Digital Twin – an Exploratory Study on its Opportunities and Challenges from a Supply Chain Perspective

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Abstract

Title: Digital Twin – an Exploratory Study on its Opportunities and Challenges from a Supply Chain Perspective

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Problem description: Northvolt, a newly established battery manufacturer in Sweden, aims to produce the greenest battery at the most competitive price. Consequently, they have high demands on their supply chain performance. Northvolt therefore seeks to look into new technologies that can help improve supply chain operations. One of these technologies is digital twin; a virtual representation of a real-world entity or system, used to understand and predict the physical equivalent's performance. They want to look into how this technology could be applied on their entire supply chain and what factors they need to consider before a potential implementation.

Purpose: The purpose of this study was to investigate digital twin in supply chain and evaluate its opportunities and challenges in relation to Northvolt.

Research questions: RQ1) How can digital twin create added value for Northvolt's supply chain? RQ2) What factors are important for Northvolt to consider before implementing digital twin?

Methodology: As there is little information available on digital twin in supply chain, the thesis was constructed as an explorative study of a qualitative nature. Firstly, a literature review was conducted on the subject. Two different types of case studies were then performed with unstructured interviews as the main data collection technique. The first type, in the thesis referred to as case study one, is a single case study. Case study one includes general information about Northvolt's product as well as supply chain and digital infrastructure characteristics, generated from in-depth interviews with eight Northvolt employees. The second type, in this thesis referred to as case study two, is a multiple case study. Case study two consists of three cases; digital twin insights from consultants, solution providers and a use case. The consultant and solution provider cases consists of three interviewees each and the use case of two interviewees.

Conclusion: Digital twin can create added value for Northvolt's supply chain, for example by ensuring that the supply chain operates at the lowest possible cost, and with a minimal emissions footprint, thus supporting Northvolt's value offering. Before implementing a digital twin it is important to consider that there is a real business case behind it and that the challenge at hand cannot be sufficiently solved with existing systems. Furthermore, Northvolt needs to be prepared with a digital infrastructure that supports the digital twin, more specifically a digital thread that entails that all supply chain operations are digitally traceable.

Keywords: Digital Twin, Supply Chain, Battery Industry, Digitalisation Strategy

Sammanfattning

Titel: Digital Tvilling – en Explorativ Studie av dess Möjligheter och Utmaningar utifrån ett Försörjningskedjaperspektiv

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Problembeskrivning: Northvolt är en nyetablerad batteritillverkare i Sverige som siktar på att producera det grönaste batteriet till det mest konkurrenskraftiga priset. Northvolt ställer därmed höga krav på försörjningskedjans prestation och vill därför undersöka nya teknologier som kan förbättra försörjningskedjan. En av dessa teknologier är digital tvilling; en virtuell representation av en verklig enhet eller system, använd för att förstå och förutse den fysiska motsvarighetens prestanda. De vill undersöka hur denna teknologi kan appliceras på hela deras försörjningskedja och vilka faktorer de behöver beakta innan en potentiell implementering.

Syfte: Syftet med den här studien var att undersöka digital tvilling i försörjningskedjan och utvärdera dess möjligheter och utmaningar i förhållande till Northvolt.

Forskningsfrågor: FF1) Hur kan en digital tvilling skapa mervärde för Northvolts försörjningskedja? FF2) Vilka faktorer är viktiga för Northvolt att beakta innan man implementerar en digital tvilling?

Metod: Då det finns begränsat med information tillgänglig om digital tvilling i försörjningskedjan, så konstruerades detta arbete som en explorativ studie av en kvalitativ natur. Först genomfördes en litteraturstudie på ämnet. Två typer av fallstudier genomfördes därefter, där ostrukturerade intervjuer utgjorde den främsta datainsamlingstekniken. Den första typen, i denna rapport refererad till som fallstudie ett, är en enskild fallstudie. Fallstudie ett inkluderar allmän information om Northvolts produkt, samt försörjningskedja- och digital infrastrukturkaraktäristik insamlat från intervjuer med åtta Northvolt-anställda. Den andra typen, i denna rapport refererad till som fallstudie två, är en multipel fallstudie. Fallstudie två består av tre fall; konsulter, lösningsleverantörer och ett användarfall. Konsult och lösningsleverantörsfallen består av intervjuer från tre personer vardera och användarfallet av intervjuer av två personer.

