using average salaries for professionals at companies of various sizes in different geographical locations. According to a TradeLens employee, the onboarding phase takes about one to twelve weeks, depending on the scope of integration required with the platform (Anonymous, 2021c). For this analysis, a period of six and a half weeks was used as the length of the onboarding phase for the Medium scenario. The cost of onboarding labour for the Medium scenario of the blockchain model is shown in Table 7.3.

TABLE 7.3: *Cost of onboarding labour for the blockchain model (Medium scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	5	2
Duration of period	Months	1.625	1.625
Percentage of time spent on project	%	15	20
Average employee salary	$/month	4 680.36	4 795.35
Onboarding labour costs	**$**	**5 704.19**	**3 116.98**

The cost of **ongoing labour** was determined in a similar way as onboarding labour. The length of the project in this case was five years, which is therefore the period for which ongoing labour costs were calculated. Table 7.4 shows these costs.

The blockchain model is based on TradeLens, where the number of partners to whom an ocean carrier can give access to their data and dashboard depends on the volume of containers committed. For

Table 7.4: *Cost of ongoing labour for the blockchain model (Medium scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	3	1
Duration of period	Months	60	60
Percentage of time spent on project	%	20	100
Average employee salary	$/month	4 680.36	4 795.35
Ongoing labour costs	**$**	**168 493.01**	**287 721.16**

example, committing 5 000 containers to TradeLens allows access for five **client partners** that receive standard onboarding; committing 10 000 containers allows for ten client partners, and so on under the Collaboration package (Anonymous, 2021c). Adding an additional client partner without increasing the volume committed incurs a once-off fee of $1 500. The number of members added were based on an interview with a TradeLens employee (Anonymous, 2021c). The costs for adding additional members to the platform are shown in Table 7.5.

Table 7.5: *Cost of adding new members to the platform for the blockchain model*

Cost Driver	**Unit**	**Low**	**Medium**	**High**
Number of new members	Members	0	2	4
Cost per new member	$/member	1500	1500	1500
New member cost	**$**	**0**	**3 000**	**6 000**

There are of course also costs that are difficult to quantify. For the blockchain model such costs include time, effort, interoperability, control and model complexity. Onboarding, which includes training, implementation and migration takes time to complete. Large amounts of effort is required to create governance models for the new technology, e.g. it is distributed across multiple nodes in different countries, so the data storage regulations of multiple countries apply to the data. The current lack of regulations for blockchain technology means that there is more grey area that causes uncertainty regarding the legality of certain matters. APIs need to be implemented to link the blockchain platform to other existing systems, such as ERP systems, which takes additional effort. Finally, effort is required to collaborate and develop industry standards for blockchain solutions.

Blockchain is still a relatively new technology, but it is also quite a complex technology that differs from commonly used solutions, so interoperability issues are present in most blockchain systems. APIs are extremely useful in integrating blockchains with other systems, but this requires research and development. Another possible cost is the loss of control over data. Data is not stored on the user's own premises, but on nodes in different locations in the cloud. Thankfully the user's data is only stored on their own nodes and those of their partners. A concern about TradeLens specifically is that Maersk is a large player in the shipping industry, so their direct competitors may be sceptical over joining the platform (Nielsen, Layman, and Beardsley, 2018).

Cost drivers of a relational database solution

The **usage cost** associated with Amazon RDS for MySQL depends on the specific instance and its specifications, as well as the number of hours that the instance is running. The costs of each scenario is based on the average cost between different deployment types, servers in different regions, and on-demand and reserved instances. For example, the Medium scenario uses the db.t3.small instance that has a single core, two vCPUs and four gigabytes of memory (AWS, 2021b). The average pricing from the Europe (Frankfurt) and Africa (Cape Town) regions were used. Both single-AZ and multi-AZ deployment types were included in the calculations to account for the fact that a solution may use either one of these deployments. Finally, on-demand usage, where the user is charged by their hourly usage, as well as one year reserved usage, where the user is charged by their yearly reserved amount were also included in the calculations (AWS, 2021a).

Since this solution will be used in a global environment, the runtime was assumed to be 24 hours a day, 30.5 days a month. See Table 7.6 for the usage costs for all the scenarios. The costs were obtained using the AWS Pricing Calculator (AWS, 2021a).

TABLE 7.6: *Usage cost paid to the service provider for the relational database model*

Type	Cost Driver	Unit	Low	Medium	High
On-demand	Per-unit usage costs	$/hour	0.040	0.080	0.160
	Instance run-time	hours/month	732	732	732
Reserved	On-demand usage costs	$/month	29.28	58.56	117.12
	Reserved per-unit usage costs	$/month	21.54	43.58	87.16
	AWS RDS Usage	*$/month*	*25.41*	*51.07*	*102.14*
		$/year	**304.38**	**612.85**	**1225.69**

Storage on RDS and its related costs (i.e. backup storage, snapshot export and data transfer) were combined in this analysis. The same deployment regions as previously were used for the usage cost, as well as the deployment types (AWS, 2021a). General purpose storage, i.e. solid states drives, were used. Since only the document metadata and other structured information is stored in the relational database, the storage requirements are much lower than what is required for storing the actual documents. Therefore, the storage capacities used in RDS for the Low, Medium and High scenarios were 1 GB, 10 GB and 100 GB respectively (Gu et al., 2009). According to AWS, there is no additional charge for backup storage up to 100% of the total database storage for a region (AWS, 2021a), therefore this cost was taken as zero. Snapshots of the database were also considered in this analysis. The size of these snapshots were taken to be a maximum of two thirds of the entire database (Kozak, 2009). Data transfer between RDS and the internet, i.e. for ERP systems linked to RDS were estimated to be around half of the database's capacity. The storage-related costs for RDS are shown in Table 7.7.

TABLE 7.7: *Storage and related costs paid to the service provider for the relational database model*

Cost driver	Unit	Low	Medium	High
Average storage cost	$/GB/month	0.287	0.287	0.287
Storage capacity	GB	1	10	100
RDS Storage	*$/month*	*0.29*	*2.87*	*28.70*
RDS Backup Storage	*$/month*	*0*	*0*	*0*
Snapshot price	$/GB	0.012	0.012	0.012
Snapshot size	GB	0.667	6.667	66.667
Number of snapshots	snapshots/month	1	1	1
RDS Snapshot Export	*$/month*	*0.01*	*0.08*	*0.8*
Transfer costs	$/GB	0.122	0.122	0.122
Transfer size	GB/month	0.5	5	50
RDS Data Transfer	*$/month*	*0.06*	*0.61*	*6.10*
RDS Storage-Related Costs	*$/month*	*0.36*	*3.56*	*35.60*
	$/year	**4.27**	**42.72**	**427.20**

The actual documents are stored in Amazon S3. As with the blockchain model, the **additional storage** requirements change each year. Therefore only the Medium scenario is shown in Table 7.8. The S3 storage cost described here include data transfer and AWS Lambda costs and were calculated using the AWS Pricing Calculator (AWS, 2021a).

TABLE 7.8: *Cost of document storage for the relational database model (Medium scenario)*

Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	112	213	314	415	517
Monthly cost	$/month	9.53	12.37	15.21	19.49	22.53
Document storage	**$/year**	**114.36**	**148.44**	**182.46**	**216.06**	**250.86**

Onboarding labour cost calculations for the relational database model are similar to those of the blockchain model, with the exception of the duration of the onboarding phase. It is longer, because the entire system and all the required services must first be set up before the rest of the onboarding process can continue (Anonymous, 2021c). The cost of onboarding labour for the Medium scenario of the relational database model is shown in Table 7.9. The number of employees and the time they spend on the project were based on the work by Odell and Fadzeyeva (2018). The values and calculations for the Low and High scenarios can be found in Appendix B. The same applies to the **ongoing labour costs** for the relational database model, which are shown in Table 7.10.

TABLE 7.9: *Cost of onboarding labour for the relational database model (Medium scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	5	2
Duration of period	Months	3.25	3.25
Percentage of time spent on project	%	30	20
Average employee salary	$/month	4 680.36	4 795.35
Onboarding labour costs	**$**	**22 816.76**	**6 233.96**

TABLE 7.10: *Cost of ongoing labour for the relational database model (Medium scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	3	1
Duration of period	Months	60	60
Percentage of time spent on project	%	40	100
Average employee salary	$/month	4 680.36	4 795.3
Ongoing labour costs	**$**	**336 986.02**	**287 721.16**

The relational database model has various costs that are difficult to quantify. The effort required to get the solution up and running is quite large. This mainly stems from the model being based on a PaaS, rather than a SaaS. The final product is not provided; it must be created using the relevant services on the platform that is provided. Firstly, the different services (i.e. RDS, S3 and Lambda) must be linked. Lambda must be programmed to extract the document data from the files in S3 and write this data to the RDS database. Some other actions that require effort include governance procedures to determine how the solution will be shared by stakeholders, and how the billing will be fairly allocated to stakeholders.

The relational database model requires more time to be successfully implemented in the global trade environment because of its generic nature. Time is thus a cost in this case. Reduced control is a cost associated with the cloud-based nature of the model. Data is now stored off-site and might be accessible by other parties if the relevant security measures are not in place. The complexity of the relational database model can be difficult to navigate due to the number of interconnected services that it requires. These services must be managed by the advanced users of the solution, as this is not done by the provider.

The centralised nature of the model leads to the common security issues associated with such technology. Storage is centralised, unless a multi-AZ deployment is used. Whoever has access to the root account's credentials has full control over the entire system. Administrators also have large amounts of power which can be misused if not properly controlled. In general, much more needs to be done to achieve a comparable level of security when compared to blockchain-based systems, due to the inherent security flaws of centralised systems. The security issues mean that a high level of trust is required between participants, which might make it more difficult to attract newer stakeholders. The more centralised control also means that administrators need to be highly trustworthy and assigned through a proper selection process. Finally, a single breach can compromise the entire system, so administrators need to be limited in what they can do on their own.

Total estimated cost and project cash outflow

This section discusses the total estimated cost of the two solutions, including the expected cash outflow over the first five years and the net present value (NPV) of the costs. The discussion follows a similar pattern than before by focussing on the Medium scenario and including the data for the Low and High scenarios in Appendix B. Tables 7.11 and 7.12 show the results for TradeLens and RDS respectively. Values in both tables have been rounded up to the next dollar value. A risk adjustment of 20% was included to account for possible increases in costs (Odell and Fadzeyeva, 2018). A discount rate of 12% was used for present value (PV) calculations, as most organisations use rates between 8% and 16%, according to Forrester (2018). The costs of these models are compared in the next section.

TABLE 7.11: *Cash outflow and NPV of costs for the blockchain model (Medium scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
TradeLens usage	$		9 636	9 636	9 636	9 636	9 636
New members	$	3 000					
Extra cloud storage	$		34	54	74	94	114
Onboarding labour	$	8 822					
Ongoing labour	$		91 243	91 243	91 243	91 243	91 243
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*14 186*	*121 095*	*121 119*	*121 143*	*121 167*	*121 191*
Discount rate	%	12					
PV	$	14 186	108 121	96 556	86 227	77 004	68 767
NPV	**$**	**300 916**					

As is apparent in Figure 7.2, ongoing labour is by far the largest cost driver for a solution based on the blockchain model, followed by usage and onboarding labour costs. The values used here are totals based on the future values of the costs and is simply the sum of each relevant row in Table 7.11.

A similar conclusion can be made about the cost breakdown for the relational database model. According to the data in Figure 7.3, ongoing labour is by far the largest cost driver for a solution based

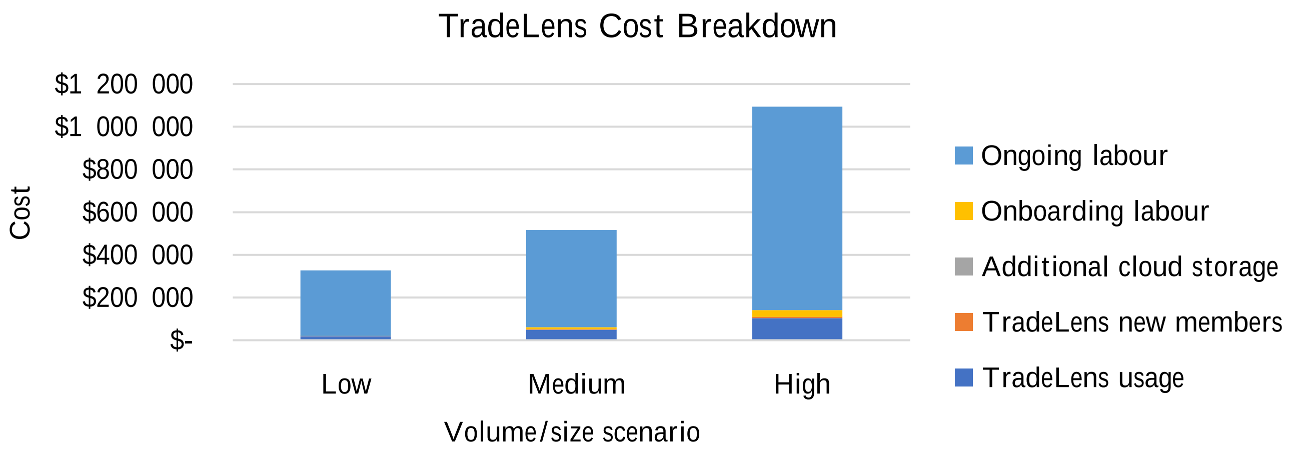


FIGURE 7.2: *Breakdown of the total cost for the blockchain model.*

TABLE 7.12: *Cash outflow and NPV of costs for the relational database model (Medium scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
RDS usage	$		613	613	613	613	613
RDS storage	$		214	214	214	214	214
S3 storage	$		115	149	183	217	251
Onboarding labour	$	29 051					
Ongoing labour	$		124 942	124 942	124 942	124 942	124 942
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*34 861*	*150 854*	*150 895*	*150 936*	*150 976*	*151 018*
Discount rate	%	12					
PV	$	34 861	134 691	120 293	107 433	95 948	85 692
NPV	**$**	**390 255**					

on the relational database model. A difference here is that the onboarding labour costs are much higher than the usage costs.

Cost comparison

Upfront cost is the first component that was compared. This cost is associated with the onboarding and implementation phase of the project, i.e. Year 0. The graph in Figure 7.4 shows that the difference in upfront cost between the two models increases further as the volume increases between scenarios. The upfront cost for the relational database model is higher than that of the blockchain model due to the longer onboarding period required for the relational database solution and thus larger labour costs. The upfront cost of TradeLens is notably lower than that of RDS, even though it consists of new member costs and onboarding labour costs, while RDS only has onboarding labour costs.

The average annual cost of both models are shown in Figure 7.5. Average values were used, since the costs vary each year, as seen in Tables 7.11 and 7.12. The graph shows that the difference in annual cost grows as the volume increases. Based on this, the blockchain solution may be more attractive to larger players in global trade when looking only at the annual cost of the solutions. For smaller and medium players the choice becomes less obvious, although blockchain still has lower annual costs than the relational database solution.

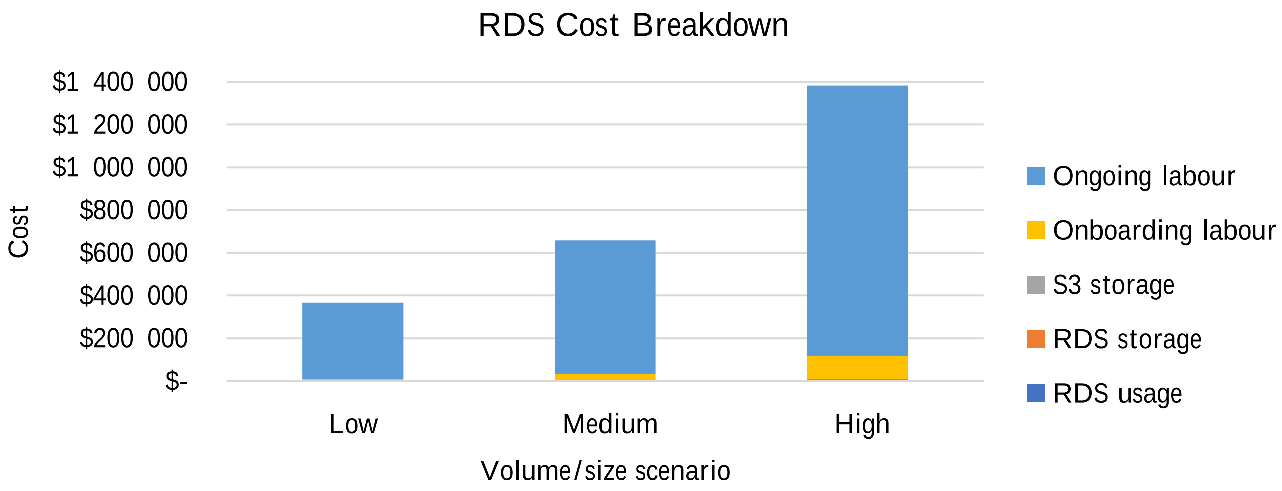
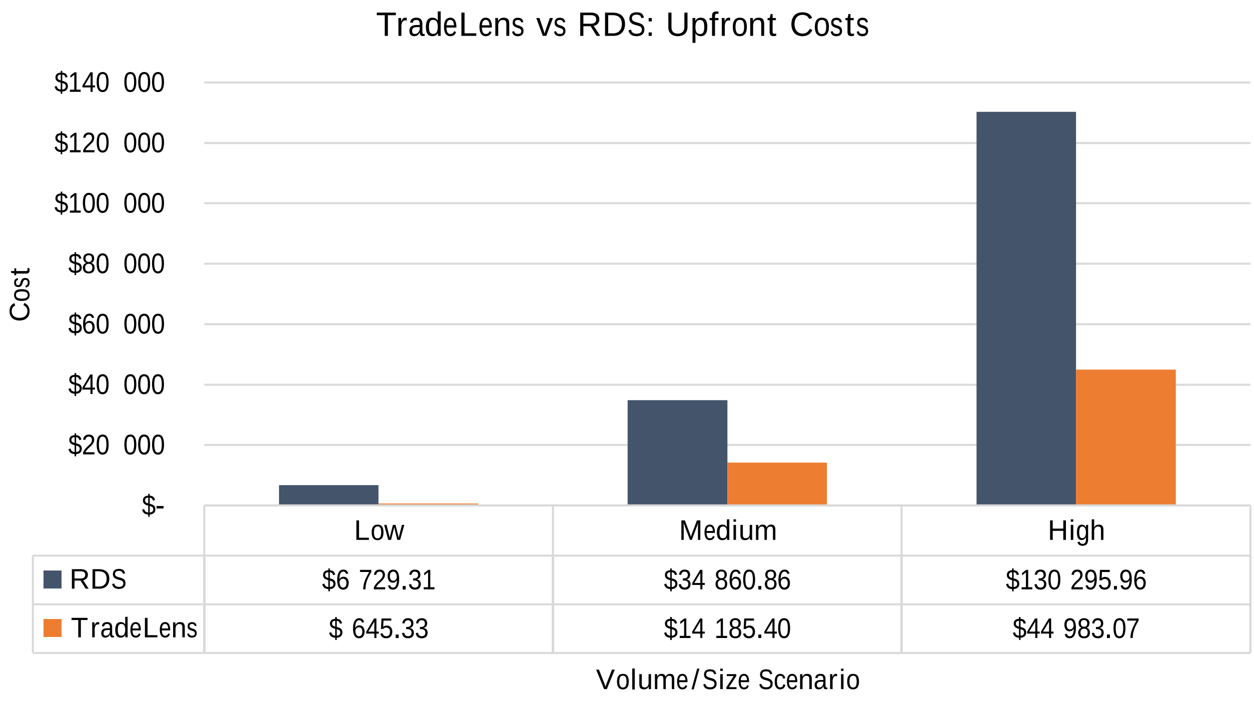


FIGURE 7.3: *Breakdown of the total cost for the relational database model.*



	Low	Medium	High
RDS	$6 729.31	$34 860.86	$130 295.96
TradeLens	$ 645.33	$14 185.40	$44 983.07

FIGURE 7.4: *Upfront costs of the blockchain and relational database models.*

The annual costs are broken down by the various cost drivers in Figure 7.6. Here it can be seen that ongoing labour is by far the largest annual cost driver for both models. This leads to a conclusion that labour costs – both onboarding and ongoing – are the largest cost drivers for both the blockchain and relational solutions. When looking at the basic usage cost, TradeLens is much more expensive than RDS, but it should be noted that the TradeLens solution is a SaaS, while the RDS solution is more of a PaaS. The RDS solution requires additional services, has a longer onboarding period, and requires more attention from employees during its lifetime.

The net present values of the costs for each model were calculated for each scenario and are shown in

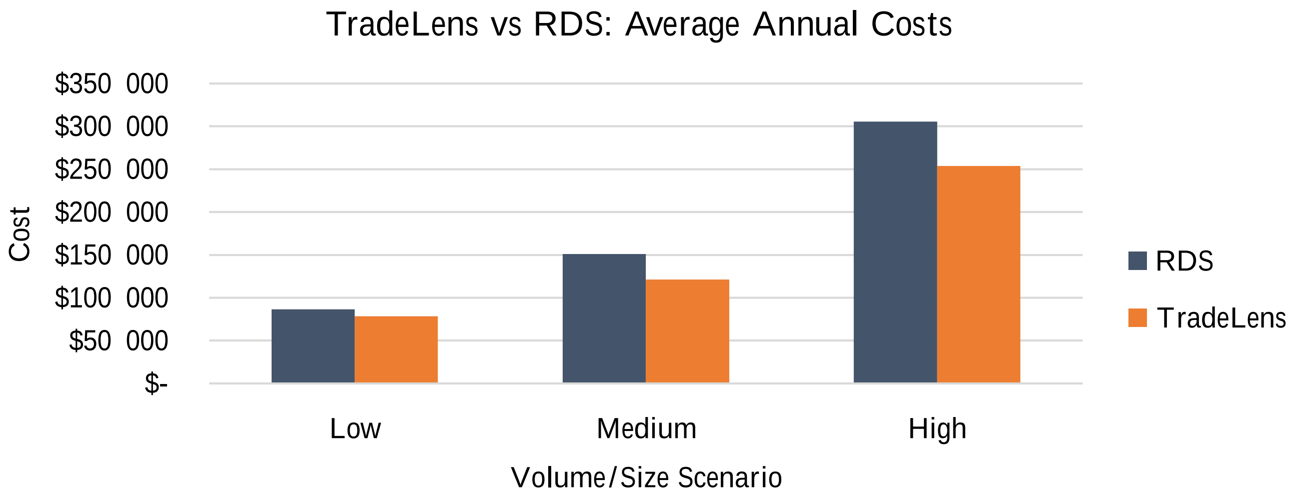


FIGURE 7.5: *Average annual costs of the blockchain and relational database models.*

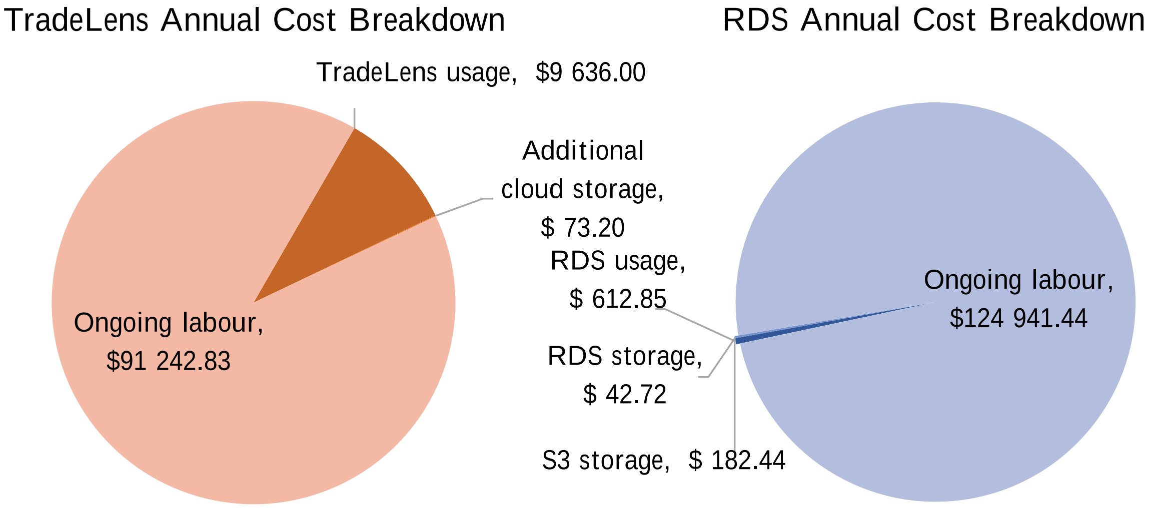


FIGURE 7.6: *Breakdown of the average annual costs of the blockchain and relational database models for the Medium scenario*

Figure 7.7. The relational database model clearly has larger financial costs than the blockchain model. It can be concluded that the relational solution is more expensive than the blockchain solution when it comes to financial costs.

Although the analysis made use of specific products, i.e. the AWS platform and TradeLens, it is also generally applicable to relational and blockchain solutions in global trade for this purpose with some variation in costs. The relational database is a mature technology and there are hundreds of generic solutions available that can be adapted for global supply chains, e.g. AWS RDS. Blockchain, on the other hand, is still an emerging technology. Therefore, applications of the technology tend to be more specific, as is the case with TradeLens. This observation explains why the onboarding period for a relational database solution will most likely be longer than that of a blockchain solution. It also explains why the relational database solution requires more attention from employees, because they need to manage the system on a daily basis to ensure it functions correctly. The benefit of a SaaS like TradeLens is that most of the back-end management is done by the service provider.

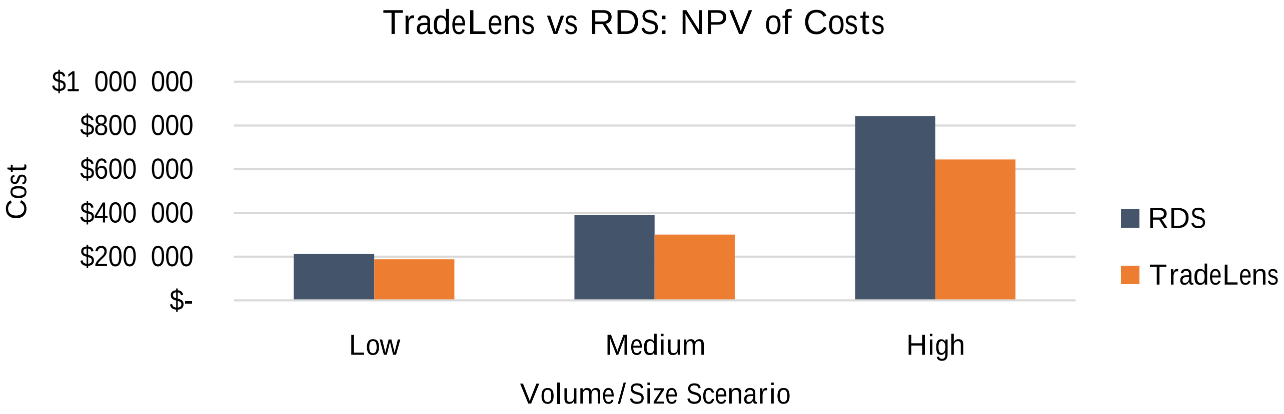


FIGURE 7.7: *NPV of costs for the blockchain and relational database models.*

7.1.2 Financial benefits

The benefits discussed in this section were identified as the most prevalent benefits associated with projects of this nature. Similar to the costs, some of these benefits are more quantifiable than others, so a distinction was made between the two types. Each scenario had its own calculations. Therefore, the Medium scenario is once again the focus of the discussion in this chapter, with the results for the Low and High scenarios included in Appendix B.

The financial benefits in this section were largely based on the study by Forrester (2018) on the total economic impact of IBM's blockchain platform, with certain adjustments made to make it more applicable to the situation in this analysis. It also used information from interviews with industry professionals (Anonymous, 2021b; Anonymous, 2021c). The quantifiable benefits have two main themes: savings due to an increase in efficiency, and savings due to the avoidance of certain costs.

The first benefit in efficiency savings is streamlined documentation (Odell and Fadzeyeva, 2018). This firstly refers to a reduction in the number of conflicting documents (i.e. incorrect paperwork) and secondly, a reduction in the cost of processing a conflicting document. A blockchain solution is expected to lead to fewer conflicting documents when compared to existing solutions, due to the automation and data integrity it provides (Forrester, 2020; Odell and Fadzeyeva, 2018).

Since the relational database model is closer to existing solutions than the blockchain model, it is expected to lead to a smaller reduction in conflicting documents. This is reflected in Table 7.13 where the projected reduction in conflicting documents is lower for the relational database solution, due to the manual verification processes that are still required. Forrester (2018) estimates a reduction of 100% of conflicting records for a blockchain solution, while a reduction of around 60% is expected for relational databases (Anonymous, 2021a; Hedman Surlien, 2018). Similarly, the reduction in cost per document is expected to be 25% for blockchain (Odell and Fadzeyeva, 2018), and 10% for relational databases (Anonymous, 2021a), once again due to the the verification processes that are required.

The table also shows the various metrics used in the calculations. The cost savings for this specific benefit are identical each year, so the annual cost savings in processing documents for both models are shown below. Figure 7.8 shows a comparison of the annual cost savings due to streamlined documentation for all scenarios between the two models. The blockchain model is the clear winner in this case for all three scenarios.

TABLE 7.13: *Annual cost savings due to streamlined documentation for both models (Medium scenario)*

Metric	**Unit**	**TradeLens**	**RDS**
Total number of documents	#	45 000	45 000
Percentage of conflicting documents	%	7	7
Number of conflicting documents to resolve	#	3 150	3 150
Average cost to resolve a dispute	$	200	200
Projected reduction in conflicting documents	%	100	60
Savings due to reduction in conflicting documents	*$*	*630 000*	*378 000*
Average cost for processing a document	$	20	20
Reduction in cost per document	%	25	10
Savings due to reduction in cost of processing documents	*$*	*225 000*	*90 000*
Savings for processing documents	**$**	**855 000**	**468 000**

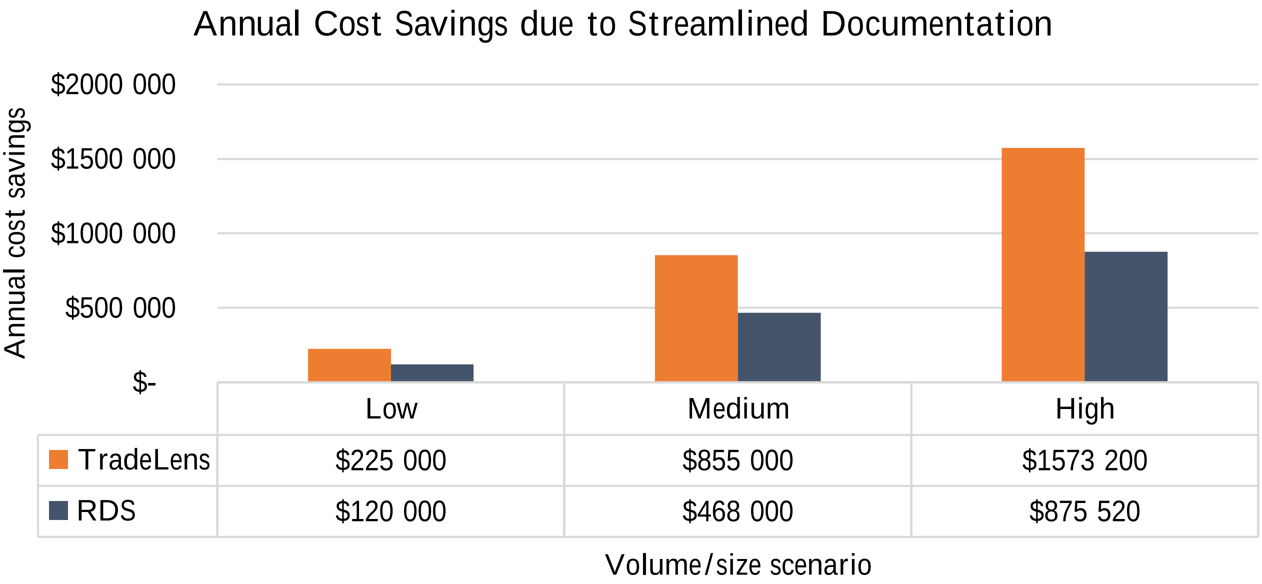


FIGURE 7.8: *Annual cost savings due to streamlined documentation for both models*

The second benefit in efficiency savings is labour cost reduction. The two drivers here are the reduction of finance- and legal resources required to resolve conflicting documents. Since the reduction in the number of conflicting documents for the relational solution is expected to be lower than for the blockchain solution, the percentage reduction in resources differ between solutions, as shown in Tables 7.14 and 7.15.

The data is based on the study by Forrester (2018), as well as an interview with an industry expert (Anonymous, 2021a) that resulted in the observation that relational databases are expected to lead to about half of the reduction of the need for resources than that of blockchains. Annual compensation of employees were derived from data on Glassdoor (2021) using average salaries for professionals at companies of various sizes in different geographical locations. This data is visualised in Figure 7.9 and shows how much more labour-related savings the blockchain model will result in when compared to the relational database model.

TABLE 7.14: *Annual cost savings due to reduced labour costs for TradeLens (Medium scenario)*

		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	5	5	5	5	5
Annual compensation	$	52 595	52 595	52 595	52 595	52 595
Reduction in finance resources	%	20	40	60	80	80
Savings due to reduction in finance resources	*$*	*52 595*	*105 190*	*157 785*	*210 379*	*210 379*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	81 867	81 867	81 867	81 867	81 867
Reduction in legal resources	%	0	30	50	70	70
Savings due to reduction in legal resources	*$*	*0*	*73 680*	*122 800*	*171 920*	*171 920*
Savings in labour costs for TradeLens	**$**	**52 595**	**178 870**	**280 585**	**382 299**	**382 299**

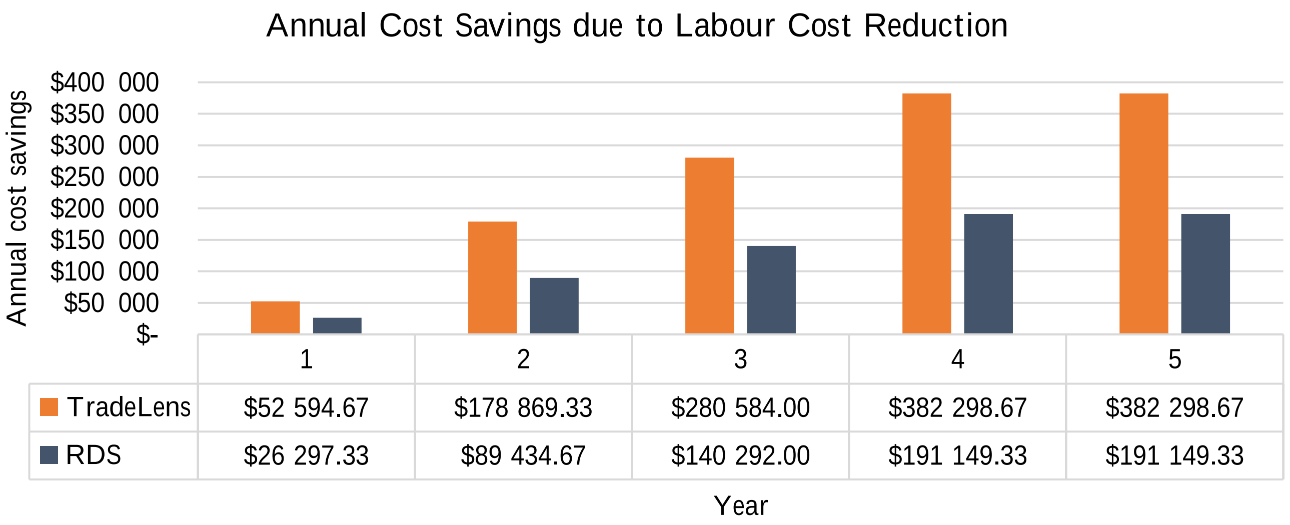
TABLE 7.15: *Annual cost savings due to reduced labour costs for RDS (Medium scenario)*

		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	5	5	5	5	5
Annual compensation	$	52 595	52 595	52 595	52 595	52 595
Reduction in finance resources	%	10	20	30	40	40
Savings due to reduction in finance resources	*$*	*26 298*	*52 595*	*78 892*	*105 190*	*105 190*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	81 867	81 867	81 867	81 867	81 867
Reduction in legal resources	%	0	15	25	35	35
Savings due to reduction in regal resources	*$*	*0*	*36 840*	*61 400*	*85 960*	*85 960*
Savings in labour costs for RDS	**$**	**26 298**	**89 435**	**140 292**	**191 150**	**191 150**

The third benefit in efficiency savings is a reduction in legacy systems, as these are replaced by the new technology (Odell and Fadzeyeva, 2018). The expected savings for this aspect are expected to be identical for both models. Since the analysis is a relative comparison, this benefit was not included. This also applies to the benefit in cost avoidance, i.e. savings in capital and operational expenses, which was also excluded.

Figure 7.10 shows the average annual benefits that can be realised for each scenario. In contrast to the average annual costs the difference between the blockchain and relational database model is much clearer – even for the Low scenario. The model based on TradeLens has much larger financial benefits when compared to the RDS model.

The average annual benefits were broken down into their major components, of which there are only two in this case. As seen in Figure 7.11, the ratio of the costs between the two models are similar



	1	2	3	4	5
■ TradeLens	$52 594.67	$178 869.33	$280 584.00	$382 298.67	$382 298.67
■ RDS	$26 297.33	$89 434.67	$140 292.00	$191 149.33	$191 149.33

FIGURE 7.9: *Annual cost savings due to labour cost reduction for both models (Medium scenario)*

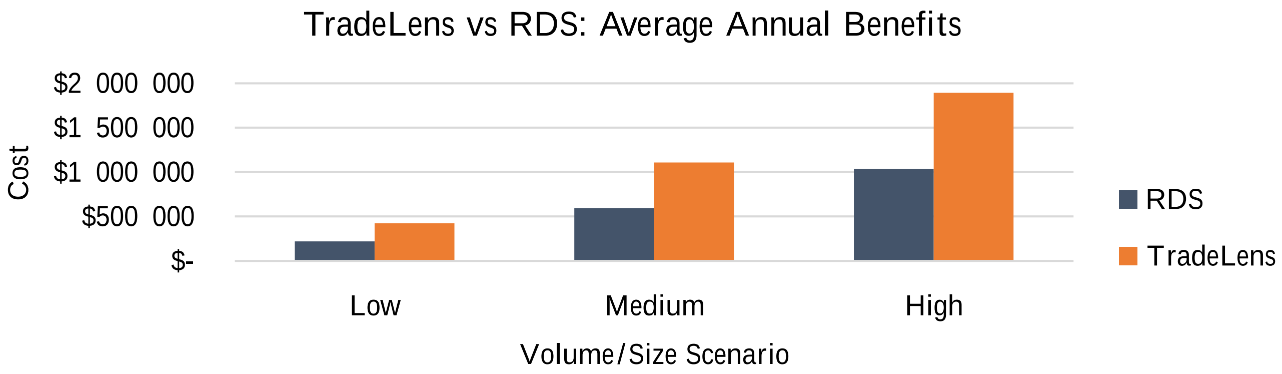


FIGURE 7.10: *Comparison of the average annual benefits of the blockchain and relational database models.*

for the Medium scenario. This is also true for the Low and High scenarios, whose information can be found in Appendix B. The labour cost reduction of the blockchain model is expected to lead to $127 664.54 more in savings than the relational database model, along with $387 000.00 more savings with streamlined documentation.

The net present value of the benefits for each model was calculated for each scenario and is shown in Figure 7.12. The blockchain model clearly has larger financial benefits than the relational database model when looking at what the future benefits would be worth today.

As discussed earlier, the analysis is generally applicable to relational database and blockchain solutions in global trade for this purpose with some variation in the figures. Relational databases are more mature than blockchain technology and have some benefits over blockchain, but there are also trade-offs where blockchain has other, potentially more attractive benefits over relational databases and similar technologies. The three major benefits of blockchain – immutability, security and reduced intermediaries due to decentralisation – allow for much greater efficiencies to be achieved by a blockchain solution when compared to a relational database solution. This is evident when looking at the cost savings in Figure 7.12.

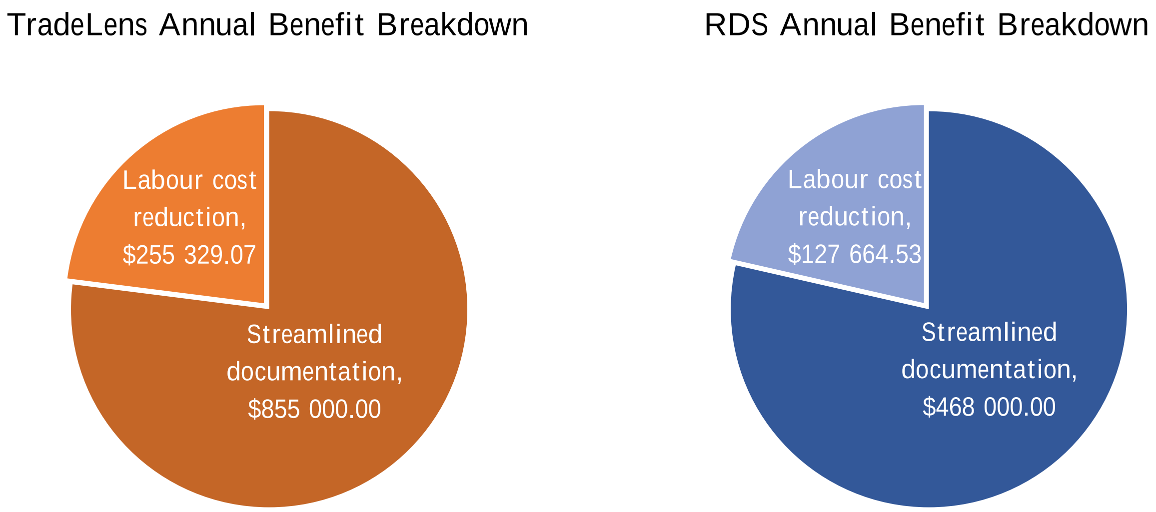


FIGURE 7.11: *Breakdown of the average annual benefits of the blockchain and relational database models for the Medium scenario*

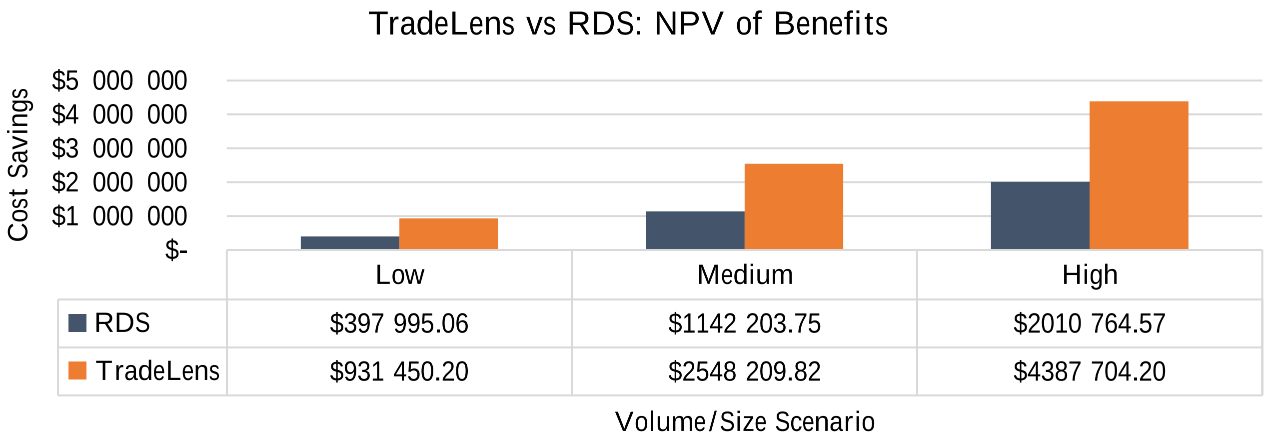
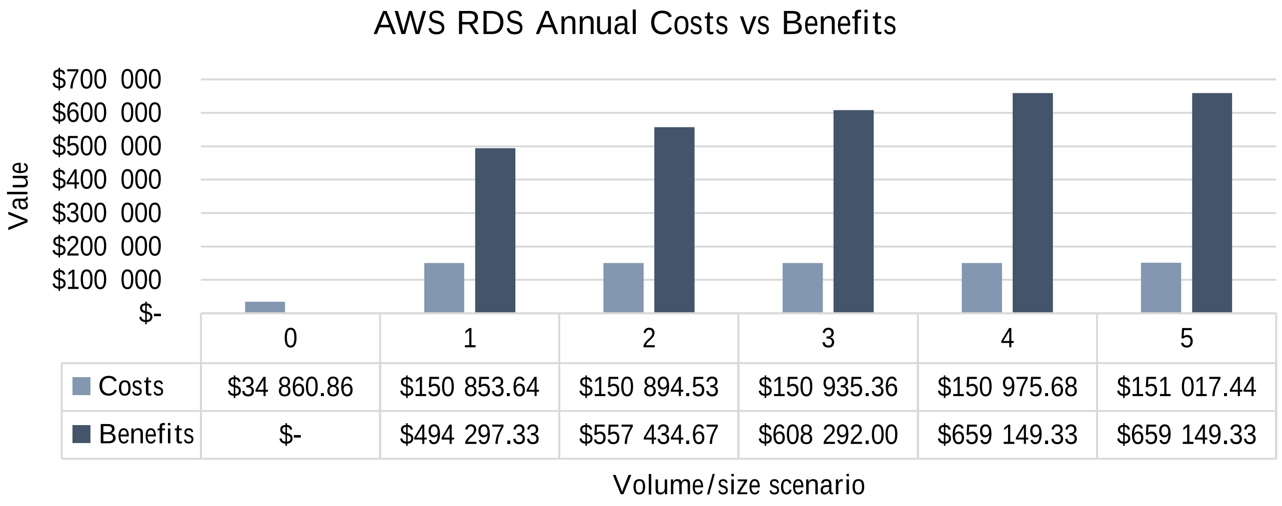


FIGURE 7.12: *Net present values of the cost savings for both models*

7.1.3 Financial cost-benefit comparison

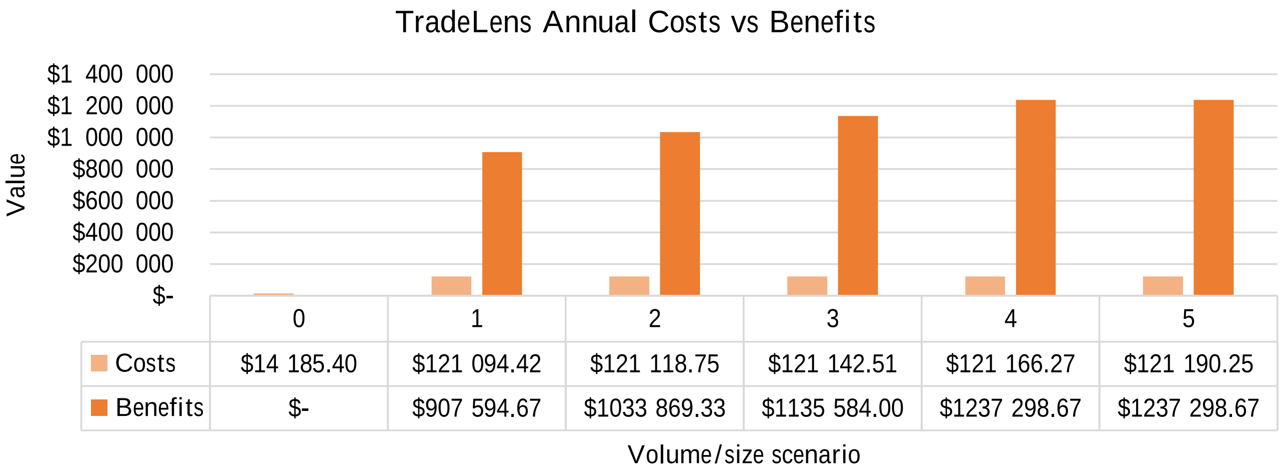
This section compares the financial costs and benefits to provide a better idea of the outcome of the financial analysis. The annual costs and benefits for the Medium scenario of the relational and blockchain models are compared in Figures 7.13 and 7.14 respectively. The benefits are clearly much larger than the costs for both models, which indicates that both solutions will be profitable each year. An exception is Year 0, the onboarding and commercialisation phase, where no major benefits are enjoyed yet, which leads to a negative cash flow. This deficit is quickly recovered in subsequent years.

The average annual costs and benefits for both models and all scenarios are visually compared in Figure 7.15. The cost-benefit ratio (CBR) was calculated by dividing the net benefits by the net costs. When calculating the CBR for each model and scenario, only positive values were found, which shows that both models are expected to lead to positive net present values regardless of the scenario. This was corroborated by the positive net benefits that both solutions are expected to provide, as shown in Figure 7.16.



	0	1	2	3	4	5
Costs	$34 860.86	$150 853.64	$150 894.53	$150 935.36	$150 975.68	$151 017.44
Benefits	$-	$494 297.33	$557 434.67	$608 292.00	$659 149.33	$659 149.33

FIGURE 7.13: *Annual costs and benefits for the relational database model (Medium scenario).*



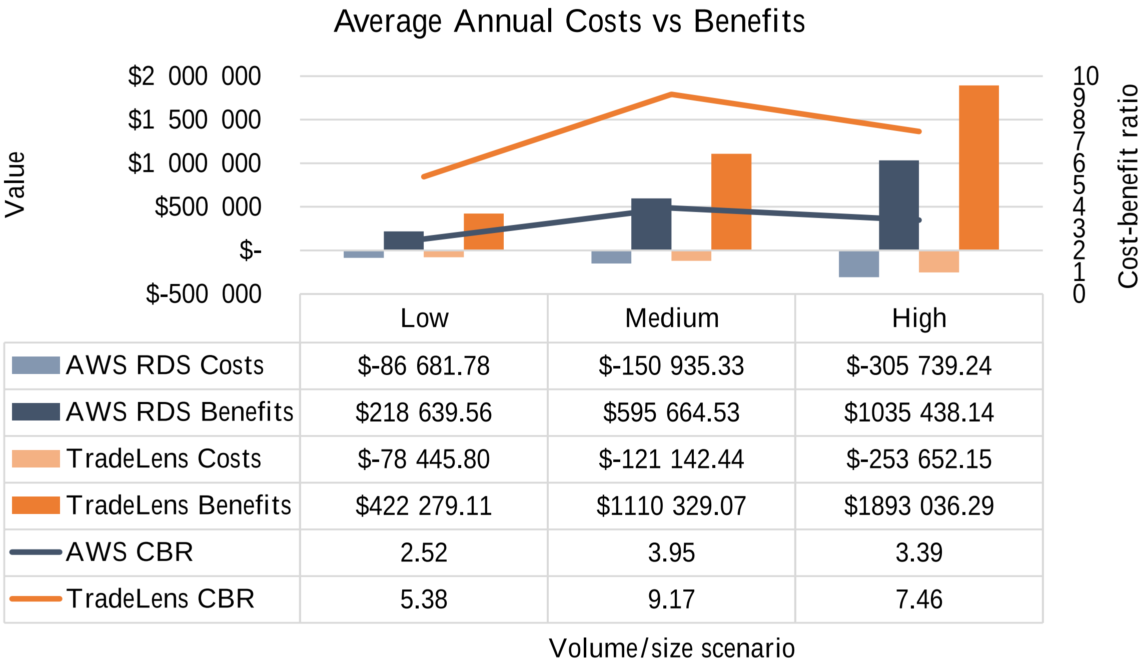
	0	1	2	3	4	5
Costs	$14 185.40	$121 094.42	$121 118.75	$121 142.51	$121 166.27	$121 190.25
Benefits	$-	$907 594.67	$1033 869.33	$1135 584.00	$1237 298.67	$1237 298.67

FIGURE 7.14: *Annual costs and benefits for the blockchain model (Medium scenario).*

Table 7.16 shows a summary of the net benefits for each scenario and model, as well as the ROI and payback periods. The ROI describes the return of a specific investment, relative to its cost. The higher the ROI, the greater the profitability of the project. The payback period refers to the time required to recover the cost of a project. The shorter the period, the quicker it will become profitable. The data shows that both models are lucrative investments.