Slutsats: Digital tvilling kan skapa mervärde för Northvolts försörjningskedja genom att till exempel möjliggöra minskning av kostnader och reducering av det ekologiska fotavtrycket och på vis stötta Northvolts värdeerbjudande. Innan implementation av en digital tvilling är det viktigt att överväga att det finns ett verkligt användarfall och att den förestående utmaningen inte kan lösas med existerande system. Northvolt behöver vara förberedd med en digital infrastruktur som stödjer den digitala tvillingen, mer specifikt en digital tråd som innefattar att all verksamhet i försörjningskedjan är digitalt spårbar.

Nyckelord: Digital Tvilling, Försörjningskedja, Batteriindustri, Digitaliseringsstrategi

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Johanna Falk & Emma Sandén

Stockholm, February 2021

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Abbreviations

AI	Artificial Intelligence
API	Application Programming Interface
CPS	Cyber Physical Systems
ERP	Enterprise Resource Planning
EV	Electric Vehicle
IoT	Internet of Things
GHG	Greenhouse Gas
ML	Machine Learning
NASA	National Aeronautics and Space Administration
S&OP	Sales and Operations Planning
SKU	Stock Keeping Unit
TMS	Transport Management System
WMS	Warehouse Management System

1 Introduction

This chapter explains the background of the thesis and provides a description of the company the thesis is centred on. The problem formulation and purpose of the research are defined and presented in research questions. Furthermore the scope is determined and delimitations stated. Lastly, the target group is presented and the structure of the thesis is outlined.

1.1 Background

At the forefront of the fourth industrial revolution, technologies enabling smart manufacturing seek to shift the way traditional manufacturing companies function (Neto et al., 2020; Fuller et al., 2020). Digital twin has recently become the centre of attention for industry and academia, and is recognised as one of the most promising technologies for accomplishing smart manufacturing (Tao et al., 2019).

The most advanced digital twin solutions involve automatic data exchange between the virtual space and the physical space (Murphy et al., 2019; Fuller et al., 2020; Shao et al. 2019; Kritzinger et al (2018); Yildiz et al. 2020). The virtual space is updated with real-time information from the physical world, and if the virtual space is authorised it is able to make decisions that are directly implemented in the physical space.

Mathematical models of real-world entities or systems have been used by engineers and industry for many years (Dohrmann et al,. 2019). These models have become more and more complex and the evolution of smart technology has enabled the linkage of offline physical objects with virtual models. The advancement of the Internet of things (IoT), cloud computing, machine learning (ML), artificial intelligence (AI), cyber-physical systems (CPS), big data and data analytics has facilitated the realisation of digital twin, which market is predicted to grow by 58% until 2026 (Shao et al. 2019; MarketsandMarkets, 2020). A pivotal challenge for smart manufacturing is the connectivity between physical and virtual spaces. Digital twin can handle such challenges by seamlessly integrating the aforementioned technologies. This allows for rapid analysis, real-time decisions and streamlined supply chains (Tao et al., 2019; Fuller et al., 2020).

As a consequence of global manufacturing, the world is facing severe environmental challenges. To date, global production comprises a global environmental cost of 4.7 trillion US dollars each year (Li et al. 2020). Natural resources are consumed to a rate that is more than 50% of the ecosystem's regeneration capacity. Furthermore, around 40% of global greenhouse gas (GHG) emissions are caused by the transport and power sector (World Economic Forum and Global Battery Alliance, 2019). These numbers will be amplified as the world population continues to grow. Smart manufacturing, which is having an unprecedented impact on world economy, will be a major enabler of increased global production capacity. On that account, it follows that increasing sustainability in the manufacturing industry, as well as in the transport and energy sector, is crucial to enable a sustainable future. Hence, it is critical to integrate sustainable development strategy into supply chain management, and production solutions must be evaluated based on feasibility with the sustainability strategy (Li et al. 2020).

The World Economic Forum and the Global Battery Alliance (2019) describe that to reduce the global GHG emissions, the transportation and energy sector needs an alternative source of energy. Batteries are a fundamental enabler of such an energy shift, and a circular, responsible battery value chain is one of the major drivers to reach the 2°C Paris Agreement goal. If done right, batteries could capacitate 30% of the required reductions in the energy and transport industry, generate 10 million sustainable jobs, and supply electricity access to 600 million people who currently lack access. However, the World Economic Forum and the Global Battery Alliance highlights that this can only be realised with a systemic strategy across all sustainability dimensions, more specifically the social, environmental and economical dimensions.