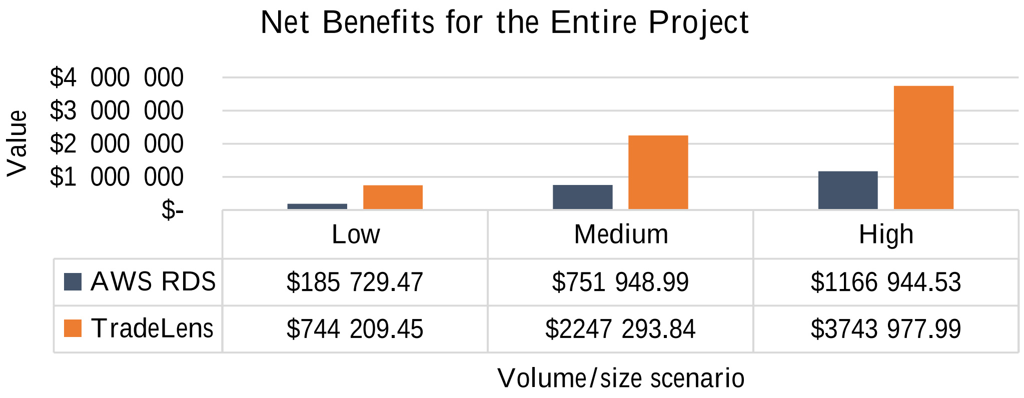
TABLE 7.16: *Net benefits, return on investment, and payback period for both models.*

			AWS RDS			**TradeLens**	
Metric		**Low**	**Medium**	**High**	**Low**	**Medium**	**High**
Total costs	$	212 272	390 255	843 821	187 241	300 916	643 726
Total benefits	$	397 996	1 142 204	2 010 765	931 452	2 548 210	4 387 705
Net benefits	*$*	*185 724*	*751 949*	*1 166 945*	*744 210*	*2 247 294*	*3 743 978*
ROI	%	87	193	138	397	747	582
Payback period	Mo.	1	3	6	1	2	3



	Low	Medium	High
■ AWS RDS Costs	$-86 681.78	$-150 935.33	$-305 739.24
■ AWS RDS Benefits	$218 639.56	$595 664.53	$1035 438.14
■ TradeLens Costs	$-78 445.80	$-121 142.44	$-253 652.15
■ TradeLens Benefits	$422 279.11	$1110 329.07	$1893 036.29
― AWS CBR	2.52	3.95	3.39
― TradeLens CBR	5.38	9.17	7.46

Figure 7.15: *Average annual financial costs and benefits for the blockchain and relational database models.*



	Low	Medium	High
■ AWS RDS	$185 729.47	$751 948.99	$1166 944.53
■ TradeLens	$744 209.45	$2247 293.84	$3743 977.99

Figure 7.16: *Net cash flow for the blockchain and relational database models.*

7.1.4 Costs used in the non-financial analysis

One of the components of the non-financial analysis in the next section is Cost. To do the required ratings, discussed in the next section, it was necessary to simplify the costs of the financial analysis into fewer components. These costs were grouped into the following criteria: fixed costs (called Investment Cost in the non-financial analysis), variable costs that vary with volume (Transaction Costs), and cost savings (called Cost Efficiency).

Investment Cost

In the non-financial analysis, Investment Cost is the sum of the annual fixed costs (i.e. ongoing labour) and initial investment costs (onboarding labour and new member costs in the case of TradeLens). The values obtained through the financial analysis for the Medium scenario are shown in Table 7.17.

Table 7.17: *Investment Costs for Blockchain and Relational Databases*

	Unit	**Relational Database**	**Blockchain**
Annual Fixed Cost	$	124 941.44	91 242.83
Initial Investment Cost	$	29 050.72	11 821.17
Investment Cost	$	**153 992.16**	**103 064.00**

Transaction Cost

In the non-financial analysis, transaction-related cost is the sum of the service usage cost, cloud storage cost, and monitoring and audit costs. The number of transactions that are processed per year were calculated using the following equation:

$$TY = TS \times \frac{(DY)}{(DS)} \tag{7.1}$$

where TY is the number of transactions per year, TS is the number of transactions per shipment, DY is the number of documents per year, and DS is the number of documents per shipment. The Medium scenario used the following values that are based on a combination of data from literature (Ganne, 2018; Australian DFAT and Chinese MofCom, 2001; Karabulut, 2020) and interviews with industry experts (Anonymous, 2021a; Anonymous, 2021c): $TS = 20$ transactions per shipment, $DY = 45\ 000$ documents per year, and $DS = 15$ documents per shipment. This led to $TY = 60\ 000$ transactions per year.

The service usage cost for blockchain was obtained from an interview with a TradeLens employee (Anonymous, 2021c), while the usage cost for the relational database, as well as the cloud storage costs for both models were determined using the AWS Pricing Calculator (AWS, 2021a). The monitoring costs are based on a study by Brody et al. (2019), which states that these are required as part of the quality assurance process associated with new solutions. Using the transaction-related cost along with the number of transactions per year, the cost per transaction for each solution were calculated, as shown in Table 7.18.

Table 7.18: *Transaction Costs for Blockchain and Relational Databases*

	Unit	**Relational Database**	**Blockchain**
Service Usage Cost	$	612.85	9 636.00
Cloud Storage Cost	$	225.16	73.20
Monitoring Costs	$	1495.00	1 495.00
Transaction-Related Costs	*$*	*2 333.00*	*11 204.20*
Number of Transactions	#	60 000	60 000
Cost per Transaction	**$**	**0.0389**	**0.1867**

Cost Efficiency

In the non-financial analysis, Cost Efficiency depends on reduced labour and streamlined documentation – the financial benefits that were discussed in Section 7.1.2.

The next section contains a detailed non-financial analysis that looks at various other measures that play a role in selecting the solution that is a better fit to the cross-border supply chain environment.

7.2 Non-Financial Analysis

This section firstly describes the methodology for the non-financial analysis. Secondly, the application of the first method and how it supports the second method is described. Thirdly, the second method is applied, which concludes the non-financial analysis.

7.2.1 Methodology

The non-financial analysis makes use of a combination of two proven scientific methods for making complex decisions. A component of the first method was used to refine and visualise the criteria used in the non-financial analysis. This was used as an input to the second method, which was used to map the complex relationships between the different criteria. More detail follow in the sections below.

The Architecture Trade-off Analysis Method (ATAM)

The first method is the Architecture Trade-off Analysis Method (ATAM), developed by Kazman, Klein, and Clements (2000). It allows one to determine whether the goals of the architecture being evaluated are achievable before large amounts of resources have been committed to it. This method helped refine the quality attribute requirements (e.g. performance, security, etc.) and design decisions (e.g. what consensus mechanism to use), and helped to determine whether these design decisions adequately address the quality requirements (Kazman, Klein, and Clements, 2000). The method has previously been used in studies regarding blockchain and complex systems (Garriga et al., 2021; Radhakrishnan, 2019).

An important part of this method is the utility tree, which helped elicit the quality attribute requirements. It is a top-down approach for translating business requirements into quality attributes (Kazman, Klein, and Clements, 2000). Although the ATAM goes further by using the utility tree to prioritise these quality attributes, the analysis in this thesis made use of a different method, as explained below. Instead, the utility tree was used to elicit the quality attributes and their sub-criteria, and to visualise and group the criteria used in this analysis.

The Analytic Network Process (ANP)

The Analytic Network Process (ANP) is the main method used in this analysis. It was developed by Saaty and Vargas (2013) and builds upon the Analytic Hierarchy Processes (AHP), developed by the same authors. The AHP and ANP take a multidimensional problem (one with various decision criteria) and reduce it to a one dimensional problem – a score that orders the alternative solutions being considered. While AHP prioritises different criteria with respect to their influence on the outcome, the ANP goes further by considering the dependence between these criteria (Saaty and Vargas, 2013). For example, AHP would ask whether performance or security is more important to the outcome, i.e. a solution for document sharing in global supply chains. ANP would also ask this question, but would also ask what effect security has on performance and vice versa. The reasons for selecting the ANP methodology include:

1. Selecting a solution for document-sharing in cross-border supply chains is a multi-criteria decision problem.
2. The criteria have interdependencies.
3. The ANP has been used in previous research regarding complex decision-making in global supply chains (Hosseini et al., 2013; Zarour et al., 2020).

The ANP has five major steps:

1. Identify interdependencies between criteria and perform pairwise comparisons.
2. Derive priorities from pairwise comparisons and create an unweighted super matrix.
3. Pairwise compare the clusters, derive the priorities and create a cluster matrix.
4. Create a weighted super matrix using the unweighted super matrix and the cluster matrix.
5. Determine the limit matrix and derive the relative priorities of the alternatives being compared.

The first step of the ANP is to make trade-offs between the criteria (Saaty and Vargas, 2013). While such trade-offs are usually done qualitatively, the ANP expresses it quantitatively by using pairwise comparisons. The first step is to link each criterion (the parent node) with other criteria (children nodes) that influence it. The children nodes are then pairwise compared to determine the priority of their influence on the parent node. This is done by giving a verbal judgement and converting it to a numeric value using the fundamental scale, as shown in Table 7.19. Matrices for each alternative are created using the numeric values for the judgements per cluster. The eigenvectors of each matrix are calculated and the principal eigenvector of each matrix is identified. The principal eigenvectors represent the priorities for the criteria in that cluster for the specific alternative. The priority vector for each cluster (symbolised by W_{ij} in Equation 7.2 below) make up the columns of the unweighted super matrix, which is the second step in the ANP.

TABLE 7.19: *The fundamental scale (Saaty and Vargas, 2013)*

Value	**Meaning**
1	Equal importance
3	Moderate importance of one over the other
5	Strong importance
7	Very strong importance
9	Extreme importance
2,4,6,8	Intermediate values

An important part of the ANP is the super matrix. It consists of clusters and their criteria, along with priority vectors derived from pairwise comparisons between these criteria, which map their interdependencies. A super matrix W consisting of n clusters is given by:

$$W = \begin{array}{cc|ccccc|}
 & & C_1 & \cdots & C_k & \cdots & C_n \\
 & & e_{11}e_{12}\ldots e_{1m_1} & \cdots & e_{k1}e_{k2}\ldots e_{km_k} & \cdots & e_{n1}e_{n2}\ldots e_{nm_n} \\
\hline
C_1 & \begin{matrix} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{matrix} & W_{11} & \cdots & W_{1k} & \cdots & W_{1n} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
C_k & \begin{matrix} e_{k1} \\ e_{k2} \\ \vdots \\ e_{km_k} \end{matrix} & W_{k1} & \cdots & W_{kk} & \cdots & W_{kn} \\
\vdots & \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\
C_n & \begin{matrix} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_n} \end{matrix} & W_{n1} & \cdots & W_{nk} & \cdots & W_{nn} \\
\hline
\end{array} \tag{7.2}$$

where C_k is the kth cluster consisting of m criteria, e_{km} is the mth criterion of the kth cluster, and W_{ij} is the priority vector obtained through pairwise comparisons of the criteria in clusters C_i and C_j (Saaty and Vargas, 2013). An example of interpreting the values from the super matrix follows. W_{k1} is the priority vector that describes the influence that criteria $e_{k1}, e_{k2}, ..., e_{km_k}$ in cluster C_k have on criteria $e_{11}, e_{12}, ..., e_{1m_1}$ in cluster C_1.

In the third step, the clusters of criteria are pairwise compared in a similar way, which yields the cluster matrix, where each entry w_{ij} represents the priority of cluster C_i over cluster C_j. This matrix is used in the fourth step to determine the weighted super matrix. This is done by multiplying each priority in W_{ij} with w_{ij}, i.e. the priority of each criterion in a cluster in the unweighted super matrix is multiplied by the priority of that cluster in the cluster matrix. In the fifth and final step of the ANP, the weighted super matrix is raised to powers (i.e. it is multiplied by itself) until it converges, which then forms the limit super matrix. The rows in this matrix show the relative values for each criterion. By normalising these values, the relative utility is obtained, i.e. what option is the better choice (Saaty and Vargas, 2013).

The rest of this section describes how the two methods were applied in the non-financial analysis to compare blockchains and relational databases with the goal of determining which solution better satisfies the requirements of a document sharing solution in a cross-border supply chain.

7.2.2 Application of the ATAM

To ensure that the alternatives were adequately compared by considering all the relevant factors, clusters of criteria that represent the most important aspects of such systems in cross-border supply chains needed to be selected for the analysis. The clusters of criteria for this analysis include *performance* (Radhakrishnan, 2019; Garriga et al., 2021 Hewett, Hanebeck, and McKay, 2019), *security* (Garriga et al., 2021; Zarour et al., 2020; Hewett, Hanebeck, and McKay, 2019), *cost* (Radhakrishnan, 2019; Garriga et al., 2021), *interoperability* (Hewett and Jensen, 2019), *reliability* (Radhakrishnan, 2019) and *functionality* (Radhakrishnan, 2019; Garriga et al., 2021).

Performance

The first criterion in the performance cluster is *scalability* (Garriga et al., 2021; Geneiatakis et al., 2020; C. Wang and Chu, 2020; Kannengießer et al., 2020), which determines how easily throughput can be increased or decreased under varying loads, e.g. changing number of peers, transactions and computational resource requirements. It is characterised by the scalability techniques used and the consensus mechanism (if applicable). Transaction *throughput* (Kannengießer et al., 2020; Geneiatakis et al., 2020; C. Wang and Chu, 2020) represents the number of transactions that are processed in a specific time frame, in this case, measured in TPS.

Transaction *latency* (Garriga et al., 2021; Geneiatakis et al., 2020; C. Wang and Chu, 2020) is the time it takes for a transaction to be finalised, i.e. written to the database and accepted by the consensus protocol in the case of blockchain. Factors that influence latency are the consensus mechanism and complexity of the query (e.g. a query with multiple criteria). *Time efficiency* (Y. Wang, Singgih, et al., 2019; Alicke, Rexhausen, and Seyfert, 2017) simply refers to how efficiently the solution makes use of the available time and is characterised by the number of processes that can easily be automated, as well as a reduction in the number of steps required in cross-border trade (e.g. time-consuming verification steps).

Security

The first aspect of security that was looked at in the analysis is *data integrity* (Hewett, Hanebeck, and McKay, 2019), which describes the overall accuracy, completeness, and consistency of data – whether the data can be trusted. It is largely influenced by the data collection methods, data sources, and the level of human involvement, which goes hand-in-hand with human errors. *Privacy* (Garriga et al., 2021) is included under security, because it entails the protection of potentially sensitive information against unwanted access and is largely influenced by the cryptography techniques that the solution utilises.

The third criterion under security is *trust* (Bienhaus and Haddud, 2018), which is the degree to which users can be sure that the solution is safe and secure, based on its nature and properties. Resistance against tampering of data plays a large role in building trust, as well as the degree of decentralisation and whether there are intermediaries in which the user must put their trust. Although *immutability* (Zarour et al., 2020) is usually associated with blockchain, it can also be associated with other technologies that facilitate the flow of data. Hashing algorithms, i.e. how data is cryptographically linked to other data and consensus, i.e. how a mutual understanding of the state of data in the database is reached among different parties, are both large factors of influence on immutability.

Cost

As discussed in Section 7.1.4, cost is one of the clusters of criteria used in the non-financial analysis. For simplicity's sake, there are three criteria that make up this cluster. Fixed costs (i.e. ongoing labour) and those that are once-off (i.e. onboarding labour) are referred to as *investment costs.* Costs that vary with the number of documents that are shared are referred to as *transaction cost*s and include usage costs, cloud storage cost, and monitoring and audit costs associated with governing the solution and ensuring it is working correctly (Brody et al., 2019). The final criteria of the cost cluster is *cost efficiency* (Chopra and Sodhi, 2014; Block and Marcussen, 2020), the degree to which costs can be reduced due to greater efficiencies, e.g. reduced labour requirements and streamlined documentation due to fewer mistakes.

Interoperability

Interoperability is the ability of systems to communicate, understand and use the functionality of one another (Chen, Doumeingts, and Vernadat, 2008; Rojko, 2017). *Standardisation* (Hewett, Hanebeck, and McKay, 2019; Korpela, Hallikas, and Dahlberg, 2017) plays a large role in the interoperability of systems and refers to the availability or degree of development of technical standards based on the consensus of various stakeholders, such as companies, governments and standards organisations (Z. Xie et al., 2016). It is characterised by the number and quality of standards that currently exist related to the solution, and the maturity of the solution – more mature technologies are more likely to have a larger number of applicable standards. Support for standardised APIs, such as REST, which play a large role in interoperability due to the integration they enable between systems (Linn and Koo, 2016), were included under this criterion.

Regulations and policies (Ganne, 2018) are closely related to standardisation, but specifically refers to the degree to which governments are working with industry players to develop new regulations and policies for the solution. Collaborative initiatives where different players (e.g. governments and companies) are working together to develop standards, regulations and policies for governing the technology, and the number of legal frameworks available for navigating the complex legal landscape of cross-border trade are some of the factors that influence this criterion.

Reliability

Availability (Hewett, Hanebeck, and McKay, 2019) refers to whether the data is accessible by users and applications when required, e.g. a user with relevant permissions should not receive an error when attempting to view a document. Since availability is part of the CAP theorem, there are certain trade-offs against consistency and partition tolerance that must be made. *Robustness* (Monostori, 2018) is the ability of the solution to remain in a properly functioning condition under disturbances, e.g. crashes and errors, which makes it so vital in cross-border supply chains. It is influenced by the level of decentralisation (as this means there is no single point of failure) and the fault tolerance (the degree to which it can withstand faults in the network, e.g. a node that fails).

Any transaction that is written to the database must change affected data only in allowed ways, i.e. must adhere to predefined rules. This is known as *consistency* (Garriga et al., 2021) and in the case of blockchain, ensures that all honest nodes produce the same order of blocks throughout the execution of the consensus protocol. Therefore, it is highly influenced by consensus, and the previously-mentioned CAP theorem. *Maturity* (Varma and Khan, 2014) describes how long the technology on which the solution is based has been in use, and is important to reliability as higher maturity ensures that most of its initial faults and inherent problems have been removed or reduced by further development. It is characterised by the degree of support that the technology has from industry players, and the level of uncertainty regarding the technology, as newer technologies tend to have higher levels of uncertainty.

Functionality

Although a broad term, *suitability* is used to describe the general fit of the solution in the cross-border trade environment, i.e. whether it is an appropriate fit for the situation (Cambridge Dictionary, 2022b). The number of proven use cases, e.g. success stories of where the solution was successfully used, and inherent properties of the solution, e.g. blockchain's security, are both important drivers of this criterion. Another criterion that should be considered is *manageability*. In this analysis, the non-specific definition of manageability was used, so it refers to the degree to which the solution can easily be controlled or managed by a small group of administrators or owners (Merriam-Webster, 2022; Cambridge Dictionary, 2022a). It depends on the ease of correcting mistakes or incorrect data and the level of control a single administrator or a small group of administrators and owners have of the database.

The clusters and each of their criteria that are described above are visualised in the utility tree in Figure 7.17.

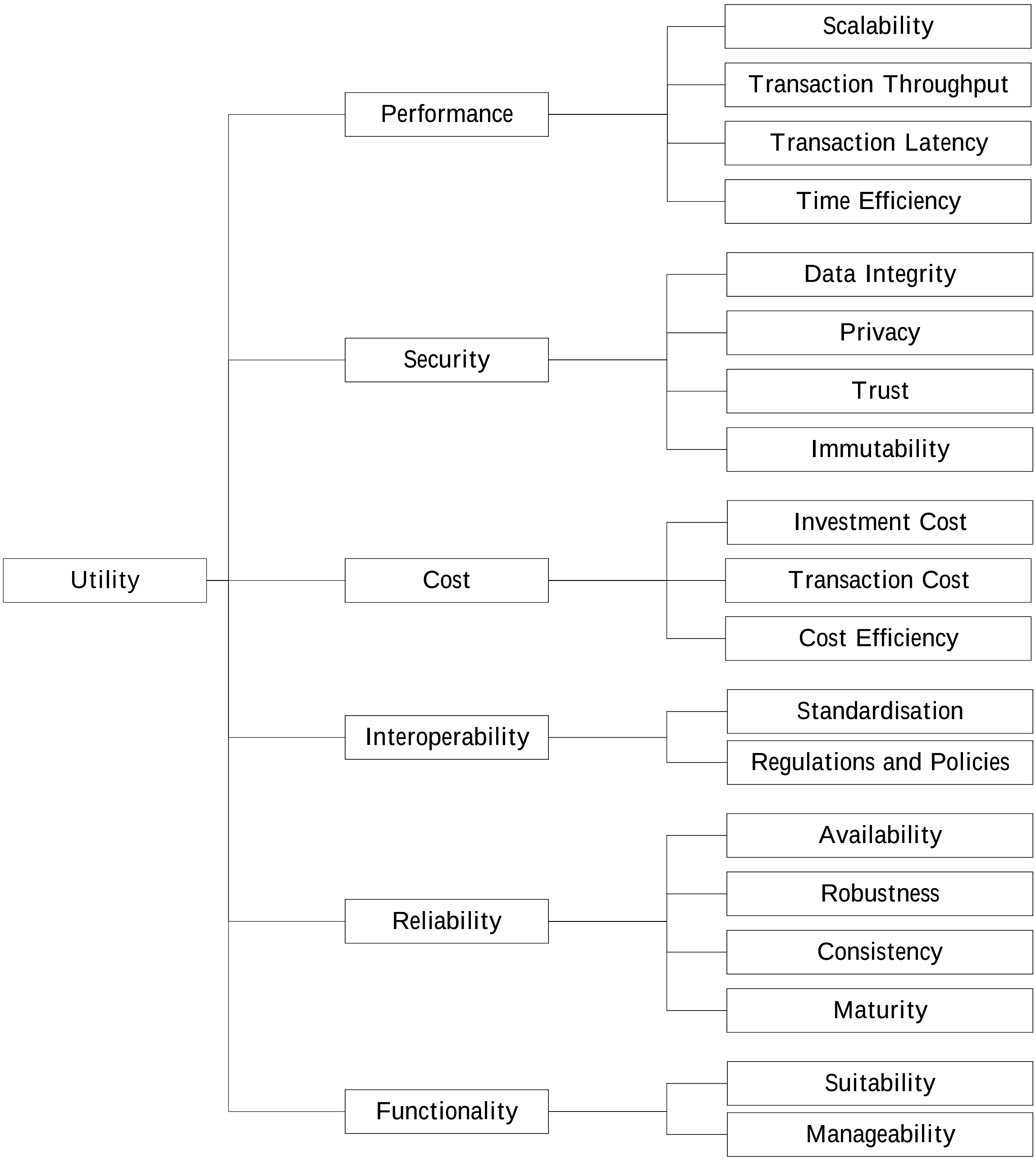


FIGURE 7.17: *Utility tree showing the quality attributes and their criteria.*

7.2.3 Application of the ANP

The output from the ATAM in the first part of the non-financial analysis, i.e. the utility tree with criteria, was used as input for the ANP. This method entailed mapping the dependencies between criteria, performing pairwise comparisons between criteria and clusters of criteria to determine the relative importance with respect to the objective, and finally creating and working with various super matrices (Saaty and Vargas, 2013). To make analysis using the ANP easier, Saaty and Vargas (2013) created an application for performing the calculations in the steps described above, and called it *SuperDecisions*. This tool was used in the non-financial analysis to perform the ANP. The rest of this section describes how the various steps of the ANP were applied.

A summary of the pairwise comparisons between the two solutions with respect to each criterion is provided in Table 7.20. *BCs* is used to refer to blockchains, while *RDBs* is used to refer to relational databases.

Unweighted Super Matrix

In ANP one considers the dependence between criteria, as well as the dependence between clusters and the criteria of other clusters. This enables the creation of a super matrix containing these dependencies. The pairwise comparisons are accompanied by a degree of bias, which creates inconsistency between the comparisons. To manage consistency, a consistency ratio was calculated by SuperDecisions with a desired value of less than 0.1, which represents a high level of consistency (Saaty and Vargas, 2013). This enabled the comparisons to be adapted to ensure a high level of consistency and to reduce the subjectivity behind them. The unweighted super matrix is shown in Table 7.21.

To explain how the priorities were derived from the pairwise comparisons, the Performance cluster of criteria for the Blockchain alternative is used as an example. The pairwise comparisons of criteria in the Performance cluster with respect to Blockchain led to the matrix in Equation 7.3. The importance of Scalability compared to Transaction Throughput was converted using the fundamental scale and resulted in a value of 2, as seen in column 2, row 1 in Equation 7.3. The value of 2 means that Scalability is equally to moderately more important than Transaction Throughput when it comes to Blockchain's utility (Ganne, 2018). The reciprocal that is 0.5 in column 1, row 2 shows the importance of Transaction Throughput compared to Scalability. This logic was followed for all other pairwise comparisons, as seen in Equation 7.3.

$$\begin{array}{c|cccc|} & Scalability & Throughput & Latency & TimeEfficiency \\ Scalability & 1 & 2 & 3 & 0.25 \\ Throughput & 0.5 & 1 & 3 & 0.333 \\ Latency & 0.333 & 0.333 & 1 & 0.25 \\ TimeEfficiency & 4 & 3 & 4 & 1 \end{array} \tag{7.3}$$

The next step was to determine the eigenvectors for the matrix in Equation 7.3 and to identify the principal eigenvector, which is characterised by the eigenvector with the largest eigenvalue. The principal eigenvector for the Performance cluster is shown in Equation 7.4. The relative priorities were obtained by converting this to a ratio scale by dividing each entry by the sum of the entries. This is shown in Equation 7.5 and corresponds to the values of the Performance cluster for Blockchain in the unweighted super matrix in Table 7.21. This process was followed for each and every criterion and cluster combination, meaning this process occurred 68 times to create the unweighted super matrix, which corresponds to the number of priority vectors that do not result in zeros and ones.

$$\begin{bmatrix} 0.415388273373206 \\ 0.31172517501849 \\ 0.15331222048701 \\ 1 \end{bmatrix} \tag{7.4}$$

$$\begin{bmatrix} 0.2209 \\ 0.16581 \\ 0.08155 \\ 0.53174 \end{bmatrix} \tag{7.5}$$

The first two rows of the unweighted super matrix – those that correspond to Blockchains and Relational Databases – represent the priorities obtained through pairwise comparisons of the alternatives and the criteria using the process described above. For example, the scalability of relational databases (0.6667) is better than that of blockchains (0.33333) while the robustness of blockchains (0.85714) is better than that of relational databases (0.14286). Standardisation does not influence Immutability, hence a value of 0, while Regulations and Policies do, hence a value of 1. In the Security cluster, Trust (0.59363) has the largest direct influence on Robustness, followed by Immutability (0.24931), and Data Integrity (0.15706), while Privacy (0) has no direct influence. Note that the priorities from each cluster sums to one. Therefore, the priorities of criteria from different clusters cannot yet be compared.

Cluster Matrix

The cluster matrix is shown in Table 7.22. Industry experts were asked to rank the clusters according to their importance (Anonymous, 2021a; Anonymous, 2021c). The rankings were used as a guideline when performing the pairwise comparisons and the magnitudes of the raw comparison values were determined using information from literature, discussed in more detail below. Priorities were determined using the same process described above. The first column, Alternatives, shows that Security (0.37653) is the most important aspect when selecting a solution from the alternatives, due to the magnitude of possible consequences when the solution's security is inadequate (Y. Chang, Iakovou, and Shi, 2020; Anonymous, 2021c; Y. Wang, Han, and Beynon-Davies, 2019; Ganne, 2018; Hewett, Ogée, and Furuya, 2019).

This is followed by Performance (0.15270), due to the time-sensitive nature of trade where the speed and time savings play a large role (Hewett, Hanebeck, and McKay, 2019; Bunduchi, 2019; Ganne, 2018; Tian, 2017). Interoperability (0.07098) has a lower priority than Reliability (0.13835) and Functionality (0.16825), because a solution must first be reliable and able to perform the required basic functions before the integration with other systems are addressed (Hewett, Hanebeck, and McKay, 2019; Forkel, Clauß, and Schumann, 2019; Ganne, 2018). Furthermore, while the cost of a solution plays a role in the selection, its reliability is more important, as an unreliable system can negatively influence the expected cost savings (Anonymous, 2021b). The process of choosing between alternatives is more sensitive towards cost than interoperability since the latter can be improved through development, while many more factors influence the former (Anonymous, 2021c).

It should also be noted that while a cluster may be more important than another cluster, its final priority may be lower due to the influence of other clusters on the two clusters under consideration. For example, in the pairwise comparison between Reliability and Functionality, both are roughly equally important (Monostori, 2018; Hintsa et al., 2012) yet the latter had a larger priority in the cluster matrix due to the effect of other clusters on Reliability and Functionality.

When looking at Security, the most influential cluster is Security (0.37929). This is due to the criteria in Security cluster having such a large influence on one another. Furthermore, Alternatives also has an influence on Security – the reason being that the choice of alternative will have an influence on the security because blockchains have inherent security mechanisms that relational databases do not have.

TABLE 7.20: *Summary of the logic behind the pairwise comparisons*

Cluster	**Criterion**	**Summary of Comparison**
Performance	Scalability	BCs known for scalability issues; less of an issue for consortium BCs. RDBs known to scale better than BC in general (Ganne, 2018).
	Transaction Throughput	Consensus mechanism and distributed nature of BCs lead to lower throughput than RDBs who do not have these (Kannengießer et al., 2020).
	Transaction Latency	Similar to above. Worse for BC than RDBs because data must travel further, among other reasons (Y. Wang, Han, and Beynon-Davies, 2019).
	Time Efficiency	BCs have greater ability to automate and reduce steps due to its security mechanisms. Less so for RDBs (Y. Wang, Singgih, et al., 2019).
Security	Data Integrity	While data sources and data collections methods are expected to be similar, immutability and time efficiency of BC give it advantage over RDBs (Y. Wang, Singgih, et al., 2019).
	Privacy	Encryption of data and hashing possible with RDBs, but must be set up, while it is part of BC and requires no additional work (Swan, 2015).
	Trust	Inherent feature of BC due to immutability and decentralisation; requires much more work for RDBs to reach acceptable level of trust (Ganne, 2018).
	Immutability	BCs immutable due to decentralised nature and consensus mechanism. Not true for RDBs, which cannot easily reach such levels of security (Chowdhury et al., 2019).
Cost	Investment Cost	Main difference due to labour costs – significantly higher for RDBs due to worse time efficiency compared to BC (refer to Section 7.1).
	Transaction Cost	Higher maturity of RDBs benefits it here – mature technologies have less uncertainty; generally lower fees (refer to Section 7.1).
	Cost Efficiency	BC much more cost efficient than RDBs due to lower labour requirements and better ability to streamline flow of documents (refer to Section 7.1).
Interoperability	Standardisation	RDBs more mature than BCs; therefore more accepted standards applicable to RDBs (Ganne, 2018).
	Regulations and Policies	RDBs also score higher due to its maturity. Many projects for BC still in development (Crosby et al., 2016).
Reliability	Availability	RDBs prioritise Availability and Consistency over Partition Tolerance (CAP theorem). BC is distributed; slightly sacrifices Availability and Consistency (Weber et al., 2017).
	Robustness	BC much more robust due to decentralisation, consensus mechanism and immutability (Galanis and Habermacher, 2019).
	Consistency	RDBs prioritise Availability and Consistency over Partition Tolerance (CAP theorem). BC has eventual (delayed) consistency (Jatana et al., 2012).
	Maturity	RDBs are much older than BCs and much more mature, mostly due to its age (Austerberry, 2006).
Functionality	Suitability	BC has multiple use cases and properties sought after in supply chains. RDBs better for structured data in high-trust environments (Cole, Stevenson, and Aitken, 2019; Jatana et al., 2012).
	Manageability	RDBs much easier to manage and control due to centralisation; good for owners, regulations, but not for security in trustless environment (Rauchs et al., 2018).

TABLE 7.21: *The unweighted super matrix from the ANP*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Block-chains	Relational Databases	Scala-bility	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immuta-bility	Investment Cost	Transaction Cost	Cost Efficiency	Standard-isation	Regulations and Policies	Avail-ability	Robust-ness	Consist-ency	Maturity	Suita-bility	Manage-ability
Alterna-tives	Blockchains	0	0	0.3333	0.25	0.33333	0.83333	0.75	0.8	0.85714	0.875	0.59906	0.2	0.83333	0.16667	0.2	0.25	0.85714	0.2	0.11111	0.8	0.125
	Relational Databases	0	0	0.6667	0.75	0.66667	0.16667	0.25	0.2	0.14286	0.125	0.40094	0.8	0.16667	0.83333	0.8	0.75	0.14286	0.8	0.88889	0.2	0.875
Perfor-mance	Scalability	0.2209	0.44305	0	0.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.25	0
	Transaction Throughput	0.16581	0.2783	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0.8	0	0	0
	Transaction Latency	0.08155	0.18277	0	0.66667	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Time Efficiency	0.53174	0.09588	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0.75	0
Security	Data Integrity	0.06101	0.33781	0.1095	0	0	0.06709	0	0.24931	0.10473	0	0.18338	0	0.09739	0	0	0	0.15706	0	0	0.12355	0
	Privacy	0.11801	0.40651	0	0.12196	0	0.1052	0.16667	0	0.25828	0.2	0.1047	0.16342	0	0	0.09534	0	0	0	0	0.082	0
	Trust	0.2325	0.1605	0.309	0.31962	1	0.4352	0	0.59363	0	0.8	0.48268	0.53961	0.33307	0	0.24986	0	0.59363	0.66667	0	0.25617	0.75
	Immut-ability	0.58848	0.09518	0.5816	0.55842	0	0.39251	0.83333	0.15706	0.63699	0	0.22924	0.29696	0.56954	0	0.65481	0	0.24931	0.33333	0	0.53827	0.25
Cost	Investment Cost	0.27056	0.11722	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Transaction Cost	0.08522	0.61441	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cost Efficiency	0.64422	0.26837	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0
Interope-rability	Standard-isation	0.5	0.8	0	1	0	0.66667	0.75	0	0.25	0	0.66667	0	0.8	0	1	0	0	0	0.5	0.5	0
	Regulations and Policies	0.5	0.2	0	0	0	0.33333	0.25	1	0.75	1	0.33333	0	0.2	1	0	0	0	0	0.5	0.5	1
Relia-bility	Availability	0.17983	0.24972	0.1174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0.25	0
	Robustness	0.59879	0.07551	0.5406	0	1	0.2	0	0	0.66667	0.8	0	0	0	0	0	0.2	0	0.2	0	0.75	1
	Consistency	0.13307	0.24972	0.2535	0	0	0	0	0	0	0.2	0	0	0	0	0	0.8	1	0	0	0	0
	Maturity	0.0883	0.42505	0.0885	0	0	0.8	0	0	0.33333	0	1	1	1	1	1	0	0	0	0	0	0
Functio-nality	Suitability	0.75	0.16667	0	0	0	1	0	0.33333	0.75	0.75	0	0	0.75	1	0	1	0.75	0.2	1	0	0
	Manage-ability	0.25	0.83333	0	0	0	0	1	0.66667	0.25	0.25	0	0	0.25	0	1	0	0.25	0.8	0	1	0

TABLE 7.22: *The Cluster Matrix*

	Alternatives	Performance	Security	Cost	Interoperability	Reliability	Functionality
Alternatives	0.00000	0.12289	0.15254	0.19383	0.19200	0.12651	0.34688
Performance	0.15270	0.42572	0.09477	0.11254	0.00000	0.08631	0.09167
Security	0.37653	0.18823	0.37929	0.16729	0.11786	0.17447	0.14668
Cost	0.09318	0.00000	0.06620	0.10888	0.00000	0.00000	0.09480
Interoperability	0.07098	0.04381	0.07892	0.25259	0.47985	0.09983	0.06393
Reliability	0.13835	0.14518	0.17915	0.09608	0.06343	0.34522	0.09767
Functionality	0.16825	0.07418	0.04914	0.06879	0.14686	0.16766	0.15838

Weighted Super Matrix and Limit Matrix

Due to its sizes, the weighted and limit super matrices are included in Appendix B in Tables B.29 and B.30 respectively.

When inspecting the weighted super matrix and comparing its values to the unweighted super matrix, one can see that the weights of the clusters influence the priorities. Instead of the priorities of each cluster summing to one, as is the case in the unweighted super matrix, the entire column now sums to one. This allows one to identify the criteria which have the largest influence on other criteria. For example, Transaction Throughput (0.48266) is the criterion that has the largest impact on Scalability out of all the criteria, and Consistency (0.43194) has the largest influence on Availability.

The limit super matrix shows the steady state priorities of criteria. Since the weighted super matrix is stochastic (all columns sum to one), the limit converges, and therefore raising the matrix to powers results in the columns of the limit super matrix being identical (Saaty and Vargas, 2013). The priorities of interest here are those of Blockchains (0.09291) and Relational Databases (0.09066).

ANP Results

The raw synthesised results were obtained from the first two rows of the first column of the limit super matrix. This was normalised and the ideal values were calculated and are shown in Table 7.23. The synthesised results show that the preferred alternative is Blockchains (0.506144) over Relational Databases (0.493856) with a tight margin. When looking at the distribution of priorities in Figure 7.18, one can see that it nearly cancels out between the two alternatives. When incorporating the importance of the clusters, as shown in Figure 7.19, it starts to make more sense why Blockchains have a narrow victory over Relational Databases.

TABLE 7.23: *Synthesised results of the ANP*

	Ideals	Normals	Raw
Blockchain	1	0.506144	0.092911
Relational Database	0.975723	0.493856	0.090656

Blockchains scored strongly for criteria in the Security cluster, which was previously determined as the most important cluster, while Relational Databases scored better in the Functionality and Performance clusters, which are the second and third most important clusters respectively. In conclusion,

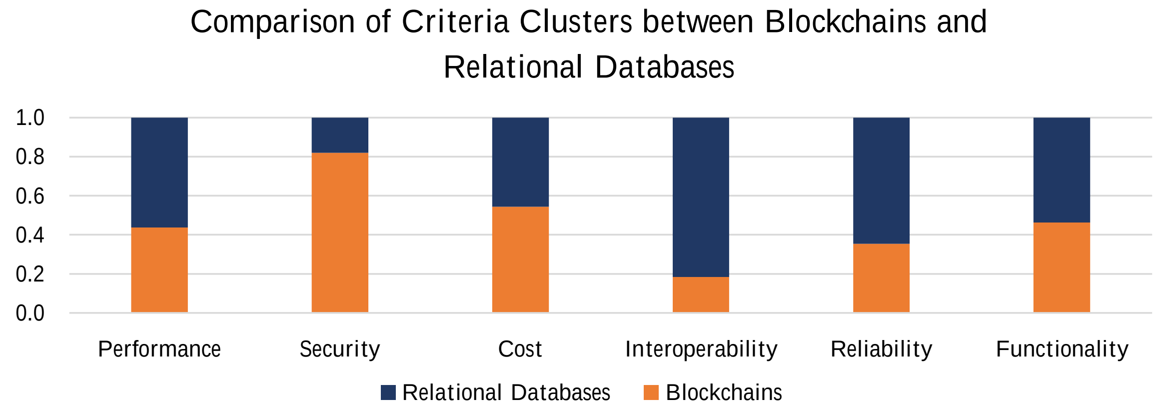


FIGURE 7.18: *Raw priorities of clusters from the unweighted super matrix with regards to the alternatives*

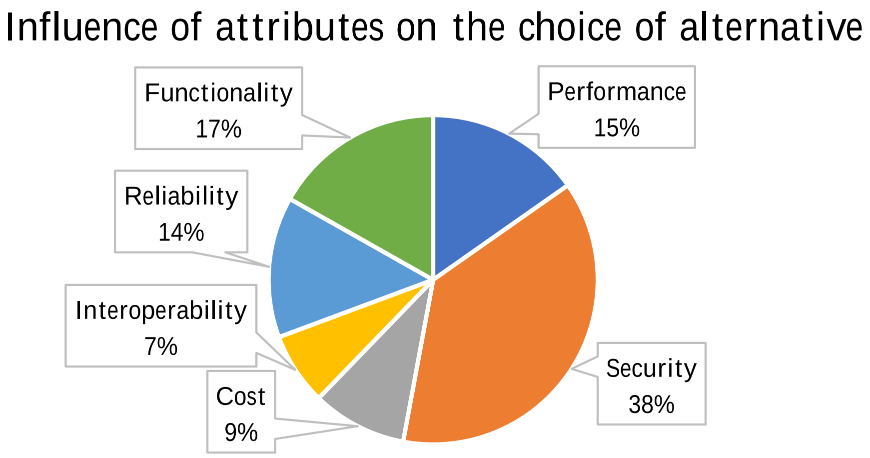


FIGURE 7.19: *Relative importance of the clusters with regards to the analysis from the cluster matrix*

Blockchains scored much higher in the most important cluster, while Relational Databases scored much better in the least important cluster.

7.3 Preliminary Recommendation

Combined findings from the literature review, case study, and analysis indicate that a suitable solution for document sharing in the global trade environment has the following characteristics:

- It is a blockchain-based solution that is built on a consortium blockchain.
- The solution is in the form of a SaaS that was specifically designed for the global trade environment.
- It is feasible for all stakeholders, regardless of their size or trade volumes.

Some considerations that must be taken into account:

- The solution will only be successful if all relevant stakeholders both accept the solution and actually use it.

- The unique benefits of blockchain must be explained to stakeholders to show how such radically different technology can be so beneficial.
- The front-end interface must be designed to be similar to existing systems to make the switch to a blockchain based system easier for its users.

7.4 Chapter Summary

This chapter presented the analysis on the applicability of a blockchain-based solution for the sharing of documents in the global trade environment. Firstly, the financial costs and benefits of the two models that were developed were compared in detail. Secondly, the solutions were analysed from a non-financial perspective. The chapter concluded with a preliminary recommendation based on the research thus far. Chapter 8 discusses the validation of the analysis by industry experts.

CHAPTER 8

Validation

This chapter discusses the process of validating the analysis in this research by requesting feedback from industry experts. It starts off with a discussion of the purpose of the validation, followed by a description of the validation procedure, the feedback from each expert, and a general discussion of the feedback. The chapter concludes with a discussion of how the advice from the experts were applied and the consequential changes that followed.

As part of the analysis validation, feedback from industry experts were requested. The validation focussed on the non-financial analysis, since the financial analysis is based on objective quantitative data and, despite its length in this thesis, makes up a relatively small part of the analysis when comparing it to the significance of the non-financial analysis. The latter also makes use of qualitative data that is more subjective, and therefore requires validation. The three experts that validated the analysis include the COO of a global fresh fruit exporter with knowledge of global supply chains (Expert 1), a regional head of TradeLens with knowledge of blockchains and global supply chains (Expert 2), and a channel specialist at a major corporate bank in South Africa with experience in blockchains and information systems (Expert 3).

8.1 Validation Purpose

The purpose of the validation was to test the completeness, accuracy and applicability of the main components of the analysis, i.e. the utility tree, clusters of criteria, and the criteria itself. The validators were asked to provide feedback on the following:

- Utility tree
  - Choice of clusters
  - Choice of specific criteria
  - Whether the selected criteria are grouped into the right clusters
- Cluster comparison
  - Priority of the clusters with regards to the alternatives
- Criteria comparison
  - Ratios of the various criteria between the two alternatives

8.2 Validation Procedure

The industry experts who agreed to the validation were contacted by email and provided with a refresher of what the research is about, as well as a description of each part of the validation document. Feedback was flexible and the validators were given the options to either provide feedback on the document itself, or through a verbal discussion.

8.2.1 Utility tree and description of criteria

The first part presented the validator with the utility tree in Figure 7.17 in Chapter 7. Each of the leaves (criteria) were described to provide the validator with context as to what the criterion represents, how it is measured and certain aspects that influence it. The goal of this part was to provide the validator with context of the analysis and the criteria that were compared.

8.2.2 Cluster comparison

The second part presented the validator with the cluster matrix in Table 7.22, the graph in Figure 7.19, and descriptions of how the matrix works, what the values mean, and the relevance of the graph. The goal of this part was to show the role that the clusters of criteria played in the analysis and to make the validator aware that the clusters themselves had an influence on the outcome.

8.2.3 Criteria comparison

The third part contained an extract of the unweighted super matrix that describes how the two alternative solutions compared among the different criteria, along with a graph to visualise the numbers and make it easier to see which solution performed better for each criterion. It also contained descriptions of the logic behind each pairwise comparison of the two solutions regarding each criterion. The purpose of this part was to provide the validator with context as to how the priorities in the unweighted super matrix were determined.

8.3 Validation Results

This section discusses the feedback obtained from the industry experts and follows the same structure as the document the validators received.

8.3.1 Utility tree and description of criteria

The utility tree is a good way of visualising the criteria used in the analysis. The validators were satisfied with the utility tree and provided little to no critique that required a change to be made in the design. In general, they agreed with the descriptions provided for each of the criteria in the context of cross-border supply chains.

Expert 1 was satisfied with the structure of the utility tree, i.e. the clusters and their criteria. They also made a comment that the selection of criteria covers a wide spectrum and addresses the relevant aspects required in a global supply chain.

Expert 2 commented that the utility tree is a good building block for the analysis. They agreed with the chosen clusters and criteria.

Expert 3 agreed with the structure of the utility, but did mention that they feel the Privacy criterion does not quite belong in the Security cluster, nor does the Regulations and Policies criterion quite belong in the Interoperability cluster. However, given the clusters used in the analysis, these two criteria are in the most applicable clusters according to the expert, since it would not make sense to put them in their own clusters.

8.3.2 Cluster comparison

The ANP was briefly explained to them to provide clarity as to what the values in the cluster matrix mean, i.e. that one cluster has an influence on the other and that the values in a certain column sum to one. No experts had strong objections against the priorities of clusters, although they did provide suggestions for where the priorities might need to be adjusted.

Expert 1 was satisfied with the priorities of clusters with respect to the alternatives and mentioned that they seem in line with what they know. They agreed that Security is the most important cluster, but questioned whether it was *that* much more important than the other clusters – it had a priority of 0.37653 compared to the second most important cluster, Functionality, with a priority of 0.16825. They also pointed out that the cost of a solution usually plays quite a big role in the selection. Furthermore, they said that Reliability should have a higher priority, as the reliability of a solution is quite vital. Finally, they were surprised with how important Functionality was and recommended that its importance be reduced. They explained that the full functionality of a solution is rarely used – it is the core functionality that matters to users.

Expert 2 said that Interoperability should be more important because the solution should be able to integrate with existing systems in supply chains. They mentioned that it was not necessarily more important than the other clusters, but roughly equally important. They noticed the importance of Security and agreed that it is by far the most important cluster of criteria, while Functionality was not as important as shown there.

Expert 3 expected Interoperability to be more important due to the importance of regulations and policies in the global trade environment, which is one of the criteria under Interoperability. They were slightly confused by the priorities of clusters with respect to themselves, e.g. Performance with respect to Performance. After explaining that criteria in a cluster can influence the other criteria in the same cluster, they had a better understanding of the fact that a cluster can influence itself.

8.3.3 Criteria comparison

Expert 1 agreed with the ratios between alternatives when looking at each criterion that was presented to them, as well as the discussions about the logic behind the pairwise comparisons with respect to the alternatives. However, they did feel that blockchain should have a better score for standardisation than it had. They noted how the importance of the clusters influence the outcome by pointing out how the importance of the Security cluster ensures that blockchain scores higher overall, despite relational databases performing better in more clusters.

Expert 2 had no issues with the criteria comparisons. They agreed with the ratios between the two solutions and specifically agreed that the standardisation of relational databases gives it an advantage over blockchain in that regard.

Expert 3 emphasised that blockchains are immutable and insisted that the score of blockchain's immutability should be increased. They also expected that the investment cost of blockchain would be higher (thus a lower score), but after explaining that the type of solution the analysis looks at is a SaaS where investment costs are likely to be much lower, they agreed that the current score makes sense. Furthermore, they recommended raising the score for both blockchain's availability (due to the decentralisation) and consistency (due to the consensus protocol).

8.4 Discussion of Feedback

In general, the feedback was overwhelmingly positive, with only minor suggested improvements. There were no aspects that the experts completely disagreed with, e.g. that the score between alternatives for a certain criterion must be swapped. The most common critique is that the score or importance of a criterion or cluster needs to be adapted. The feedback is summarised as follows:

Performance. All experts agreed with the ratings of criteria, as well as the importance of the cluster.

Security. All experts agreed that the Security cluster is the most important one, but Expert 1 and 2 suggested lowering the importance. Expert 3 said that Blockchain's score for Immutability should be even higher.

Cost. Expert 1 felt the importance of the cluster should be increased, while the other two were satisfied by its importance. All experts agreed with the scores of criteria between the alternatives.

Interoperability. Experts 2 and 3 said that the importance of the cluster needed to be increased. Expert 1 suggested increasing Blockchain's score for Standardisation, while the other two were satisfied.

Reliability. Expert 1 suggested that the importance of the cluster should be increased. Expert 3 said they would increase the score of Blockchain's availability and consistency.

Functionality. Expert 1 and 2 would decrease the importance of functionality. All experts agreed on the scores between alternatives.

The three experts from different backgrounds and industries helped to provide feedback covering a wide perspective. While there were some overlap, the specific feedback each expert provided showed what aspects are important to them as an expert in their respective areas.

8.5 Application of Feedback from Experts

This section discusses the application of the feedback from experts and the consequent changes in the analysis.

8.5.1 Super matrices

Changes to the pairwise comparisons between alternatives with respect to the various criteria were made based on the feedback. Table 8.1 shows the changes in the outcome of the pairwise comparisons. These new values can be found in the first two rows of the new unweighted super matrix, which is shown in Appendix B in Table B.31. Since the initial priorities as well as the cluster influences were adapted, the weighted and limit super matrices were also affected. These are shown in Appendix B in Tables B.33 and B.34.

TABLE 8.1: *Changes in scores of criteria based on expert feedback.*

	Original		**Adapted**	
	Blockchains	**Relational Databases**	**Blockchains**	**Relational Databases**
Immutability	0.875	0.125	0.9	0.1
Standardisation	0.16667	0.83333	0.25	0.75
Availability	0.25	0.75	0.4	0.6
Consistency	0.2	0.8	0.4	0.6

8.5.2 Cluster matrix

Similar to above, changes to the pairwise comparisons between alternatives with respect to the various clusters were made. Table 8.2 shows the new priorities of the clusters with respect to the choice of alternative. These new values can be found in the first column of the new cluster matrix, which is shown in Appendix B in Table B.32.

TABLE 8.2: *Changes in priorities of clusters based on expert feedback.*

	Original	**Adapted**
Security	0.37653	0.266997
Cost	0.09318	0.154552
Reliability	0.13835	0.181734
Functionality	0.16825	0.073509

8.5.3 Synthesised results

The updated results due to feedback are shown and compared to the initial results in Table 8.3. When looking at the Normals column, the score of blockchain only increased by about 0.007 points, or 0.7%.

TABLE 8.3: *Changes in synthesized results based on expert feedback.*

	Original			**Adapted**		
	Ideals	Normals	Raw	Ideals	Normals	Raw
Blockchain	1	0.506144	0.092911	1	0.512898	0.093163
Relational Database	0.975723	0.493856	0.090656	0.949707	0.487102	0.088478

8.6 Chapter Summary

This chapter presented the validation of the analysis on the applicability of a blockchain-based solution for the sharing of documents in the global trade environment. Firstly, the procedure that was followed for the validation was described. Secondly, the feedback from each expert was discussed. Thirdly, the feedback in general was summarised. The chapter concluded with a discussion of the changes made based on the feedback from experts and how it affects the outcome of the analysis. Chapter 9 discusses the findings from the literature review, case study, analysis and validation.