Northvolt is a Swedish company with the mission to facilitate the deployment of sustainable, high-quality battery cells and systems. The company is a part of the European Battery Association, working towards achieving a sustainable circular battery economy for the European market. The commitment to sustainability is the company's backbone and also the reason for building battery manufacturing operations that are fundamentally different to traditional battery production as of today. This means that sustainability needs to be incorporated throughout all company activities, with the end-to-end supply chain being a very important aspect.

In addition to the sustainability challenges that global manufacturing companies are facing, additional challenges such as political and economic instability are further risks to account for. Global supply chains are inherently sophisticated and complex systems, profoundly vulnerable to disruptions (Saberi et al. 2018). The COVID-19 pandemic has resulted in a situation for global manufacturers marked by volatility, uncertainty, complexity and ambiguity. As Harapko (2020) describes, the COVID-19 pandemic has shown the importance of transparent and real-time information in order to manage such disruptions. According to him, the key for a successful supply chain is end-to-end visibility. End-to-end visibility is also highlighted by Steinberg (2020) who explains that it will help companies to mitigate risk and reduce cost across the supply chain. With a transparent supply chain, companies can conduct what-if analyses on what impact disruption has on all levels of suppliers, i.e. tier N suppliers, and make proactive decisions to select the optimal approach. Steinberg also states that the COVID-19 pandemic should remind companies of the persistent risk of an unanticipated disruptive event and that proactive planning is systemic to mitigate the potential effects of such an event.

Barykin et al. (2020) make a distinction between operational risks and risks caused by force majeure. The abovementioned disruptions and risks are classified as the second of these two. Operational risks pertain to risks generated by supply and demand uncertainty along with interference in information flows across the supply chain. These two types of risks lead to supply chains with low reliability and stability and is, according to Barykin et al., the reason for the need of digital twin in supply chain. Harapko (2020) argues that industries with complex manufacturing operations are perfectly suited to gain from implementing a digital twin, in terms of visibility, cost and sustainability. Opportunities such as, demand sensing, streamlined operations, risk identification and improved supplier collaboration could be lost without the end-to-end visibility (Steinberg, 2020). With a digital twin the key drivers to cost inefficiency and environmental footprint could easily be identified from the end-to-end supply chain exposure it gives.

1.2 Company Description

Founded in 2016, Northvolt is in the process of establishing its supply chain. In Skellefteå, Sweden, the company's primary manufacturing site is currently being built, a Gigafactory with an expected annual capacity of 32 GWh and a future potential of 40 GWh. The commissioning phase of Northvolt Ett is expected to finish in the fourth quarter of 2021, with production up and running by the end of 2021. A joint venture with Volkswagen has enabled a second Gigafactory, Northvolt Zwei, which will be located in Salzgitter, Germany, with an expected initial annual output of 16GWh. Additionally, the initial facility set-up comprises of a demonstration and research facility named Northvolt Labs in Västerås, Sweden, an industrialisation and assembly facility in Gdansk, Poland, and an electric vehicle (EV) battery recycling facility in Fredrikstad, Norway, which is a joint venture with Hydro.

Specialised in lithium-ion technology, Northvolt will offer two product solutions, more precisely battery cells and battery systems. These two solutions will be offered in four major markets; portable and micro mobility, automotive, grid and industrial. In the list below, the market applications are further explained.

- The portable and micro mobility market relates to battery powered tools and appliances as well as mopeds and bicycles.
- Automotive market covers EVs, i.e. electric cars, trucks and buses.
- Grid market refers to solar and wind power, saunas and cranes.
- Industrial market relates to areas as agriculture, mining and construction machines as well as ships, trains and planes.

With the mission to have a closed loop for their batteries, a circular end-to-end supply chain is being established. A complete battery recycling ecosystem will be developed, involving automated dismantling and crushing, cutting-edge hydromet technologies and a distributed smart recovery infrastructure. Their factory in Skellefteå will be equipped with a comprehensive recycling plant that is planned to be ready for operations in 2022 with the aim of recycling 50% of Northvolt's batteries in 2030. A circular approach diminishes the need for mining raw materials, decreases the environmental footprint per battery and is more cost-effective. These aspects are of high importance for Northvolt as their goal is to develop the world's greenest battery cell at the most competitive price.

1.3 Problem Formulation

Northvolt have high demands on their supply chain performance as they want to deliver the world's greenest battery to the most competitive price. Northvolt therefore wants to investigate digital twin to see if it can help them build a well-functioning supply chain that supports the company's goals and objectives. In addition, Northvolt wants to understand important implementation aspects of the technology, seeing as they are in the process of not only establishing their supply chain but also their digital infrastructure. By understanding this, they can make sure they do not risk building it in a way that does not support digital twin.