CHAPTER 9

Discussion and Findings

This chapter discusses key findings from the literature review, case study, analysis and validation. Section 9.1 looks at global supply chains in general by addressing the findings from literature and the analysis. Section 9.2 narrows the discussion down to the case company and refers to data collected during interviews. A critical discussion of the research is held in Section 9.3. A final recommendation based on the literature, case study, analysis and the validation is made in Section 9.4.

9.1 Key Findings from the Literature and Analysis

This section discusses findings from the literature and the analysis. The viewpoint includes the global trade environment and makes conclusions that are generally applicable to this environment. The key findings are as follows:

- There exist blockchain solutions specifically for managing documents in cross-border trade (answers RQ 4).
- A solution that is designed for the global trade environment can help reduce complexity when compared to a more generic solution that must integrate different products and services.
- Blockchain solutions seem to cater more closely to the requirements of document sharing in global trade: immutable information that makes verification quicker; more decentralised to ensure parties have similar levels of control; more reliable and less chances of failing completely (no single point of failure); and lower need for trust in parties that do not trust/know one another very well (answers RQ5).
- Labour is a massive cost driver and is highly influenced by the length of the project's phases, as well as the time that employees must dedicate to the project. Reducing labour costs may thus be the best way to reduce the costs of the solutions.
- The main benefit of the two solutions is in reducing existing costs by increasing efficiencies.
- PaaS solutions require more upfront investment and effort than SaaS, but its usage costs (price for using the platform) are lower in general.
- The increase in efficiency and reduction in inaccurate information brought by blockchain is larger than for a relational database solution, so cost savings are larger.
- Deciding between a blockchain and relational database solution is more difficult for smaller trade volumes than for larger trade volumes. Blockchain is the less expensive solution in all scenarios considered in the analysis, but this is more evident for larger volumes.

The observations made above are used to make a brief conclusion on the applicability of a blockchain solution for sharing trade documents between stakeholders in a global supply chain. Firstly, a blockchain solution is better suited for document sharing in global trade than a relational database solution. This is mostly due to the security it provides in terms of immutable data, which allows information to be trustworthy without the need for intensive time-consuming verification processes further downstream.

A second point is that blockchain solutions lead to larger cost savings than more conventional solutions for various trade volumes. The analysis showed how much the improved efficiency influences the cost savings between solutions. Because of its automated verification of the authenticity on information, blockchain is able to greatly reduce the number of conflicting documents, which leads to various different cost savings, as shown in the analysis.

Thirdly, there are more relational database solutions available than blockchain solutions and they usually have lower usage costs (fees for using the platform). This is due to its maturity, but it also means that selecting and finding a specific relational database solution is more challenging. The well-known solutions are usually more generic to make it applicable to various industries for different applications. This can be useful in most cases, but revolving a solution for document sharing in global supply chains around a relational database does not seems like the optimal approach, as shown by the analysis.

A fourth point is that SaaS is a better solution in a complex environment such as cross-border supply chains where many different stakeholders will be using the solution. The reason being that it leaves less effort for stakeholders, since the back-end processes are managed by the service provider. It reduces complexity because stakeholders do not have to work out a governance plan and collaborate to collectively manage the system.

The fifth and final point is that a specific solution such as a SaaS may better address the issues experienced and it usually requires less time, effort and labour to get up and running than a more generic solution such as a PaaS. Specific solutions target a certain problem and is designed to be compatible in that environment. Ideally, the solution can be adapted to solve other problems that the user may have. For example, TradeLens was initially designed to track the whereabouts of shipping containers, but its functionality has since been expanded to include document sharing between stakeholders. SaaS is usually a more complete package than PaaS, so if its purpose matches the user's need, getting it fully functional will be much quicker than a PaaS where the solution must first be "assembled", so to speak.

9.2 Key Observations From the Case Company

This section discusses findings from the interviews with an employee from the case company (Anonymous, 2021a). It also discusses the implications of the outcome of the analysis on the case study. While many of these findings are also applicable to the general cross-border trade environment, the ones described here are in the context of the fresh fruit industry. The key findings are as follows:

- The fresh fruit industry is a highly complex environment with many different stakeholders, information flows and regulations.
- There are many vital documents that are handled by multiple stakeholders in different locations on which various processes depend (answers RQ 1).
- The specific information flows and stakeholders may differ greatly depending on the type of product that is traded.
- Processes are highly manual: communication, document sharing, data capturing, validation and verification. This means that such processes are usually slow and that there are lots of room for

human error (answers RQ 2).

- Various disjoint products, services and systems are used to handle documents. There is currently no solution that integrates most of the document-management processes (answers RQ 3).
- High levels of complexity exist due to different regulations depending on what countries/regions and what products are involved.

The models that were examined in the analysis can help the case company in various ways. Firstly, many of the problems related to slow and inaccurate information flows can be solved by automation. This is because fewer processes would need human input to continue, which not only speeds up the processes, but also eliminates the possibility of human errors. The solutions would thus address this issue, as they will digitise and automate the flow of vital documents and information to some degree.

Secondly, the solutions will integrate document-sharing processes by providing a single platform for the documents to be shared on. The digital nature will allow stakeholders to be integrated because the platform and its content will be available to them, regardless of their geographical location. Something that will help with integration is interoperability. The platform will require information flows to be standardised, which reduces complexity and will play a large role in integrating the solution with existing systems due to the standardisation.

Thirdly, immutability and the ability of blockchain to ensure that data is accurate, i.e. has not been changed since it was uploaded to the blockchain, can be vital. This eliminates the need for the strict downstream validation and verification processes that take so much time which may eventually lead to a shift in the industry where these processes are not required any more.

Fourthly, there will be regulatory issues for any solution. The regulations in such an environment are plenty and strict. Any new solution would need to conform to these regulations, or provide a concrete case why it should be exempt from these regulations. An example is how blockchain can theoretically entirely remove the need for independent validation and verification processes. Understandably, concrete evidence of the blockchain solution's immutability would be required before authorities and other stakeholders would even consider removing these processes.

The analysis, along with information obtained from the interviews indicate that the supply chain in the case study would benefit more from a blockchain-based solution such as the one examined in this research, than for one based on a relational database. The impact that a blockchain solution can have on the supply chain in the case study is shown in Figure A.2, where certain flows will be more efficient. According to information obtained from the employee of the case company (Anonymous, 2021a), costs related to the phyto, certificate of origin and the PPECB inspections add up to a minimum of $140 per shipment. This makes up a small portion of the total cost that can be saved per shipment.

9.3 Critical Discussion of the Analysis

As is shown with both conceptual models, neither a relational database, nor a blockchain is the perfect technology for *storing* documents. However, a system that mainly runs on these technologies, with additional document storage databases, as is the case with both models, can work well while also providing the benefits inherent to the respective technologies. It might be possible to use such a system without dedicated file storage in the future if the industry is able to completely move away from unstructured documents (such as pdf files) to structured files (such as those in the JSON format) that can be recorded directly on the main database. The actual profitability and feasibility of the solution will vary greatly depending on the product or service that is used, but this analysis shows that there is great potential for these two conceptual models to be successful, especially for a blockchain solution.

This research analysed the alternative solutions with a focus on two different aspects: financial and non-financial. This section provides a critical reflection on the analysis presented in this chapter by looking at it from various different perspectives that are important in cross-border supply chains. These perspectives include (Compigneaux et al., 2020):

1. *Economic*: how various supply chain costs are affected by the solution.
2. *Trade*: the effect on trade processes and diversity of international trade.
3. *Social*: the influence on stakeholders of different sizes, backgrounds and geographical locations.
4. *Technical*: the maturity of the technology, its practicality, and how it functions.
5. *Data protection, privacy and security*: how data is protected from unauthorised access and how sensitive data is kept private.
6. *Transparency*: the degree to which relevant, trustworthy information is accessible by users in a timely fashion.
7. *Environmental*: the impact on the environment, including power consumption and emissions.

The analysis aimed to look at the solutions in detail, yet be generic enough to be widely applicable to various different supply chain environments, regions, and firms. Finding the right level of detail can be challenging and maintaining an adequate level of accuracy becomes harder when assumptions need to be made, as was the case in this analysis. For example, the scope of the analysis excludes the option for a firm to develop its own solution. Therefore, this analysis may not be applicable to supply chains that require tailored solutions, or those stakeholders that want to develop their own solutions.

With regards to accuracy, various assumptions had to be made due to constraints and because of the goal to make the research generally applicable to a wide variety of supply chains. Therefore the accuracy of quantitative data may be impacted. Regardless of these limitations, the analysis still provides stakeholders with valuable insights to solutions for document sharing in global supply chains and will be a significant starting point for future research.

A combination of literature and interaction with industry experts were used as data collection tools, although most of the data was obtained through literature, while the industry experts were mostly used to confirm the validity of what was learnt from the literature. On the one hand, greater input from industry experts may help with accuracy of the data, but on the other hand, may make the data more biased towards a certain type of supply chain or stakeholder.

In terms of generalisation, both models used for the analysis are based on well-known and widely used services, so the analysis would be applicable to a large number of stakeholders. TradeLens is a well-known blockchain solution built on Hyperledger Fabric, a blockchain platform that is widely used in many applications in supply chains. Using a different blockchain-based model will likely not lead to vastly different results, as other comparable solutions are likely to also use consortium blockchains that have a great chance of being built on Hyperledger Fabric, due to its popularity. Where this is not the case, differences are to be expected. Compared to more mature relational databases, blockchain solutions may have larger differences, so increasing the number of blockchain solutions in the analysis would increase its significance.

Amazon RDS for MySQL uses the widely standardised MySQL. AWS is also widely used for various web applications. Although other cloud-based relational database services exist, they are not likely to be much different due to the high maturity of these services. Nevertheless, including more solutions in the analysis would make it more representative of the diverse selection of solutions that are used in global supply chains.

9.3.1 Economic perspective

The financial analysis showed that both solutions based on relational databases and blockchains lead to collective financial gains for supply chain stakeholders. A large reason is the digitalisation and automation associated with these solutions, as it will allow information to be digitised, the associated flows to be automated and various time-consuming processes to be eliminated, resulting in vastly improved efficiencies. This is echoed in the literature where the effects of digitalisation have been thoroughly examined.

While digitalisation may play a large role in financial gains, there might be some barriers that must be overcome. A prerequisite for the digitisation of information is that the supply chain must be far enough in its digital transformation to support this, which is problematic in developing areas of the world. Therefore, additional infrastructure, and thus additional costs may be required to get to this point. This includes, but is not limited to computers with internet access, internet infrastructure with adequate bandwidth, and technically competent personnel. The analysis did not account for the fact that stakeholders may be in different stages of their digital journey.

With the blockchain solution there is inherent trust in the data on the platform due to its immutability, which will further accelerate verification and other processes that rely heavily on accurate information. This is much harder for relational databases to achieve, which explains the difference in efficiencies examined in the analysis. The difference in maturity explains various financial aspects. Since relational databases are much more mature than blockchains, various factors such as competition and years of development enable service providers to charge lower prices when compared to blockchain solutions, which is one aspect that explains the lower cost per transaction. However, since relational database solutions tend to be more generic than blockchain solutions, their initial costs are higher due to the time required to adapt it to the supply chain environment.

By simplifying the cost drivers into only two criteria, the non-financial analysis did not fully capture the financial benefit that a blockchain solution has over a relational database solution, which means the priorities of the cost criteria may not have been adequately reflected in the non-financial analysis.

9.3.2 Trade perspective

International trade spans different legal systems, cultures and languages, technical standards and norms, and tax systems, which presents challenges in ensuring standardised data and processes that are supported by all the users. Therefore, any new digital solution that changes the status quo will face barriers. Comparatively, though, relational databases are more mature and already adhere to various standards and regulations, which gives it the benefit over blockchains in this regard. The literature confirms the difference in standards and regulations between the two solutions, which supports the findings of the analysis. One point of criticism in this regard is that the *Standardisation* and *Regulations and Policies* criteria in the ANP did not go into much depth, but rather covered a range of related sub-criteria, so the true ratio between the solutions may differ from the analysis, even if it is only slightly.

The automation and digitisation of information flows that these models enable would greatly facilitate global trade by making processes more efficient and reliable. Furthermore, the burden of proving compliance in the form of documents may be reduced if the integrity of the data can be ensured, thus replacing the need for physical documents and allowing information to be made available to customs authorities much earlier in the trade cycle due to its digital nature. The analysis addressed this through the efficiencies and certain security aspects that it examined, such as data integrity, trust and immutability.

The analysis confirmed what the literature says about blockchain's security and reliability, and certain efficiencies that can be realised because of its data integrity and immutability. It showed that blockchains perform better than relational databases from this perspective. What can be improved though, is finding more concrete indicators to represent these criteria. For example, calculating the number of hours that can be saved due to improved time efficiencies will make the pairwise comparisons much easier and create more certainty. This can be seen with the cost efficiencies in the ANP where exact figures are used.

9.3.3 Social perspective

Both solutions require a certain level of digitalisation in supply chains to work effectively. Therefore, it may disproportionately benefit the wealthier, more digitised parts in developed countries of the supply chain, while potentially negatively affecting poorer, less digitised parts in developing countries that do not necessarily have adequate resources or infrastructure. Both solutions are cloud-based, so the minimum requirement for using them is an internet-connected device (computer or mobile) with an internet browser, which does lower the barriers of entry.

The points made above were not addressed by the analysis for the following reason. The literature and interviews with industry experts revealed the most vital documents in cross-border trade, along with the key stakeholders. These documents, i.e. the bill of lading, export certificate, phytosanitary certificate and customs documents, originate and are shared among stakeholders further downstream in the supply chain, where higher levels of digitisation are present when compared to upstream areas. Therefore, at least all the parties relevant to the document-sharing process (e.g. pack houses, exporters, freight forwarders, shipping lines, customs authorities, etc.) are expected to have internet-connected devices capable of accessing the respective platforms (Anonymous, 2021a).

Another social aspect where some stakeholders disproportionately enjoy more benefits than others has to do with the level of integration, which depends on the stakeholders' technological readiness (Compigneaux et al., 2020). Both solutions have web-based user interfaces, as well as the ability to completely integrate with the systems of stakeholders. The former requires basic technical knowledge and minimal training, while the latter requires more advanced technical knowledge from IT professionals. The level of integration and automation differs vastly between the two ways of accessing the platforms, which influences the amount of time and costs that are saved, thus providing more benefits for larger stakeholders with higher levels of digitalisation who are able to fully integrate their systems with the platform. This was not addressed in the analysis, since it examined the difference between the two solutions, not between existing conventional and new digital solutions.

9.3.4 Technical perspective

Maturity of a technology plays a massive role when considering its adoption. Relational database-technology has been around since the 1970s (Karaarslan and Konacaklı, 2020), during which it has matured significantly. Now, in the 2020s, it is a tried and tested technology, of which all the benefits, applications and limitations are known. Its maturity also means that there are many different offerings by various service providers. Blockchain is still on the long road to maturing, since it was only created in 2008 (Nakamoto, 2008) and only started gaining momentum in 2013 when Ethereum was created (Ganne, 2018). Current solutions cater for specific scenarios, as seen with TradeLens, one of the more mature blockchain solutions in cross-border trade. Maturity and its wide range of influences on the various criteria were adequately addressed by the analysis through the mapping of relationships between the criteria.

The practicality of the alternative solutions is also worth considering. More generic relational databases are ideal for storing data, information and documents that have structured formats. Unfortunately, due to its generic design for applicability to more applications, they are not specifically geared towards document-sharing in cross-border environments. Thankfully, additional services can be used to make this solution more practical, but this requires more work and incurs additional costs to implement. A blockchain solution is ideal for secure, transparent storing and transmission of information. Furthermore, blockchain products are currently mostly dedicated solutions, in this case made for the supply chain environment where it specialises in improving visibility and facilitating information-sharing. Therefore, it is a tailored out-of-the-box solution that requires no additional services to perform its desired function. This aspect was addressed by the analysis, mostly through the Functionality criteria.

Speed and scalability are also important technical measures to take into account. Centralised databases are known for being fast, flexible, scalable and efficient. Coupled with cloud computing, the relational database has even better performance, because all computations are performed on dedicated infrastructure that is easily scalable. This type of solution does not require users to have high-end equipment, which lowers the technological barriers faced by smaller participants with lower levels of digitalisation. The same is true for the blockchain solution in terms of dedicated infrastructure. This benefits the platform by making it more scalable in terms of available resources. However, since relational databases do not require consensus mechanisms, their scalability is likely to continue beating that of blockchain. The analysis examined this aspect through the Performance and Reliability clusters of criteria.

9.3.5 Data protection, privacy and security perspective

A vital aspect of any database service is securing data against unauthorised access and manipulation from third parties, and controlling authorised access by limiting the extent thereof. Both solutions offer comprehensive permission management and various encryption options, as described in their respective sections in Chapter 6.

The processing of sensitive data is a topic that frequently arises when discussing databases – especially in cross-border environments that span different jurisdictions and are subject to multiple data protection and privacy laws. One such law is the Regulation (EU) 2016/679 (General Data Protection Regulation), also known as the GDPR, which governs the use of personal data of European Union (EU) citizens outside the EU and European Economic Areas (Compigneaux et al., 2020). Trade documents shared in the supply chain contain information that is not anonymised, such as names, contact details, signatures, etc., and can be used to personally identify individuals, even if it is encrypted, which means that this data is subject to data protection rules and regulations.

The right to be forgotten is one implication of some privacy laws that refers to an individual's right to have their private information removed from a database. Since relational databases are centralised, their data are most likely not immutable, so any data can be altered if required. They do, however, have limited ability to keep track of these changes when compared to blockchain solutions, which makes it more vulnerable to fraud. This was reflected in the analysis when looking at the Security criteria and the Regulations and Policies criterion.

TradeLens shows that blockchain solutions can be GDPR compliant (Biazetti, 2019a). This is because no sensitive data (including personal information) is stored on the blockchain itself. On-chain storage is reserved for document hashes, document actions and metadata, and internal object references (TradeLens, 2021c). Off-chain storage in relational-, object- and document-databases are used for the remaining data that must be stored, including the trade documents and sensitive information (TradeLens, 2021f). Data in these off-chain databases are not immutable and can therefore be altered if legally required, which allows personal data to be anonymised. A benefit is the built-in audit trail of blockchain which will record evidence of these changes, as the hash values corresponding to the information will change.

9.3.6 Transparency perspective

"Transparency" is a keyword that arises in nearly every supply chain environment discussion because it is such a sought-after feature. Both solutions integrate all the parties in global supply chains by providing a single and secure platform to share and receive documents and other trade-related information. This makes the information easy to access and available to all relevant stakeholders in real-time, which positively affects transparency. What gives blockchain the edge over relational databases is the built-in audit trail where the transaction history is recorded and the public addresses of participants are linked to their activities. This is not an inherent feature of relational databases and must be added after the fact. The analysis accounted for this through the Trust and Immutability criteria.

End-to-end transparency can only be achieved if all the relevant stakeholders in the various parts of the supply chain are participants on the platform that contribute the required data (Compigneaux et al., 2020), which can be challenging in such a complex environment. This applies to both solutions. Where the analysis can improve, is by having a criterion dedicated to transparency, since it is so important in supply chains.

The level of transparency for both solutions can be influenced to a certain extent by administrators, who can choose to restrict access to such information if they wish. High levels of transparency are thus possible, although the administrators can easily limit transparency, which may not be favourable towards participants. On the one hand, the digitalisation and automation brought by modern relational database solutions is certainly a step towards higher levels of transparency. On the other hand, the centralised architecture of relational databases where control is shared among a select few parties can severely limit the increase in transparency in the global supply chain.

With blockchain, the transaction history, ownership history, and editing history are available to all participants and auditing this information is easy, because it can be trusted due to its immutable blockchain nature. Any changes to the database are automatically recorded to the blockchain, so uploading and downloading documents, transferring ownership of documents, updating documents, etc. all form part of the audit trail. This information is available to all the relevant stakeholders by default without the need for additional services or tools, thus already having an advantage over non-blockchain solutions. The trade-off between manageability and immutability in the solutions was addressed by the analysis through the similarly named criteria.

9.3.7 Environmental perspective

The environmental impact of industry solutions is an aspect of increasing importance as the effects of accelerating climate change on the world continue to grow ever-more prevalent. Since this model entails the digitisation of physical documentation, various processes will be more efficient and less time-consuming. For example, waiting times for customs clearance will be shortened, thus reducing transport-related emissions and the negative environmental impact. Although increased digitisation may lead to more energy consumption to power the necessary infrastructure, if all the physical documents can be digitised, the amount of paper consumed and its consequent impact on the environment is vastly reduced.

A major concern of blockchain is its energy consumption. Although this concern is mostly only applicable to public blockchains that use PoW or other energy-intensive consensus mechanisms (Gatteschi et al., 2018), it is usually part of any blockchain discussion. Thankfully, this problem is not one associated with most blockchain solutions in supply chains, since they tend to be consortium blockchains. These tend to use more efficient consensus mechanisms like the voting-based Raft protocol used in Hyperledger Fabric (Hyperledger, 2020). An extremely secure consensus mechanism like PoW is not required on a consortium or private blockchain, because all users go through an onboarding process and are therefore known, verified and trusted. This means that a simpler, less time- and resource-intensive algorithm can be used (Compigneaux et al., 2020).

The analysis did not take into account the effect that the solutions have on the environment, which is a limitation, given the growing concern of the massive impact that global trade has on the environment. A cluster of sustainability criteria could provide another important perspective for the analysis.

The input from industry experts provided greater insight into the importance of certain aspects that are relevant to document-sharing systems in supply chains, as well as how certain aspects differ between blockchains and relational databases. The outcome as to which solution to use did not change, which indicates that the analysis covered the relevant aspects, used good logic and had a relatively accurate outcome.

9.4 Final Recommendation

A blockchain-based solution is preferred for a digital document-sharing system in global supply chains. The picture painted of blockchain in literature creates the sense that blockchain is a revolutionary technology that provides clear benefits over existing solutions. While this may be true in many cases and certainly in the future when the technology is more mature, the analysis showed that, currently, blockchain is only a slightly better solution than relational databases for document sharing in cross-border supply chains. Blockchains may have excellent security, which is a necessity in cross-border supply chains, but the excellent security comes at the cost of performance, certain aspects of reliability and manageability. Blockchain's low level of maturity is another major aspect that currently holds it back. Maturity influences many of the criteria used in the analysis, which negatively impacts blockchain's utility.

It is clear, both from the analysis and what is said in literature, that effort must be exerted to help blockchain mature by developing industry standards and ensuring regulations and policies account for the novelty of blockchain. Further development and research will help reduce the above-mentioned trade-offs and will also help blockchain grow more mature. Its potential is massive, but in order to come close to reaching its full potential and live up to its hype, various obstacles must first be overcome. Blockchain has more potential for growth than relational databases, which makes it a solution worth pursuing.

9.5 Chapter Summary

This chapter contained a discussion of the key findings of the research. It started by focussing on the literature study and analysis, then looked specifically at the case study. Next, a critical discussion of the analysis addressed its strong and weak points by looking at it from various perspectives. The chapter concluded with a final recommendation as to what type of solution is the better option in global supply chains. Chapter 10 wraps up the research by providing a summary of the thesis, an appraisal of the research contributions, a discussion of the limitations, and recommendations for future work on the topic of blockchains in supply chains.

CHAPTER 10

Summary, Conclusion and Recommendations for Future Studies

This chapter reflects on the research discussed in this thesis. It starts off with a summary of the thesis, followed by an appraisal of the contributions that this thesis made, limitations of the study, and finally, suggestions for future work.

10.1 Thesis Summary

This thesis presents the research that aims to fill the gap in current research regarding business cases for blockchain solutions in supply chains – specifically solutions that facilitate the flow of trade documents and related information flows in global supply chains.

Chapter 1 introduced the research. It provided background and the rationale to the research and was followed by an initial review of the literature. Next, the research problem statement and derived research questions were presented, followed by the related research objectives. The research contribution, research design and research methodology were then discussed, along with the scope of the research and the ethical considerations. The last section provided an outline of the thesis.

Chapter 2 presented the first part of the literature review. It focussed on two main topics: the fourth industrial revolution and cross-border supply chains. Chapter 3 covered three topics: the digitalisation of supply chains, blockchain technology, and the application of blockchain in supply chains. Chapter 4 concluded the literature review by discussing databases and current centralised conventional solutions, as well as decentralised alternatives to blockchain.

Chapter 5 presented the case study that was created to collect additional information from an industry perspective. Firstly, it provided background to the case company and their supply chain. Secondly, the critical stakeholders in the supply chain were identified and discussed, followed by the critical trade documents in the third section. Fourthly, the important information flows in the supply chain were mapped to show the complex interactions between stakeholders. Finally, the relevant issues experienced in that supply chain and how it relates to the findings from literature were discussed.

Chapter 6 introduced the conceptual models that were designed and used for analysis in this research. The requirements for these models were identified and discussed in the first section. The second section focussed on the relational database model. It firstly compared various relational databases and then described how one was selected for the model. Secondly, the actual solution on which the model is based was described. The third section focussed on the blockchain solutions. Similar to the previous section, alternative blockchain solutions were compared, the best one was selected, and the model was described.

Chapter 7 presented the analysis in this research. It was split into two parts: the financial and non-financial analysis. The financial analysis looked at costs and benefits of each solutions, and then compared these. The non-financial analysis made use of two scientific methods. The methodology of the two methods were briefly described, followed a by a discussion of how the two models were applied. After the analysis, a preliminary recommendation based on what has been learnt thus far was made.

Chapter 8 described how the analysis in the previous chapter was validated by industry experts. Firstly, the validation procedure was discussed, followed by the feedback from each expert in the second section. The feedback was summarised in the third section and applied to the analysis in the fourth section.

Chapter 9 contains a discussion of the findings in the research. It first discussed key findings from the literature and the analysis from a holistic viewpoint. The second section shifted the focus to the case company and discussed the implications of the solutions on their supply chain. Thirdly, a critical discussion with a focus on the analysis highlighted the strengths and weaknesses of the analysis. The chapter concluded with a final recommendation that includes the feedback from industry experts.

10.2 Appraisal of Thesis Contributions

This research contributes to the knowledge of supply chain digitisation and automation, and its link to the 4IR. More specifically, the main contribution is to blockchain as a way to facilitate digitisation in supply chains with a focus on reducing paper flows, thus not only decreasing the carbon footprint, but also increasing visibility and efficiency. In general, this research sheds light on the importance of automating and further digitalising supply chains during the 4IR, the need for supply chain visibility in dealing with disruptions, and how blockchain can be used to improve supply chain efficiency, security and visibility. Researchers on any of the topics of the 4IR, supply chain digitalisation and automation, blockchain and its role in supply chains, or a combination of these will find this research valuable, although the last two topics may provide greater value, as they are the focus of this research.

Furthermore, it will help those exploring the 4IR or supply chain digitalisation to realise the potential of blockchain to have a positive impact on various industries. Companies that form part of a supply chain that are looking into more effective information systems or are searching for ways to improve visibility within their supply chain will benefit from the business case created by this research. They may be considering implementing blockchain and this study, specifically the business case for blockchain, may help them make an informed decision. The novelty in this research lies in the business case that compares the costs and benefits of blockchain to those of conventional centralised solutions. Finally, blockchain developers and researchers may also find this research useful and use it as an opportunity to work with companies to implement blockchain in their supply chains.

10.3 Limitations of the Research

Some limitations of the research can be identified when reflecting on what was done. The first limitation is the number of stakeholders in the supply chain that were interviewed. Although the case study method was used where the focus is on a single company, interviewing stakeholders in different roles other than the exporter might have provided even more insight into the problems experienced in cross-border supply chains from the perspective of the stakeholders.

Another limitation can be the number of alternatives that were examined. For example, instead of only looking at blockchains and relational databases, it would be more diverse if other DLTs and NoSQL databases were included in the analysis. Furthermore, relational databases may not be the best alternative to blockchain in this case, but the technology was selected over other types of databases since it is a widely used in conventional solutions throughout supply chains due to its maturity.

What could further improve the analysis is by increasing the number of solutions per technology. For example, comparing two solutions based on relational databases and two solutions based on blockchains, instead of one for each technology. This would not only show how the solutions differ between technologies, as was shown in the analysis, but also how solutions using the same technology differs, especially regarding costs. This would further increase the significance of the analysis, as mentioned in the critical discussion of the analysis in Chapter 9.

Consulting more industry experts would help to further diversify the validation. For example, a freight forwarder and a customs official would most likely find different criteria more important than other validators.

The final limitation that was identified is the focus on solutions by service providers, i.e. SaaS and PaaS. Although the reason for this choice was articulated when discussing the scope in the introduction, it is nevertheless still a limitation. Outsourcing versus developing a solution in-house has major differences – especially in the cost of the solution. The scope would be too broad and the analysis would be based on a large number of assumptions between the two types of offerings.

10.4 Suggestions for Future Work

The discussion of limitations can be used to illicit suggestions for future research. The first suggestion is to include a wider range of alternative solutions in the analysis, e.g. non-relational databases and other types of DLTs. In the future there might be more mature solutions, which would make comparing them easier. While the focus of this research is on comparing blockchains to more conventional solutions, future research might want to focus on putting more effort into the selection of alternatives (blockchains and relational databases) and more specifically the alternatives of a specific technology (TradeLens, GSBN and CargoX).

The two solutions used in this research use completely different technologies, yet share many similar cost drivers, as seen in the financial analysis. TradeLens has one cost driver that stands out: the cost of adding additional members to the platform. The service providers of other blockchain-based solutions may decide to approach this differently, such as absorbing it into the usage cost. They may also have additional cost drivers that TradeLens does not have, e.g. explicit transaction costs. Therefore, it will be useful to consider additional blockchain solutions that might make the analysis more representative of blockchain solutions in general. At the time of this research, though, other solutions were not as widely available on a commercial level like TradeLens was. This is likely to change over time as more solutions emerge and mature, thus being applicable to future research.

A second suggestion would be to look at solutions that would be developed in-house to cater for stakeholders that are interested in such solutions. The analysis would likely differ significantly and may possibly lead to different outcomes.

Thirdly, it will be more insightful to perform multiple case studies in different types of supply chains and possibly in different geographical regions. Greater interaction with industry experts would benefit future work by providing greater and more diverse insights.

Although only part of the ATAM was used in this analysis, future research might solely use this method to compare alternatives by utilising the entire method, not just the utility tree. Furthermore, future research can follow the CBA method step-by-step, as described by Kazman, Asundi, and Klien (2002), in addition to the ATAM which precedes it.

The blockchain landscape remains relatively unexplored, despite the large amounts of research being conducted on the topic. It shows that blockchain is still on the road to maturity. It is important to identify gaps in literature that can be fulfilled by further research to contribute to the development of blockchain technology.

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APPENDIX A

Ethics and Case Study

A.1 Ethical Considerations

This research required input from industry experts – firstly, to provide information from a perspective other than literature and secondly, to validate the analysis. Therefore, ethical considerations were necessary, as the personal information of interviewees and potentially sensitive information from their companies were collected. This section describes how such information was secured and how anonymity was ensured.

As part of this study, a semi-structured interview was conducted with an employee of the case company. Some questions required responses that may contain confidential company information that is not available in the public domain. This included information on certain product lines offered by the organisation and certain processes that the organisation follows, e.g. how they go about doing specific things. Additional interviews that were for data collection and validation purposes were held with professionals from other organisations in the global trade environment. The participants could withdraw from the interview at any time without consequence. Any data collected up to that point would be disregarded. They may also have refused to answer any questions and still remain in the interview.

Participants that wanted themselves and their company to stay anonymous were not requested to provide any personal information during the interview that could identify them as an individual. Any information shared during this study and that could possibly identify a participant were not disclosed or published if anonymity is requested. Anonymity was upheld by referring to the participant as “the industry expert” or a similar title. The only form of personal data required was the participant’s area of expertise. Furthermore, the research reported no links to any personal identifiers and the responses obtained during the interviews were assigned a unique reference, which was used to identify data in the thesis itself.

Any correspondence was kept confidential in the researcher’s university email inbox that only he has access to. Any data collected during the semi-structured interviews were securely stored on a password-protected laptop and backed up to a password-protected cloud storage account only accessible by the researcher. This information was not shared with anyone else, nor will it be used for future studies or publications, unless explicit permission from participants are given. Ethical procedures were followed as outlined by the Research Ethics Committee at Stellenbosch University, who granted ethical clearance and classified the project as low risk.

A.2 Interview Guide

The interviews performed for data collection purposes during the course of the research followed a guide that outlines the rough structure of the interviews. The general guide is discussed in this section.

Introduction

The participant is welcomed and thanked for their willingness to participate in the interview. The research is introduced and context is provided as to where the participant fits into the big picture. It includes a discussion of the purpose of the interview and the information that is expected to be obtained through the interview.

Ethical considerations

The various ethical considerations that need to be accounted for are discussed with the participant to ensure they understand what is expected of them and of the researcher, and to reassure them that a thorough ethics application process has been completed to ensure a high level of ethical standards are followed. It includes going through the information on the consent form, such as their participation and withdrawal, protection of their information, confidentiality and identity, recording of the interview, and storage of data collected during the interview. The various documents that must be signed, such as the permission letter and informed consent form are discussed to ensure that the ethical requirements from both the company and university are met.

Discussion of interview questions

Next the interview questions are posed to the participant in a conversational style, giving the participant freedom to discuss what they think are relevant to the question at hand. Follow-up questions are asked when applicable to ensure enough relevant information is obtained from the interview and to keep the conversation flowing.

Conclusion

The participant is thanked for their time and knowledge shared. Any further steps, such as sharing any quotes from the interview that is used in the research, are discussed and the interview is concluded.

A.2.1 Case Study: Interview 1 – Problems Experienced in Supply Chains

The following questions were discussed with the participant of the first interview. They are an employee at the case company on which the case study is based.

Supply chain mapping

- Which fruit or category of fruit pose the greatest challenges regarding information flows, cross-border trade and regulations, and why is this the case?
- What does the physical process flow of this fruit category look like in this cross-border supply chain?
- Which documents are involved in the cross-border trading process for this fruit category and what information do they typically contain?
    - Who are the different stakeholders that create and handle each of these documents?
    - How long do these documents take on average to create, process and reach their destination?
    - Describe how these documents flow between different parties through the supply chain.

Degree of digitalisation and automation

- What is the current state of digitalisation and automation in your specific supply chain regarding information and document flows and why do you think your supply chain is in this state?
- What is the current state of digitalisation and automation in your industry as a whole — not just your supply chain?
- Describe how these documents flow between different parties through the supply chain.

Existing information systems

- Describe your company's information system that is used to record, process, and share data.
  - Do you use an ERP system, or a similar system for example?
  - How are documents recorded, stored, and shared in the company?
  - How does one access these documents and other information when required?
  - Do you have any shared databases whatsoever with other companies in your supply chain?
- To what degree is information recording, processing and exchange automated in your supply chain?

Intra-company flows

- What problems does your company experience regarding the flow of information and documents within the company itself, e.g. between different offices, departments, or employees?

Inter-company flows

- What problems does your company experience regarding the flow of information and documents between actors in the supply chain, e.g. between your company and your suppliers?
- How important is trust between parties in your supply chain?
- What is the degree of mistrust between the various role players in your supply chain?
- In which areas of your supply chain is trust more important than others?
- If communication between parties were to be automated, where would possible trust issues emerge?
- How likely are you to collaborate and share sensitive information with other players in your supply chain?

General problems

- What problems are commonly experienced when goods need to cross the border?
- How often do you experience document-related issues that may cause delays?

Data security

- What problems do you experience with the security and privacy of data?
- How secure are the current systems used for information and document exchange? Would enhanced security be beneficial to your company's supply chain?

Standards and regulatory requirements

- What is the level of standardisation in your company or supply chain with regards to recording and sharing data?
- What is your opinion on the current state of standards regarding documentation and information flows in the global supply chain environment? Do you feel there is a lack of standards or an abundance of complex and possibly redundant standards?
- Do you feel new reliable standards for emerging digital technologies such as blockchain and IoT are being developed fast enough? What would help to improve the process of developing these new standards?
- What are the regulatory requirements that your company needs to comply with to move goods across borders?

Supply chain visibility and traceability

- How visible is the rest of the supply chain to your company, i.e. do you collaborate with and are able to access data from companies other than your direct neighbours such as tier 1 suppliers?
- How easily is your company able to anticipate supply chain risks and make provisions to either prevent the risks from becoming reality or to reduce the impact of these risks?
- How easily are goods tracked throughout the supply chain? What systems do you have in place for this?
- How easily are any issues traced back through the supply chain to their origins?

COVID-19

- How has the COVID-19 pandemic impacted your supply chain in terms of information, documentation, and product flows?
- What flaws in your supply chain or global supply chains in general do you feel have been exposed by the COVID-19 pandemic?
- How quickly was your company or supply chain able to react to the uncertainty caused by COVID-19?
- What has your company done to adapt to functioning during the COVID-19 pandemic?

Blockchain

- Are you familiar with blockchain technology? If yes, please explain briefly how it may benefit supply chains.
- Where in your company's supply chain does blockchain have the largest potential?
- Has your company looked at possible blockchain solutions and considered implementing them in your supply chain? If yes,
  - Where would you implement this project in your company's supply chain?
  - What would be the main goal of the project? What is your reason for considering blockchain as a solution?
  - What alternatives have you considered to blockchain, if any?
  - What is your current experience with the pilot, and do you see it as potentially growing beyond a pilot into a full-scale project that is implemented across the supply chain?
  - What are the major problems and challenges that you have faced so far with this pilot?

A.2.2 Case Study: Interview 2 – Experience with TradeLens and Blockchain (Case Company)

The following questions were discussed with the participant in the second interview. They are the same employee at the case company on which the case study is based.

TradeLens alternatives

- How did your company hear about TradeLens?
- Why did you decide on TradeLens specifically and have you heard of and considered other options? E.g. the Global Shipping Business Network (GSBN), CargoX, etc.
- What option would your company rather pursue: using a software-as-a-service (SaaS) such as TradeLens, or developing your own solution? Please explain why.

TradeLens use cases

- What are the different use cases for blockchain-based platforms such as TradeLens in your supply chain?
- Which specific use case did your TradeLens pilot focus on?
- What pain points/issues did you experience that led you to pursue this use case?

Platform participants

- Who are the generic stakeholders in a cross-border supply chain such as yours and what are their functions? E.g. suppliers/farmers, banks, insurance companies, freight forwarders, customs authorities, etc.
- Which of these stakeholders in your supply chain are involved with the TradeLens platform?

- Which of these stakeholders would your company like to be involved with TradeLens?
- Which of these stakeholders would not be needed any more when using a platform such as TradeLens? E.g. no need for certain inspections/checks due to the immutability provided by blockchain, which can reduce costs.
- Do authorities widely accept the digital versions of documents that were previously physical such as the eBL?
- What do you think TradeLens needs to do to attract more users to their platform?

Documentation requirements

- What are the physical trade documents in supply chains that need to be digitised?
- For each document, what specific information does it contain? E.g. name of exporter, description of package contents, port of load, date, relevant signature and stamp, etc.
- For each document, what are typical problems experienced? Please include any issues in the past that have been solved since then. E.g. delays and their impact, mistakes, etc.
- What are typical requirements for digitising these documents and their flows?
- From the list of documents, which ones are most relevant to your company and platforms such as TradeLens, even if they are not problematic to your company?

Usage requirements

- How many of each of the previously identified trade documents are associated with a single trade/export?
- How many trades/exports do you have per month?
- What is the unit of trade with which the documents are associated? E.g. container, pallet, box, etc.
- What is the average file size for the various types of trade documents? I.e. phyto, export certificate, BoL, etc.

TradeLens offerings

- What are the different tiers of services and packages (i.e. platform options) and their features that TradeLens offers that you are aware of?

TradeLens pilot

- What are the beginning and end dates of your company's TradeLens pilot?
- Please describe the entire process of joining the TradeLens platform that you company went through. I.e. what does the onboarding process look like?
- How long would you expect the full-scale adoption of TradeLens to take?

- Which of the blockchain-related benefits provided by TradeLens are important to your company?
- Which of the blockchain-related drawbacks applicable to TradeLens are your company concerned about?
- What are the key features that TradeLens provides to your company? E.g. event notifications.
- What are the key issues or shortcomings of TradeLens that is concerning to your company? E.g. lack of features, participants, etc.
- What TradeLens package/platform option did your company test in its pilot?
- Would you consider using the option that allows document sharing to be able to share trade documents electronically with other stakeholders?
- What are the different costs and their approximate values that your company incurred with the TradeLens platform? E.g. membership, data usage, storage, support, etc.
- How much money and time would you estimate your company could save per month by using TradeLens?
- How was the implementation process and what did you need to do from your side to successfully implement TradeLens in your company? E.g. required training to use the platform, required new infrastructure to use the platform.
- How did maintenance on the platform affect your company? E.g. downtime during maintenance.

Technical aspects of TradeLens

- How does the signing and stamping of documents work with TradeLens? Are they digitally signed or stamped, or are the physical documents signed or stamped and then scanned?
- How has TradeLens ensured that the documents shared on their platform are secure and accepted by authorities?
- How interoperable is TradeLens with the various systems that each stakeholder has, for example, your ERP system? E.g. easy integration through use of APIs.
- How does TradeLens handle non-standardised information? E.g. different formats for bills of lading, depending on which country is involved; different formats depending on the specific system.

The future of TradeLens

- What is required for TradeLens to be successful?
- What are your company's plans for TradeLens in the future?

A.2.3 Case Study: Interview 3 – Experience with TradeLens and Blockchain (TradeLens)

The following questions were discussed with the participant of the third interview. They are an employee at TradeLens.

Employee's experience with TradeLens

- What has your experience been like managing document flows using blockchain? Is it the right technology for the job?
- What are the constraints that you have experienced of using blockchain for sharing trade documents? E.g. laws and regulations, high investment costs, etc.
- What are the current limitations or shortcomings of TradeLens? Which of these do you plan to address, and which of these do not fall within the scope of TradeLens?

TradeLens competitors and users

- Who are the competitors of TradeLens, however small or large they may be?
- Who are the most common supply chain stakeholders that use the TradeLens platform? E.g. exporters, shipping lines, freight forwarders, customs authorities, etc.
- Do authorities widely accept the use of TradeLens for sharing certified documentation? What problems do you experience in convincing authorities to support and use TradeLens?
- How does TradeLens attract more users to the platform? What challenges have you experienced in attracting new users?
- Which stakeholders are likely to resist the use of TradeLens?

TradeLens use cases

- What are the different packages/tiers offered by TradeLens and which one(s) are the most popular?
- Which trade documents would benefit supply chains the most if they were shared on the platform instead of traditional ways? E.g. export certificate, bill of lading, phytosanitary certificate, etc.
- What does the onboarding process of TradeLens look like?
- How long would you expect the full adoption of TradeLens to take if a company were to fully integrate their relevant systems with TradeLens?

Costs of TradeLens

- What are the different costs that a company and their supply chain incur when using TradeLens? E.g. membership fees, consumption of computational resources, storage, support, etc.
- How does billing work? E.g. usage-based, container-based, fixed amount per period, etc.

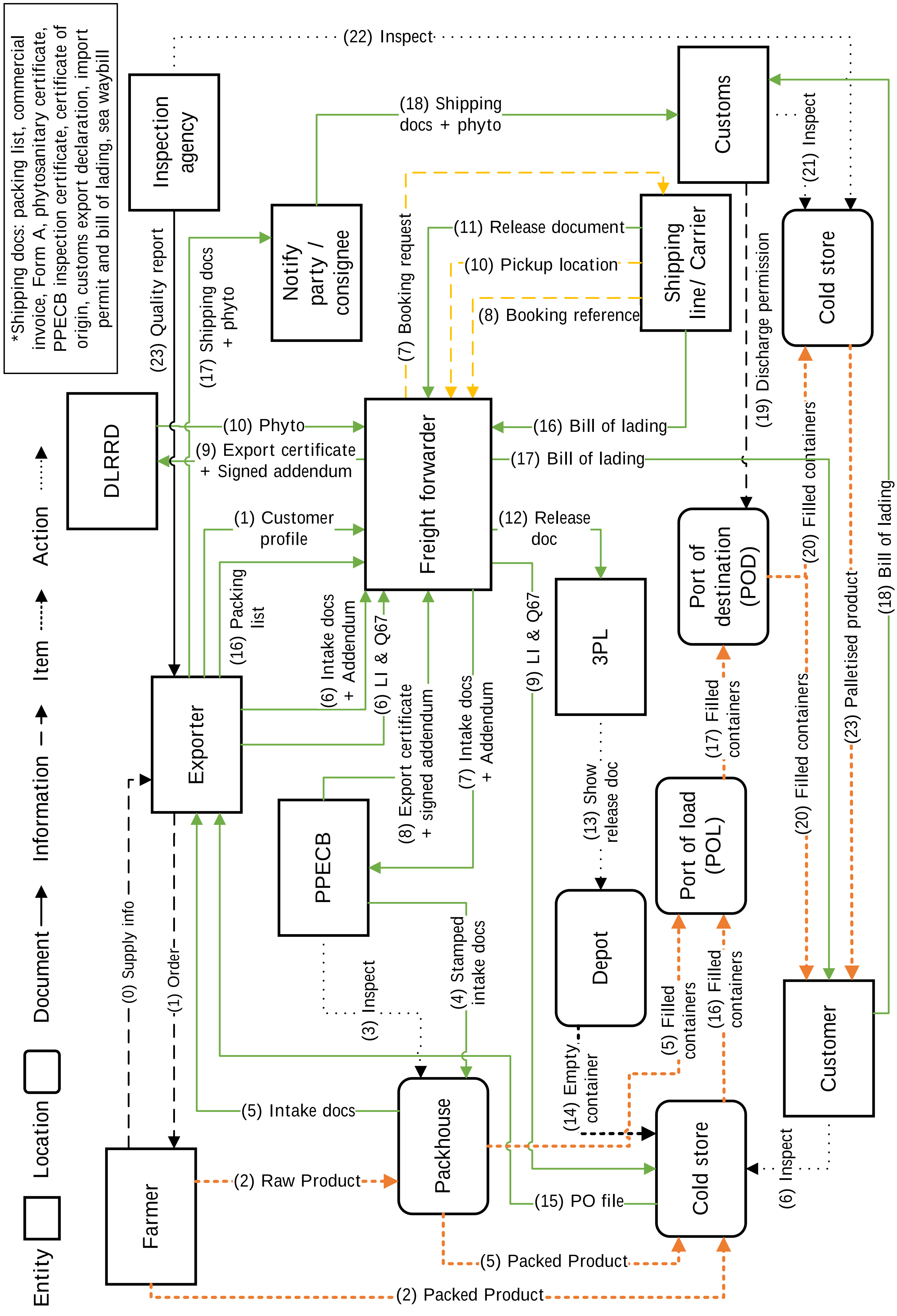
Technical aspects of TradeLens

- How does the signing and stamping of documents work with TradeLens? Are they digitally signed and stamped, or are the physical documents signed, stamped, and then scanned?

- How has TradeLens ensured that the documents shared on the platform are secure and accepted by authorities?
- How interoperable is TradeLens with the various systems that each stakeholder has, for example, their ERP systems? E.g. easy integration through use of APIs.
- How does TradeLens handle non-standardised information? E.g. different formats for bills of lading, depending on which country is involved; different formats depending on the specific system.
- What are typical requirements for digitising documents and their flows?
- What laws and regulations are obstacles for TradeLens?

A.3 Case Study: Information Flows

An overview of the major information flows in the case study, as discussed in Chapter 5, are visualised in Figure A.1. The effect of a blockchain solution on these information flows in the form of increased efficiencies and reduced labour is shown in Figure A.2.



*Shipping docs: packing list, commercial invoice, Form A, phytosanitary certificate, PPECB inspection certificate, certificate of origin, customs export declaration, import permit and bill of lading, sea waybill

FIGURE A.1: *Overview of the major information flows in the case supply chain.*

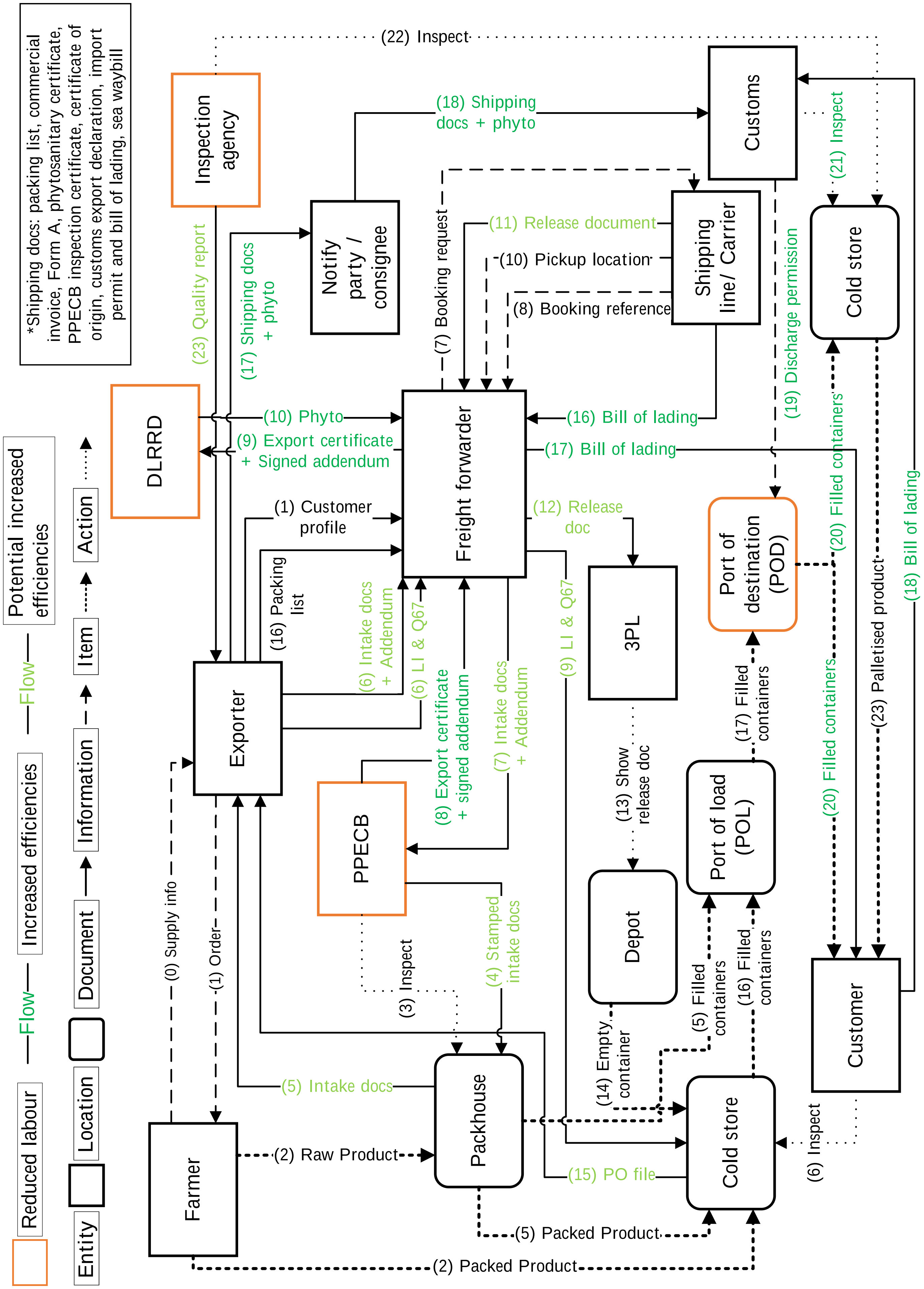


FIGURE A.2: *Overview of the major information flows in the case supply chain with the influence of blockchain indicated.*

APPENDIX B

Analysis and Validation

This appendix contains additional data from the analysis – specifically information on the Low and High scenarios that were mentioned and briefly explained in the analysis in Chapter 7.