1.4 Purpose

The purpose of this study was to investigate digital twin in supply chain and evaluate its opportunities and challenges in relation to Northvolt.

1.5 Research Questions

The purpose of the thesis was achieved by answering the following research questions. The first question aims to provide a point of view on the value offering of digital twin with regard to Northvolt's supply chain. The second question aims to identify implementation aspects that are important for Northvolt to consider.

RQ1) *How can digital twin create added value for Northvolt's supply chain?*

RQ2) *What factors are important for Northvolt to consider before implementing digital twin?*

In order to answer the main research questions, the following sub-questions were formulated.

SQ1) *What are the characteristics of Northvolt's supply chain and it's digital infrastructure?*

SQ2) *What is digital twin?*

SQ3) *What are the opportunities and challenges with digital twin in supply chain?*

1.6 Scope

In order to be able to handle the task at hand within the timeframe of 20 weeks, the scope is limited to describing the characteristics of the supply chain pertaining to Northvolt Ett. This has been agreed with Northvolt to provide a satisfactory point of view that can be applied throughout all company operations. However, as Northvolt is already implementing a digital factory, the major focus of this thesis is not on manufacturing, but on the other supply chain entities. Moreover, only internal supply chain entities have been considered due to the fact that Northvolt is still in its commissioning phase and the supply chain is not completely in place yet.

The characteristics of Northvolt Ett's supply chain have been reviewed at an entity level and not on a process or item specific level. Additionally, in order to not lose the systems view, all the entities will be looked at from an integrated perspective.

Lastly, this thesis investigates digital twin as a concept with a focus on supply chain and will therefore not provide an in-depth technical explanation of the technology.

1.7 Target Group

The thesis has been created for Northvolt and aims to explore and describe the opportunities and challenges of digital twin for the company's supply chain. However, there are two additional identified target groups for the thesis.

Any company seeking to investigate digital twin can use this thesis to broaden their knowledge of the technology as well as gain insights into important implementation factors.

Lastly, academics can benefit from reading this thesis as it provides a practical aspect of the supply chain application of digital twin, which to date is rare to find in the existing literature.

1.8 Structure of the Thesis

To provide the reader an overview of the thesis, the structure of the thesis is presented in Table 1.1 below.

Table 1.1: Structure of the Thesis

1. Introduction	*This chapter explains the background of the thesis and provides a description of the company the thesis is centred on. The problem formulation and purpose of the research are defined and presented in research questions. Furthermore the scope is determined and delimitations stated. Lastly, the target group is presented and the structure of the thesis is outlined.*
2. Methodology	*The methodology chapter presents the methods that have been used for this thesis. The chapter is introduced by describing the overall research approach for the thesis and followed by a detailed description of the research methods. The logic behind and reasons for the approach are explained. The chapter ends with an elaboration on research validation and reliability.*
3. Literature Review	*In this chapter, the background of digital twin is presented along with its definition and concept. The technological structure of digital twin is also described and supply chain applications and challenges are presented.*
4. Case Study	*This chapter consists of two case studies; the single case study (case study one) and the multiple case study (case study two). Case study one presents the reader with general knowledge about Northvolt's product as well as in-depth interview reports with eight Northvolt employees. The second case study contains interview reports from three different actors; consultants, solution providers and a use case. The consultant and solution provider groups consist of three candidates each, and the use case of two candidates.*

5. Analysis and Results	*In the following chapter findings from the case studies are presented and analysed together with the literature review. The first two sections focus on summarising the two case studies and answering SQ1, SQ2 and SQ3. The third section consists of a cross case analysis and aims to answer RQ1. Finally, the last section focuses on RQ2.*
6. Conclusions	*In this chapter, the research questions are answered and recommendations for Northvolt are presented.*
7. Discussion	*This chapter discusses the generalisation of results and the contribution to research. Lastly, limitations and future research recommendations are presented.*

2 Methodology

The methodology chapter presents the methods that have been used for this thesis. The chapter is introduced by describing the overall research approach for the thesis and followed by a detailed description of the research methods. The logic behind and reasons for the approach are explained. The chapter ends with an elaboration on research validation and reliability.

2.1 Overall Research Approach

Arbnor and Bjerke (2009) describe that the study of a subject can be approached with different methodological views, each generating different presumptions about the subject. The presumptions influence how the studied subject is understood, explained and analysed, wherefore it is important to reflect upon how the view is affecting the research. Arbnor and Bjerke present three methodological views that are particularly suitable when studying a business; the analytical view, the systems view and the actors view. When studying logistics and supply chain management, two of these three approaches are relevant; the analytical approach and the systems approach (Gammelgaard, 2004). The systems view and systems theory creates a suitable framework when studying a group of objects or components that congruently produces results (Arbnor and Bjerke, 2009). These objects can for example be the different functional areas in a supply chain.