B.1 Financial Analysis: Costs

This section contains the costs of both models that were not included in the financial analysis in Chapter 7. Firstly, it looks at the financial costs of the blockchain model, secondly, the costs of the relational model, and thirdly, the total estimated cost and project cash outflow.

B.1.1 Financial costs of the blockchain solution

Additional storage

Table B.1: *Cost of additional data storage for the blockchain model (Low scenario)*

Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	25	58	92	126	160
Monthly cost	$/month	1.02	1.56	2.12	2.67	3.23
Additional storage	**$/year**	**12.24**	**18.72**	**25.38**	**32.04**	**38.70**

Table B.2: *Cost of additional data storage for the blockchain model (High scenario)*

Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	75	229	382	536	690
Monthly cost	$/month	4.21	6.88	9.38	11.89	14.40
Additional storage	**$/year**	**50.46**	**82.50**	**112.50**	**142.62**	**172.80**

Onboarding labour

Table B.3: *Cost of onboarding labour for the blockchain model (Low scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	2	1
Duration of period	Months	0.25	0.25
Percentage of time spent on project	%	15	20
Average employee salary	$/month	4 332.79	4 256.28
Onboarding labour costs	**$**	**324.96**	**212.81**

Table B.4: *Cost of onboarding labour for the blockchain model (High scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	8	4
Duration of period	Months	3	3
Percentage of time spent on project	%	15	20
Average employee salary	$/month	5 174.43	5357.48
Onboarding labour costs	**$**	**18 627.94**	**12 857.95**

Ongoing labour

Table B.5: *Cost of ongoing labour for the blockchain model (Low scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	1	1
Duration of period	Months	60	60
Percentage of time spent on project	%	20	100
Average employee salary	$/month	4 332.79	4 256.28
Ongoing labour costs	**$**	**51 993.45**	**255 37.96**

Table B.6: *Cost of ongoing labour for the blockchain model (High scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	5	2
Duration of period	Months	60	60
Percentage of time spent on project	%	20	100
Average employee salary	$/month	5 174.43	5357.48
Ongoing labour costs	**$**	**310 465.69**	**642 897.39**

B.1.2 Financial costs of the relational solution

Additional storage

Table B.7: *Cost of additional data storage for the relational model (Low scenario)*

Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	44	78	112	145	179
Monthly cost	$/month	2.51	3.47	4.42	5.35	6.30
Document storage	**$/year**	**30.12**	**41.58**	**52.98**	**64.20**	**75.54**

TABLE B.8: *Cost of additional data storage for the relational model (High scenario)*

Cost Driver	**Unit**	**1**	**2**	**3**	**4**	**5**
Storage required	GB/year	164	318	472	626	780
Monthly cost	$/month	21.69	26.02	33.42	37.94	38.99
Document storage	**$/year**	**260.28**	**312.18**	**364.08**	**415.92**	**467.82**

Onboarding labour

TABLE B.9: *Cost of onboarding labour for the relational model (Low scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	2	1
Duration of period	Months	1.625	1.625
Percentage of time spent on project	%	30	20
Average employee salary	$/month	4 332.79	4 256.28
Onboarding labour costs	**$**	**4 224.47**	**1 383.29**

TABLE B.10: *Cost of onboarding labour for the relational model (High scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	8	4
Duration of period	Months	6.5	6.5
Percentage of time spent on project	%	30	20
Average employee salary	$/month	5 174.43	5357.48
Onboarding labour costs	**$**	**80 721.08**	**27 858.89**

Ongoing labour

TABLE B.11: *Cost of ongoing labour for the relational model (Low scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	1	1
Duration of period	Months	60	60
Percentage of time spent on project	%	40	100
Average employee salary	$/month	4 332.79	4 256.28
Ongoing labour costs	**$**	**103 986.91**	**255 376.96**

Table B.12: *Cost of ongoing labour for the relational model (High scenario)*

Cost Driver	**Unit**	**IT, developers, engineers**	**Legal, business owners, IT management**
Number of employees	Workers	5	2
Duration of period	Months	60	60
Percentage of time spent on project	%	40	100
Average employee salary	$/month	5 174.43	5357.48
Ongoing labour costs	**$**	**620 931.38**	**642 897.39**

B.1.3 Total estimated cost and project cash outflow

Blockchain model

Table B.13: *Cash outflow and NPV of costs for the blockchain model (Low scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
TradeLens usage	$		3 872	3 872	3 872	3 872	3 872
TradeLens new members	$	0					
Additional cloud storage	$		13	19	26	33	39
Onboarding labour	$	538					
Ongoing labour	$		61 475	61 475	61 475	61 475	61 475
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*646*	*78 430*	*78 438*	*78446*	*78 454*	*78 462*
Discount rate	%	12					
PV	$	646	70 027	62 531	55 837	49 859	44522
NPV	**$**	**187 240**					

Table B.14: *Cash outflow and NPV of costs for the blockchain model (High scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
TradeLens usage	$		20 592	20 592	20 592	20 592	20 592
TradeLens new members	$	6 000					
Additional cloud storage	$		51	83	113	143	173
Onboarding labour	$	31 486					
Ongoing labour	$		190 673	190 673	190 673	190 673	190 673
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*44 984*	*253 579*	*253 617*	*253 653*	*253 689*	*253 725*
Discount rate	%	12					
PV	$	44 984	226 410	202 182	180 545	161 224	143 971
NPV	**$**	**643 727**					

Relational database model

TABLE B.15: *Cash outflow and NPV of costs for the relational model (Low scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
RDS usage	$		305	305	305	305	305
RDS storage	$		22	22	22	22	22
S3 storage	$		31	42	53	65	76
Onboarding labour	$	5 608					
Ongoing labour	$		71 873	71 873	71 873	71 873	71 873
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*6 730*	*86 655*	*86 669*	*86 682*	*86 696*	*86 709*
Discount rate	%	12					
PV	$	6730	77 371	69 092	61 699	55 097	49 201
NPV	**$**	**212 265**					

TABLE B.16: *Cash outflow and NPV of costs for the relational model (High scenario)*

					Year		
Cost Driver		**0**	**1**	**2**	**3**	**4**	**5**
RDS usage	$		1 226	1 226	1 226	1 226	1 226
RDS storage	$		2 136	2 136	2 136	2 136	2 136
S3 storage	$		261	313	365	416	468
Onboarding labour	$	108 580					
Ongoing labour	$		252 766	252 766	252 766	252 766	252 766
Risk adjustment	%	20	20	20	20	20	20
Total cost	*$*	*130 296*	*305 615*	*305 677*	*305 740*	*305 802*	*305 864*
Discount rate	%	12					
PV	$	130 296	272 871	243 684	217 620	194 343	173 556
NPV	**$**	**843 821**					

Annual cost breakdown

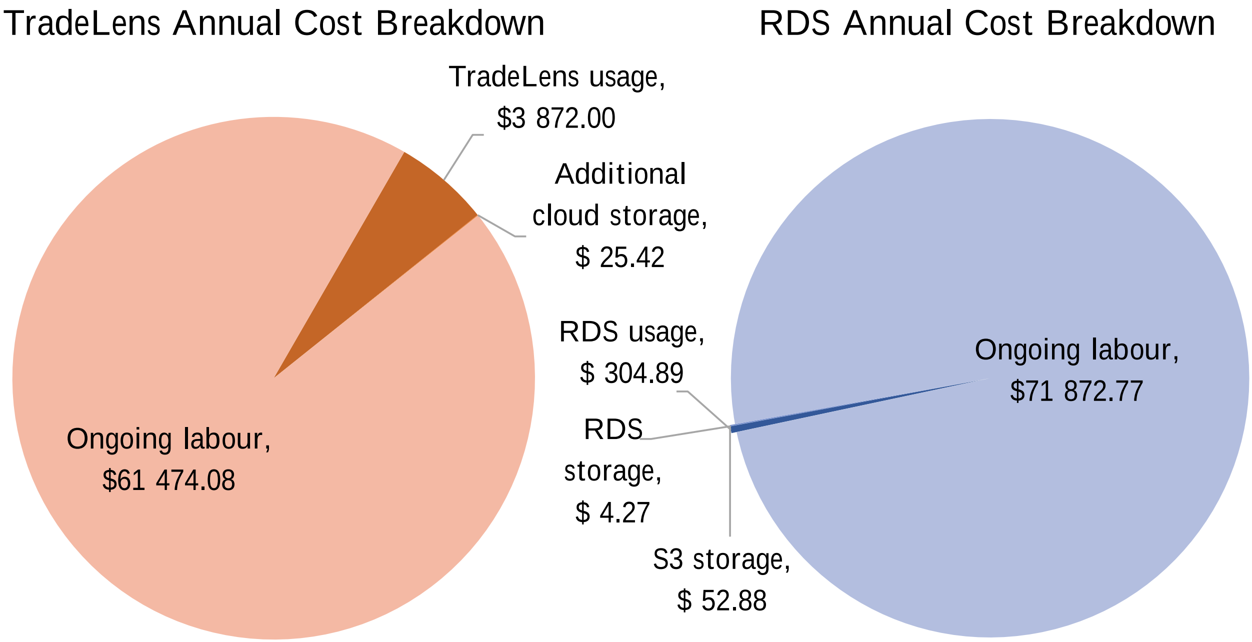


FIGURE B.1: *Breakdown of the average annual costs of the blockchain and relational models for the Low scenario*

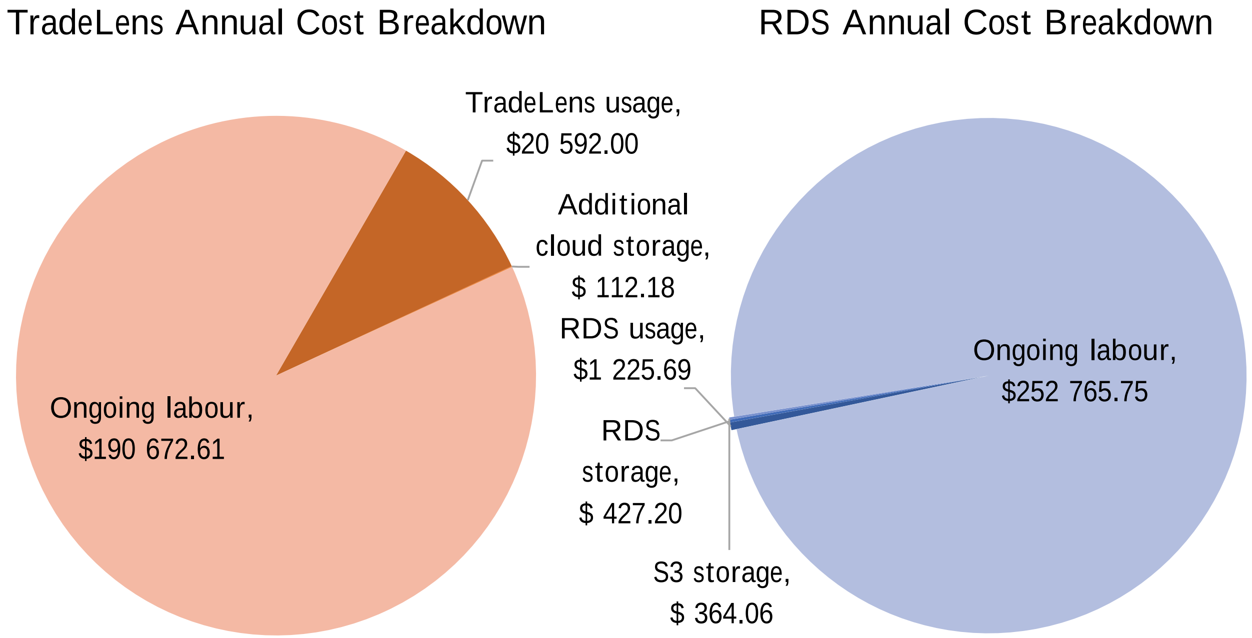


FIGURE B.2: *Breakdown of the average annual costs of the blockchain and relational models for the High scenario*

B.2 Financial Analysis: Benefits

B.2.1 Financial benefits

Streamlined documentation

Table B.17: *Annual cost savings due to streamlined documentation for both models (Low scenario)*

Metric	**Unit**	**TradeLens**	**RDS**
Total number of documents	#	15 000	15 000
Percentage of conflicting documents	%	5	5
Number of conflicting documents to resolve	#	750	750
Average cost to resolve a dispute	$	200	200
Projected reduction in conflicting documents	%	100	60
Savings due to reduction in conflicting documents	*$*	*150 000*	*90 000*
Average cost for processing a document	$	20	20
Reduction in cost per document	%	25	10
Savings due to reduction in cost of processing documents	*$*	*75 000*	*30 000*
Savings for processing documents	**$**	**225 000**	**120 000**

Table B.18: *Annual cost savings due to streamlined documentation for both models (High scenario)*

Metric	**Unit**	**TradeLens**	**RDS**
Total number of documents	#	68 400	68400
Percentage of conflicting documents	%	9	9
Number of conflicting documents to resolve	#	6156	6156
Average cost to resolve a dispute	$	200	200
Projected reduction in conflicting documents	%	100	60
Savings due to reduction in conflicting documents	*$*	*1 231 200*	*738 720*
Average cost for processing a document	$	20	20
Reduction in cost per document	%	25	10
Savings due to reduction in cost of processing documents	*$*	*342 000*	*136 800*
Savings for processing documents	**$**	**1 573 200**	**875 520**

Reduced labour costs

Table B.19: *Annual cost savings due to reduced labour costs for TradeLens (Low scenario)*

		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	4	4	4	4	4
Annual compensation	$	48 169	48 169	48 169	48 169	48 169
Reduction in finance resources	%	20	40	60	80	80
Savings due to reduction in finance resources	*$*	*38 535*	*77 070*	*115 605*	*154 140*	*154 140*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	67 714	67 714	67 714	67 714	67 714
Reduction in legal resources	%	0	30	50	70	70
Savings due to reduction in legal resources	*$*	*0*	*60 942*	*101 570*	*142 198*	*142 198*
Savings in labour costs for TradeLens	**$**	**38 535**	**138 012**	**217 175**	**296 338**	**296 338**

Table B.20: *Annual cost savings due to reduced labour costs for TradeLens (High scenario)*

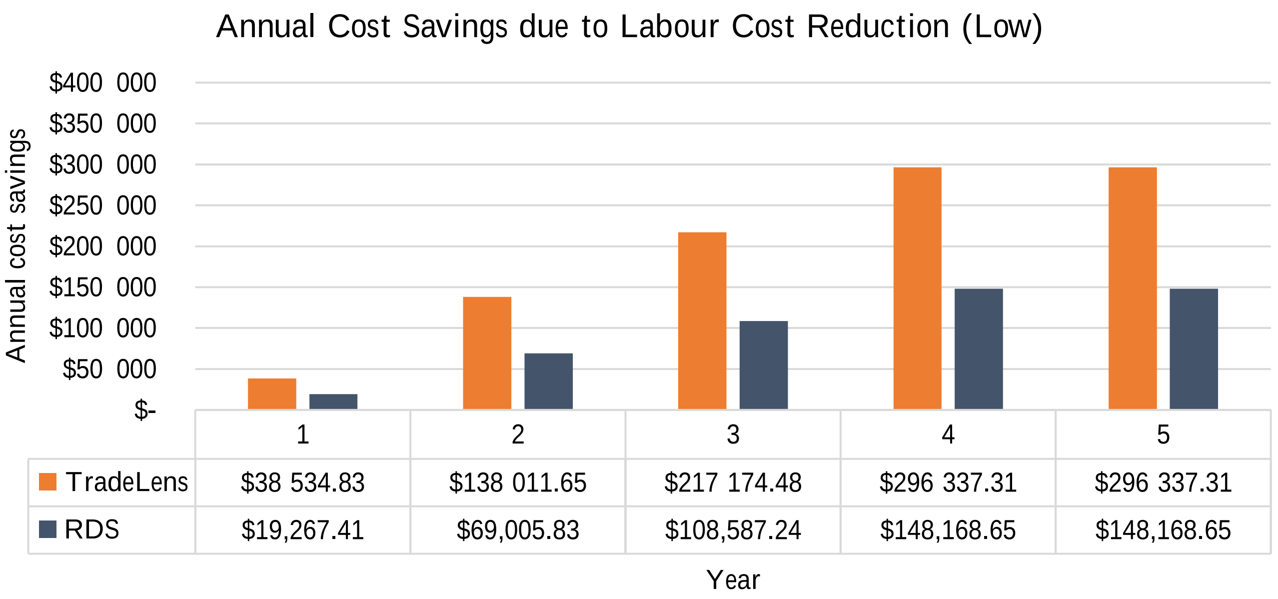
		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	6	6	6	6	6
Annual compensation	$	56 355	56 355	56 355	56 355	56 355
Reduction in finance resources	%	20	40	60	80	80
Savings due to reduction in finance resources	*$*	*67 625*	*135 250*	*202 875*	*270 500*	*270 500*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	98 854	98 854	98 854	98 854	98 854
Reduction in legal resources	%	0	30	50	70	70
Savings due to reduction in legal resources	*$*	*0*	*88 968*	*148 280*	*207 592*	*207 592*
Savings in labour costs for TradeLens	**$**	**67 625**	**224 218**	**351 155**	**478 092**	**478 092**

TABLE B.21: *Annual cost savings due to reduced labour costs for RDS (Low scenario)*

		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	4	4	4	4	4
Annual compensation	$	48 169	48 169	48 169	48 169	48 169
Reduction in finance resources	%	10	20	30	40	40
Savings due to reduction in finance resources	*$*	*19 268*	*38 535*	*57 803*	*77 070*	*77 070*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	67 714	67 714	67 714	67 714	67 714
Reduction in legal resources	%	0	15	25	35	35
Savings due to reduction in regal resources	*$*	*0*	*30 471*	*50 785*	*71 099*	*71 099*
Savings in labour costs for RDS	**$**	**19 268**	**69 006**	**108 588**	**148 169**	**148 169**

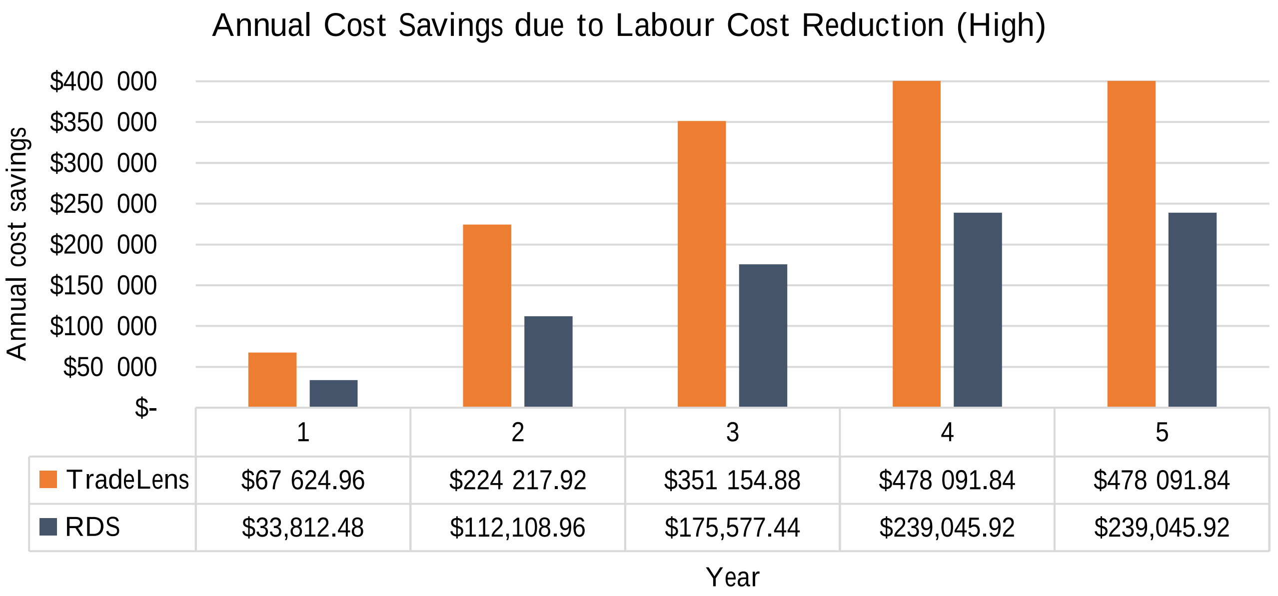
TABLE B.22: *Annual cost savings due to reduced labour costs for RDS (High scenario)*

		Year				
Metric	**Unit**	**1**	**2**	**3**	**4**	**5**
Finance employees resolving conflicting documents	#	6	6	6	6	6
Annual compensation	$	56 355	56 355	56 355	56 355	56 355
Reduction in finance resources	%	10	20	30	40	40
Savings due to reduction in finance resources	*$*	*33 813*	*67 625*	*101 438*	*135 250*	*135 250*
Legal employees resolving conflicting documents	#	3	3	3	3	3
Annual compensation	$	98 854	98 854	98 854	98 854	98 854
Reduction in legal resources	%	0	15	25	35	35
Savings due to reduction in regal resources	*$*	*0*	*44 484*	*74 140*	*103 796*	*103 796*
Savings in labour costs for RDS	**$**	**33 813**	**112 109**	**175 578**	**239 046**	**239 046**



	1	2	3	4	5
🟧 TradeLens	$38 534.83	$138 011.65	$217 174.48	$296 337.31	$296 337.31
■ RDS	$19,267.41	$69,005.83	$108,587.24	$148,168.65	$148,168.65

Figure B.3: *Annual cost savings due to labour cost reduction for both models (Low scenario)*



	1	2	3	4	5
🟧 TradeLens	$67 624.96	$224 217.92	$351 154.88	$478 091.84	$478 091.84
■ RDS	$33,812.48	$112,108.96	$175,577.44	$239,045.92	$239,045.92

Figure B.4: *Annual cost savings due to labour cost reduction for both models (High scenario)*

B.2.2 Total estimated benefits and project cash inflow

Annual benefit breakdown

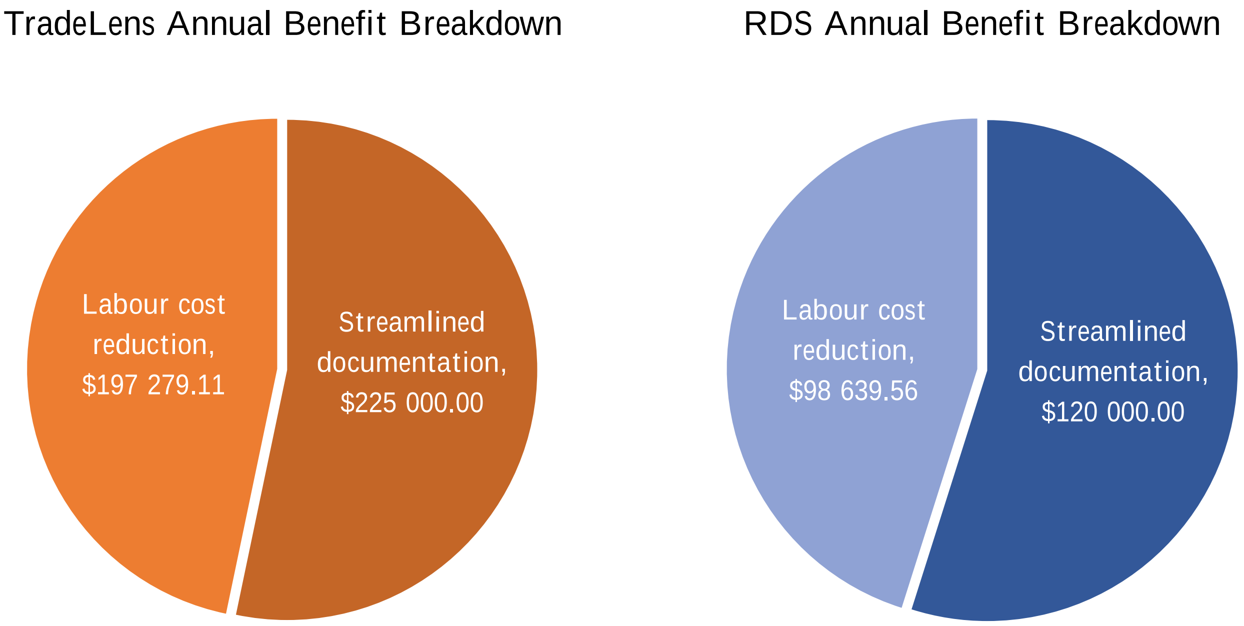


FIGURE B.5: *Breakdown of the average annual benefits of the blockchain and relational models for the Low scenario*

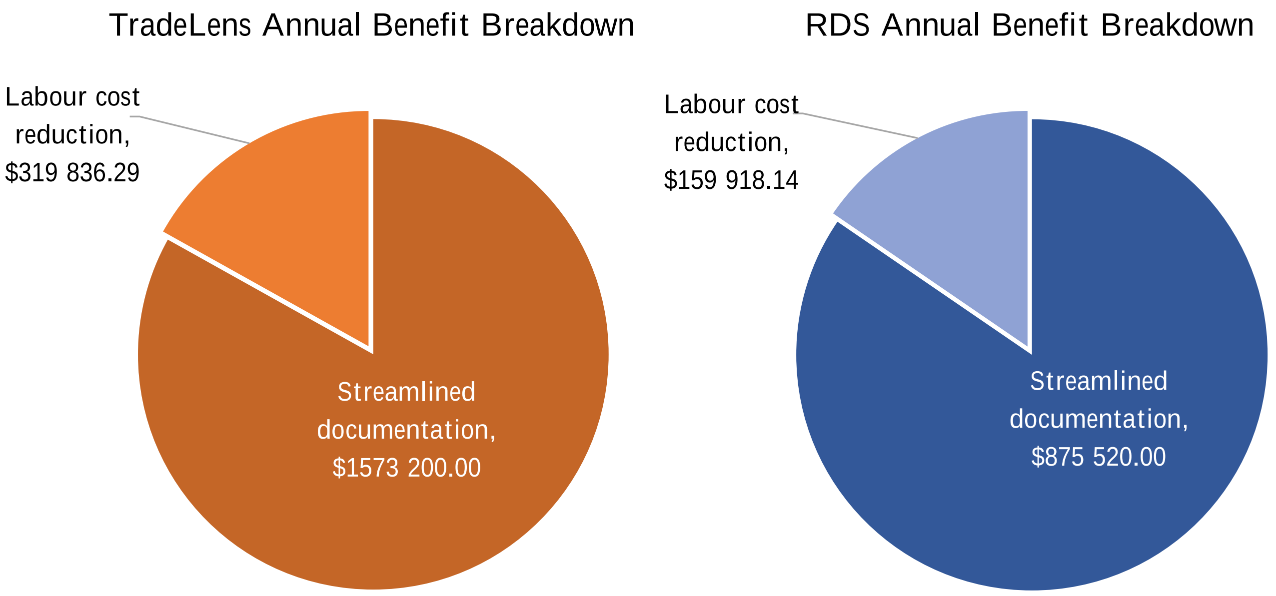


FIGURE B.6: *Breakdown of the average annual benefits of the blockchain and relational models for the High scenario*

B.3 Non-Financial Analysis

Cluster and Criteria Description

Table B.23: *Performance criteria used in the ANP*

Performance
Scalability
How easily throughput can be increased or decreased under varying loads, e.g. number of peers, transactions and computational resource requirements (Raikwar, Gligoroski, and Velinov, 2020). Characterised by: scalability techniques and the consensus mechanism
Transaction Throughput
An important indicator of speed that represents the number of transactions that are processed in a specific time frame (C. Wang and Chu, 2020). Characterised by: transactions per second (TPS)
Transaction Latency
The time it takes for a transaction to be finalised, i.e. written to the database and accepted by the consensus protocol in the case of blockchain (C. Wang and Chu, 2020). Characterised by: consensus mechanism and query complexity (e.g. a query with multiple criteria)
Time Efficiency
Refers to how efficiently the solution makes use of the available time Y. Wang, Singgih, et al., 2019. Characterised by: the number of processes that can easily be automated and a reduction in the number of steps required in cross-border trade (e.g. verification steps)

Table B.24: *Security criteria used in the ANP*

Security
Data Integrity
The overall accuracy, completeness, and consistency of data – whether the data can be trusted (Hewett, Ogée, and Furuya, 2019). Characterised by: how data collection take place and which sources it uses, and the level of human involvement (which goes hand-in-hand with human errors)
Privacy
Protection of potentially sensitive information against unwanted access (Garriga et al., 2021). Characterised by: Cryptography (whether data is encrypted)
Trust
How sure the user can be that the solution is safe and secure, based on its nature and properties. Characterised by: resistance against the tampering of data and the degree of decentralisation (and whether there are intermediaries in which the user must put their trust).
Immutability
How difficult it is to manipulate/change data that has been written to the database (Kouhizadeh and Sarkis, 2018). Characterised by: hashing algorithms (how data is cryptographically linked to other data) and consensus (how consensus of the data in the database is reached among different parties).

TABLE B.25: *Cost criteria used in the ANP*

Cost
Investment Cost
Upfront/initial investment costs: those costs that are incurred before the solution can be operational, including onboarding labour. Fixed costs: those costs that don't vary with the number of transactions or documents that are sent among stakeholders in the supply chain, including ongoing labour.
Transaction Cost
Costs that vary or depend on the number of transactions, including the cost of using the solution (service cost), the cost of storing data in the cloud, and also monitoring and audit costs associated with governing the solution and insuring it is working correctly.
Cost Efficiency
The degree to which costs can be reduced due to greater efficiencies. This includes reduced labour requirements and streamlined documentation (e.g. fewer mistakes).

TABLE B.26: *Interoperability criteria used in the ANP*

Interoperability
Standardisation
The availability or degree of development of technical standards based on the consensus of different parties that include firms, users, interest groups, standards organizations and governments (Z. Xie et al., 2016). Characterised by: the number and quality of standards that currently exist related to the solution, and the maturity of the solution (more mature technologies are more likely to have a larger number of applicable standards).
Regulations and Policies
The degree to which governments are working with industry players to develop new regulations and policies for the solution. Characterised by: collaborative initiatives where different players (e.g. governments and companies) are working together to develop standards, regulations and policies for governing the technology, and the number of legal frameworks available for navigating the complex legal landscape of cross-border trade.

Table B.27: *Reliability criteria used in the ANP*

Reliability
Availability
Whether the data is available for users and applications to access it when required (e.g. a user with relevant permissions should not receive an error when attempting to view a document) (Raikwar, Gligoroski, and Velinov, 2020). Characterised by: trade-offs between consistency, availability and partition tolerance (the CAP theorem), i.e. a database solution can only have two of the three characteristics.
Robustness
The ability of the solution to remain in a properly functioning condition under disturbances, e.g. crashes and errors (Monostori, 2018). Characterised by: the level of decentralisation (as this means there is no single point of failure) and fault tolerance (the degree to which it can withstand faults in the network, e.g. a node that fails)
Consistency
Any transaction that is written to the database must change affected data only in allowed ways, i.e. must adhere to predefined rules (Austerberry, 2006). In the case of blockchain, this ensures that all honest nodes output the same sequence of blocks throughout the execution of the consensus protocol. Characterised by: consensus (how consensus of the data in the database is reached among different parties), and the previously-mentioned CAP theorem.
Maturity
How long the technology on which the solution is based has been in use, as higher maturity ensures that most of its initial faults and inherent problems have been removed or reduced by further development. Characterised by: the degree of support that the technology has from industry players, and the level of uncertainty regarding the technology (newer technologies have higher levels of uncertainty).

Table B.28: *Functionality criteria used in the ANP*

Functionality
Suitability
Refers to the general suitability of the solution in the cross-border trade environment. Characterised by: the number of proven use cases (e.g. success stories of where the solution was successfully used) and inherent properties of the solution (e.g. blockchain is know for its security).
Manageability
The degree to which the solution can be managed by a small group of administrators or owners. Characterised by: error correction/editability (the ease of correcting mistakes or incorrect data), and control (the ease with which a single/small group of admins and owners can influence the database).

Weighted Super Matrix

TABLE B.29: *The weighted super matrix from the ANP*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Block-chains	Relational Databases	Scala-bility	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immuta-bility	Investment Cost	Transaction Cost	Cost Efficiency	Standard-isation	Regulations and Policies	Avail-ability	Robust-ness	Consist-ency	Maturity	Suita-bility	Manage-ability
Alterna-tives	Blockchains	0	0	0.0464	0.03935	0.08977	0.17832	0.1516	0.16807	0.15583	0.14294	0.12469	0.05713	0.18126	0.03628	0.0384	0.0495	0.12046	0.02811	0.03568	0.2775	0.06618
	Relational Databases	0	0	0.0929	0.11806	0.17954	0.03566	0.05053	0.04202	0.02597	0.02042	0.08346	0.2285	0.03625	0.18137	0.1536	0.1484	0.02008	0.11243	0.28542	0.06938	0.46327
Perfor-mance	Scalability	0.03373	0.06766	0	0.18178	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01918	0	0.02292	0
	Transaction Throughput	0.02532	0.0425	0.4827	0	0	0	0	0	0	0.10148	0	0	0	0	0	0	0.09589	0.07671	0	0	0
	Transaction Latency	0.01245	0.02791	0	0.36356	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Time Efficiency	0.0812	0.01464	0	0	0	0	0.12557	0	0	0	0.12086	0.16584	0.12629	0	0	0	0	0	0	0.06875	0
Security	Data Integrity	0.02297	0.1272	0.0234	0	0	0.02199	0	0.13023	0.04734	0	0.03294	0	0.01828	0	0	0	0.03044	0	0	0.01812	0
	Privacy	0.04443	0.15306	0	0.02941	0	0.03448	0.08377	0	0.11676	0.08124	0.01881	0.04029	0	0	0.01124	0	0	0	0	0.01203	0
	Trust	0.08754	0.06043	0.0659	0.07707	0.41252	0.14264	0	0.3101	0	0.32494	0.08671	0.13302	0.06253	0	0.02945	0	0.11506	0.12921	0	0.03758	0.16792
	Immut-ability	0.22158	0.03584	0.1241	0.13465	0	0.12865	0.41883	0.08204	0.28795	0	0.04118	0.07321	0.10692	0	0.07718	0	0.04832	0.06461	0	0.07895	0.05597
Cost	Investment Cost	0.02521	0.01092	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Transaction Cost	0.00794	0.05725	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cost Efficiency	0.06003	0.02501	0	0	0	0	0	0.09117	0	0	0.11692	0.16044	0	0	0	0	0	0	0	0.0948	0
Interope-rability	Standard-isation	0.03549	0.05679	0	0.05612	0	0.05085	0.07843	0	0.02352	0	0.18083	0	0.22676	0	0.47985	0	0	0	0.12668	0.03197	0
	Regulations and Policies	0.03549	0.0142	0	0	0	0.02543	0.02614	0.10869	0.07054	0.08451	0.09042	0	0.05669	0.54396	0	0	0	0	0.12668	0.03197	0.09758
Relia-bility	Availability	0.02488	0.03455	0.0193	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3068	0	0.02442	0
	Robustness	0.08284	0.01045	0.089	0	0.31817	0.05056	0	0	0.14235	0.15348	0	0	0	0	0	0.108	0	0.0767	0	0.07326	0.14908
	Consistency	0.01841	0.03455	0.0417	0	0	0	0	0	0	0.03837	0	0	0	0	0	0.4319	0.3835	0	0	0	0
	Maturity	0.01222	0.0588	0.0146	0	0	0.20225	0	0	0.07117	0	0.10318	0.14158	0.10782	0.07191	0.06343	0	0	0	0	0	0
Functio-nality	Suitability	0.12619	0.02804	0	0	0	0.12916	0	0.02256	0.04393	0.03947	0	0	0.05789	0.16648	0	0.2622	0.13969	0.03725	0.42553	0	0
	Manage-ability	0.04206	0.14021	0	0	0	0	0.06512	0.04512	0.01464	0.01316	0	0	0.0193	0	0.14686	0	0.04656	0.149	0	0.15837	0

Limit Super Matrix

TABLE B.30: *The limit super matrix from the ANP*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Block-chains	Relational Databases	Scala-bility	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immuta-bility	Investment Cost	Transaction Cost	Cost Efficiency	Standard-isation	Regulations and Policies	Avail-ability	Robust-ness	Consist-ency	Maturity	Suita-bility	Manage-ability
Alterna-tives	Blockchains	0.09291	0.09291	0.0929	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.09291	0.0929	0.09291	0.09291	0.09291	0.09291	0.09291
	Relational Databases	0.09066	0.09066	0.0907	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.09066	0.0907	0.09066	0.09066	0.09066	0.09066	0.09066
Perfor-mance	Scalability	0.01798	0.01798	0.018	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.01798	0.018	0.01798	0.01798	0.01798	0.01798	0.01798
	Transaction Throughput	0.03484	0.03484	0.0348	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.03484	0.0348	0.03484	0.03484	0.03484	0.03484	0.03484
	Transaction Latency	0.01635	0.01635	0.0164	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.01635	0.0164	0.01635	0.01635	0.01635	0.01635	0.01635
	Time Efficiency	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021	0.021
Security	Data Integrity	0.02892	0.02892	0.0289	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.02892	0.0289	0.02892	0.02892	0.02892	0.02892	0.02892
	Privacy	0.04445	0.04445	0.0445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.04445	0.0445	0.04445	0.04445	0.04445	0.04445	0.04445
	Trust	0.10343	0.10343	0.1034	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.10343	0.1034	0.10343	0.10343	0.10343	0.10343	0.10343
	Immut-ability	0.10171	0.10171	0.1017	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.10171	0.1017	0.10171	0.10171	0.10171	0.10171	0.10171
Cost	Investment Cost	0.00333	0.00333	0.0033	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.00333	0.0033	0.00333	0.00333	0.00333	0.00333	0.00333
	Transaction Cost	0.00593	0.00593	0.0059	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.00593	0.0059	0.00593	0.00593	0.00593	0.00593	0.00593
	Cost Efficiency	0.01963	0.01963	0.0196	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.01963	0.0196	0.01963	0.01963	0.01963	0.01963	0.01963
Interope-rability	Standard-isation	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625	0.0625
	Regulations and Policies	0.07341	0.07341	0.0734	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.07341	0.0734	0.07341	0.07341	0.07341	0.07341	0.07341
Relia-bility	Availability	0.02082	0.02082	0.0208	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.02082	0.0208	0.02082	0.02082	0.02082	0.02082	0.02082
	Robustness	0.06554	0.06554	0.0655	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.06554	0.0655	0.06554	0.06554	0.06554	0.06554	0.06554
	Consistency	0.04362	0.04362	0.0436	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.04362	0.0436	0.04362	0.04362	0.04362	0.04362	0.04362
	Maturity	0.03079	0.03079	0.0308	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.03079	0.0308	0.03079	0.03079	0.03079	0.03079	0.03079
Functio-nality	Suitability	0.06742	0.06742	0.0674	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.06742	0.0674	0.06742	0.06742	0.06742	0.06742	0.06742
	Manage-ability	0.05475	0.05475	0.0548	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.05475	0.0548	0.05475	0.05475	0.05475	0.05475	0.05475

B.4 Updated Analysis

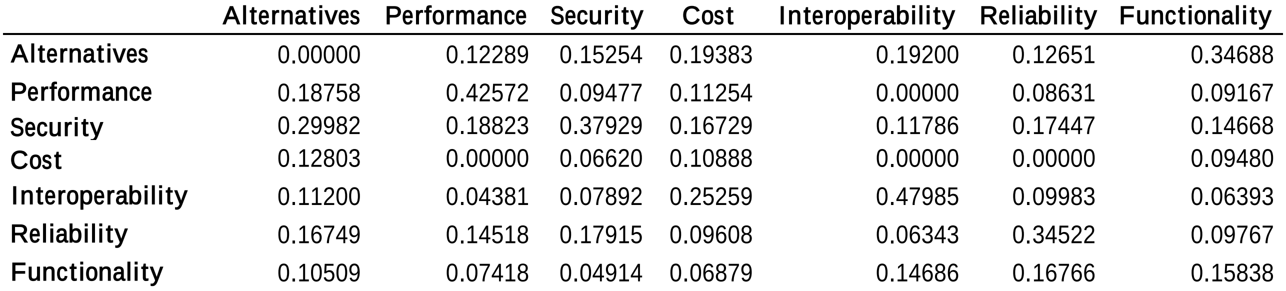
Updated Unweighted Super Matrix

TABLE B.31: *The adapted unweighted super matrix from the ANP based on expert feedback*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Block-chains	Relational Databases	Scala-bility	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immuta-bility	Investment Cost	Transaction Cost	Cost Efficiency	Standard-isation	Regulations and Policies	Avail-ability	Robust-ness	Consist-ency	Maturity	Suita-bility	Manage-ability
Alterna-tives	Blockchains	0	0	0.3333	0.25	0.33333	0.83333	0.75	0.8	0.85714	0.88889	0.59906	0.2	0.83333	0.25	0.2	0.3333	0.85714	0.25	0.11111	0.8	0.125
	Relational Databases	0	0	0.6667	0.75	0.66667	0.16667	0.25	0.2	0.14286	0.11111	0.40094	0.8	0.16667	0.75	0.8	0.6667	0.14286	0.75	0.88889	0.2	0.875
Perfor-mance	Scalability	0.2209	0.44305	0	0.33333	0	0	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.25	0
	Transaction Throughput	0.16581	0.2783	1	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0.8	0	0	0
	Transaction Latency	0.08155	0.18277	0	0.66667	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Time Efficiency	0.53174	0.09588	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0	0	0.75	0
Security	Data Integrity	0.06101	0.33781	0.1095	0	0	0.06709	0	0.24931	0.10473	0	0.18338	0	0.09739	0	0	0	0.15706	0	0	0.12355	0
	Privacy	0.11801	0.40651	0	0.12196	0	0.1052	0.16667	0	0.25828	0.2	0.1047	0.16342	0	0	0.09534	0	0	0	0	0.082	0
	Trust	0.2325	0.1605	0.309	0.31962	1	0.4352	0	0.59363	0	0.8	0.48268	0.53961	0.33307	0	0.24986	0	0.59363	0.66667	0	0.25617	0.75
	Immut-ability	0.58848	0.09518	0.5816	0.55842	0	0.39251	0.83333	0.15706	0.63699	0	0.22924	0.29696	0.56954	0	0.65481	0	0.24931	0.33333	0	0.53827	0.25
Cost	Investment Cost	0.27056	0.11722	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Transaction Cost	0.08522	0.61441	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cost Efficiency	0.64422	0.26837	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0
Interope-rability	Standard-isation	0.5	0.8	0	1	0	0.66667	0.75	0	0.25	0	0.66667	0	0.8	0	1	0	0	0	0.5	0.5	0
	Regulations and Policies	0.5	0.2	0	0	0	0.33333	0.25	1	0.75	1	0.33333	0	0.2	1	0	0	0	0	0.5	0.5	1
Relia-bility	Availability	0.17983	0.24972	0.1174	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.8	0	0.25	0
	Robustness	0.59879	0.07551	0.5406	0	1	0.2	0	0	0.66667	0.8	0	0	0	0	0	0.2	0	0.2	0	0.75	1
	Consistency	0.13307	0.24972	0.2535	0	0	0	0	0	0	0.2	0	0	0	0	0	0.8	1	0	0	0	0
	Maturity	0.0883	0.42505	0.0885	0	0	0.8	0	0	0.33333	0	1	1	1	1	1	0	0	0	0	0	0
Functio-nality	Suitability	0.75	0.16667	0	0	0	1	0	0.33333	0.75	0.75	0	0	0.75	1	0	1	0.75	0.2	1	0	0
	Manage-ability	0.25	0.83333	0	0	0	0	1	0.66667	0.25	0.25	0	0	0.25	0	1	0	0.25	0.8	0	1	0

Updated Cluster Matrix

TABLE B.32: *The adapted cluster matrix from the ANP based on expert feedback*



	Alternatives	Performance	Security	Cost	Interoperability	Reliability	Functionality
Alternatives	0.00000	0.12289	0.15254	0.19383	0.19200	0.12651	0.34688
Performance	0.18758	0.42572	0.09477	0.11254	0.00000	0.08631	0.09167
Security	0.29982	0.18823	0.37929	0.16729	0.11786	0.17447	0.14668
Cost	0.12803	0.00000	0.06620	0.10888	0.00000	0.00000	0.09480
Interoperability	0.11200	0.04381	0.07892	0.25259	0.47985	0.09983	0.06393
Reliability	0.16749	0.14518	0.17915	0.09608	0.06343	0.34522	0.09767
Functionality	0.10509	0.07418	0.04914	0.06879	0.14686	0.16766	0.15838

Updated Weighted Super Matrix

TABLE B.33: *The adapted weighted super matrix from the ANP based on expert feedback*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Blockchains	Relational Databases	Scalability	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immutability	Investment Cost	Transaction Cost	Cost Efficiency	Standardisation	Regulations and Policies	Availability	Robustness	Consistency	Maturity	Suitability	Manageability
Alternatives	Blockchains	0	0	0.0464	0.03935	0.08977	0.17832	0.1516	0.16807	0.15583	0.1452	0.12469	0.05713	0.18126	0.05441	0.0384	0.066	0.12046	0.03514	0.03568	0.2775	0.06618
	Relational Databases	0	0	0.0929	0.11806	0.17954	0.03566	0.05053	0.04202	0.02597	0.01815	0.08346	0.2285	0.03625	0.16324	0.1536	0.1319	0.02008	0.10541	0.28542	0.06938	0.46327
Performance	Scalability	0.04144	0.08311	0	0.18178	0	0	0	0	0	0	0	0	0	0	0	0	0	0.01918	0	0.02292	0
	Transaction Throughput	0.0311	0.0522	0.4827	0	0	0	0	0	0	0.10148	0	0	0	0	0	0	0.09589	0.07671	0	0	0
	Transaction Latency	0.0153	0.03428	0	0.36356	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Time Efficiency	0.09974	0.01799	0	0	0	0	0.12557	0	0	0	0.12086	0.16584	0.12629	0	0	0	0	0	0	0.06875	0
Security	Data Integrity	0.01829	0.10128	0.0234	0	0	0.02199	0	0.13023	0.04734	0	0.03294	0	0.01828	0	0	0	0.03044	0	0	0.01812	0
	Privacy	0.03538	0.12188	0	0.02941	0	0.03448	0.08377	0	0.11676	0.08124	0.01881	0.04029	0	0	0.01124	0	0	0	0	0.01203	0
	Trust	0.06971	0.04812	0.0659	0.07707	0.41252	0.14264	0	0.3101	0	0.32494	0.08671	0.13302	0.06253	0	0.02945	0	0.11506	0.12921	0	0.03758	0.16792
	Immutability	0.17644	0.02854	0.1241	0.13465	0	0.12865	0.41883	0.08204	0.28795	0	0.04118	0.07321	0.10692	0	0.07718	0	0.04832	0.06461	0	0.07895	0.05597
Cost	Investment Cost	0.03464	0.01501	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Transaction Cost	0.01091	0.07866	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Cost Efficiency	0.08248	0.03436	0	0	0	0	0	0.09117	0	0	0.11692	0.16044	0	0	0	0	0	0	0	0.0948	0
Interoperability	Standardisation	0.056	0.0896	0	0.05612	0	0.05085	0.07843	0	0.02352	0	0.18083	0	0.22676	0	0.47985	0	0	0	0.12668	0.03197	0
	Regulations and Policies	0.056	0.0224	0	0	0	0.02543	0.02614	0.10869	0.07054	0.08451	0.09042	0	0.05669	0.54396	0	0	0	0	0.12668	0.03197	0.09758
Reliability	Availability	0.03012	0.04182	0.0193	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3068	0	0.02442	0
	Robustness	0.10029	0.01265	0.089	0	0.31817	0.05056	0	0	0.14235	0.15348	0	0	0	0	0	0.108	0	0.0767	0	0.07326	0.14908
	Consistency	0.02229	0.04182	0.0417	0	0	0	0	0	0	0.03837	0	0	0	0	0	0.4319	0.3835	0	0	0	0
	Maturity	0.01479	0.07119	0.0146	0	0	0.20225	0	0	0.07117	0	0.10318	0.14158	0.10782	0.07191	0.06343	0	0	0	0	0	0
Functionality	Suitability	0.07882	0.01752	0	0	0	0.12916	0	0.02256	0.04393	0.03947	0	0	0.05789	0.16648	0	0.2622	0.13969	0.03725	0.42553	0	0
	Manageability	0.02627	0.08758	0	0	0	0	0.06512	0.04512	0.01464	0.01316	0	0	0.0193	0	0.14686	0	0.04656	0.149	0	0.15837	0

Updated Limit Super Matrix

TABLE B.34: *The adapted limit super matrix from the ANP based on expert feedback*

		Alternatives		Performance				Security				Cost			Interoperability		Reliability				Functionality	
		Blockchains	Relational Databases	Scalability	Transaction Throughput	Transaction Latency	Time Efficiency	Data Integrity	Privacy	Trust	Immutability	Investment Cost	Transaction Cost	Cost Efficiency	Standardisation	Regulations and Policies	Availability	Robustness	Consistency	Maturity	Suitability	Manageability
Alternatives	Blockchains	0.09264	0.09264	0.0926	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.09264	0.0926	0.09264	0.09264	0.09264	0.09264	0.09264
	Relational Databases	0.08958	0.08958	0.0896	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.08958	0.0896	0.08958	0.08958	0.08958	0.08958	0.08958
Performance	Scalability	0.02029	0.02029	0.0203	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.02029	0.0203	0.02029	0.02029	0.02029	0.02029	0.02029
	Transaction Throughput	0.03661	0.03661	0.0366	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.03661	0.0366	0.03661	0.03661	0.03661	0.03661	0.03661
	Transaction Latency	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178	0.0178
	Time Efficiency	0.02317	0.02317	0.0232	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.02317	0.0232	0.02317	0.02317	0.02317	0.02317	0.02317
Security	Data Integrity	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252	0.0252
	Privacy	0.03929	0.03929	0.0393	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.03929	0.0393	0.03929	0.03929	0.03929	0.03929	0.03929
	Trust	0.09743	0.09743	0.0974	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.09743	0.0974	0.09743	0.09743	0.09743	0.09743	0.09743
	Immutability	0.09428	0.09428	0.0943	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.09428	0.0943	0.09428	0.09428	0.09428	0.09428	0.09428
Cost	Investment Cost	0.00455	0.00455	0.0046	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.00455	0.0046	0.00455	0.00455	0.00455	0.00455	0.00455
	Transaction Cost	0.00806	0.00806	0.0081	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.00806	0.0081	0.00806	0.00806	0.00806	0.00806	0.00806
	Cost Efficiency	0.02227	0.02227	0.0223	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.02227	0.0223	0.02227	0.02227	0.02227	0.02227	0.02227
Interoperability	Standardisation	0.07073	0.07073	0.0707	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.07073	0.0707	0.07073	0.07073	0.07073	0.07073	0.07073
	Regulations and Policies	0.07877	0.07877	0.0788	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.07877	0.0788	0.07877	0.07877	0.07877	0.07877	0.07877
Reliability	Availability	0.02229	0.02229	0.0223	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.02229	0.0223	0.02229	0.02229	0.02229	0.02229	0.02229
	Robustness	0.06521	0.06521	0.0652	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.06521	0.0652	0.06521	0.06521	0.06521	0.06521	0.06521
	Consistency	0.04491	0.04491	0.0449	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.04491	0.0449	0.04491	0.04491	0.04491	0.04491	0.04491
	Maturity	0.03376	0.03376	0.0338	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.03376	0.0338	0.03376	0.03376	0.03376	0.03376	0.03376
Functionality	Suitability	0.06481	0.06481	0.0648	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.06481	0.0648	0.06481	0.06481	0.06481	0.06481	0.06481
	Manageability	0.04835	0.04835	0.0484	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.04835	0.0484	0.04835	0.04835	0.04835	0.04835	0.04835