Gammelgaard and Nilsson (2012) accentuates the importance of understanding supply chain systems to value total cost and prevent sub-optimising. Thus, when studying an end-to-end or multiple entities of a supply chain, all functional areas of the supply chain need to be viewed as a system, supporting each other to achieve common goals. The desired synergy effect, Arbnor and Bjerke (2009) explain is possible in systems, wherefore the systems view is suitable when studying this topic.

When using the systems view as a research approach, breaking down reality into parts is useless. Reality must rather be understood contextually than universally, with mutually dependent objects and feedback mechanisms. Instead of looking for universal cause-effect-relations, cases should be studied. The systems view is a pragmatic approach searching for a problem solution that works in reality, rather than the absolute truth (Gammelgaard, 2004).

Furthermore, when selecting the methodological approach for the study, Höst et al. (2006) explain that the characteristics and purpose of the subject of study should be considered. Based on Robson's classification of the purposes, Höst et al. (2006) delineates the study of a subject into four categories, descriptive, exploratory, explanatory or problem-solving. Since this thesis researches a relatively unknown phenomena, it is according to Höst et al. of an exploratory nature.

2.2 Research Methods

2.2.1 Introduction

When selecting research methods they need to be in harmony with the chosen methodological view (Arbnor and Bjerke 2009). Gammelgaard (2004) suggests that for a systems approach, the method should be qualitative and quantitative case studies and that when performing data analysis mapping and modelling is of preference. This laid the foundation for the research approach in this thesis.

As the thesis was of an explorative nature, with the purpose of creating an in-depth understanding of digital twin from a supply chain perspective, the selected methods were chosen due to their ability of providing comprehensive knowledge and understanding. When performing exploratory research, a case study methodology is ideal since it provides deeper insight into subjects that are relatively unexplored (Höst et al., 2006; Ellram, 1996; Gammelgaard, 2003).

In Figure 2.1 below, the unit of analysis of this thesis has been highlighted in the black triangle. The thesis focuses of the particular value digital twin can create for Northvolt's supply chain, and the factors that need to be considered before implementing it.

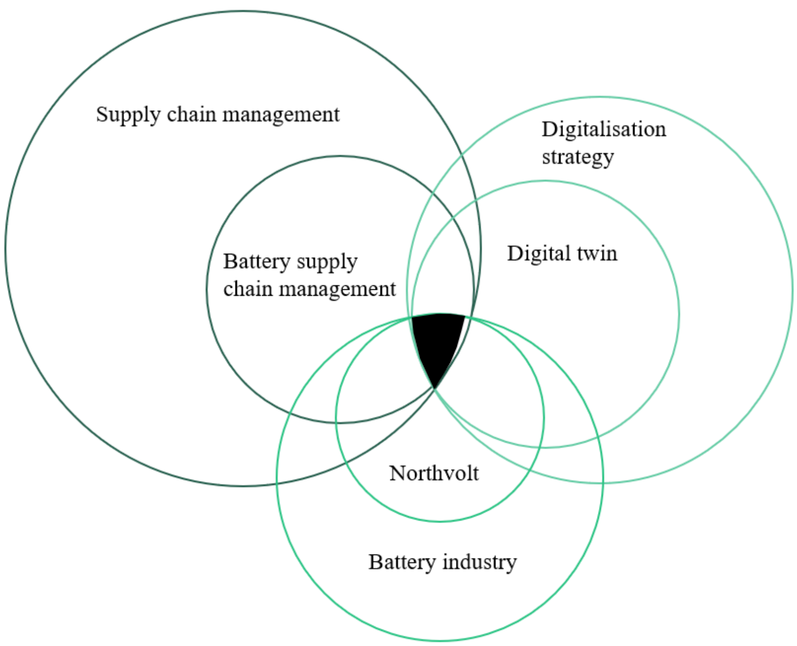

Figure 2.1: The Thesis' Unit of Analysis

The investigation model used when developing this thesis can be seen in Figure 2.2. To answer the research questions, two types of case studies were used, namely a single case study (case study one) and a multiple case study (case study two). The two types are further explained in the subsequent sections. The knowledge base on digital twin used in the case studies was provided by the literature review. The literature review further supported the development of the data collection methods as well as contributed with insights for the analysis and conclusions.

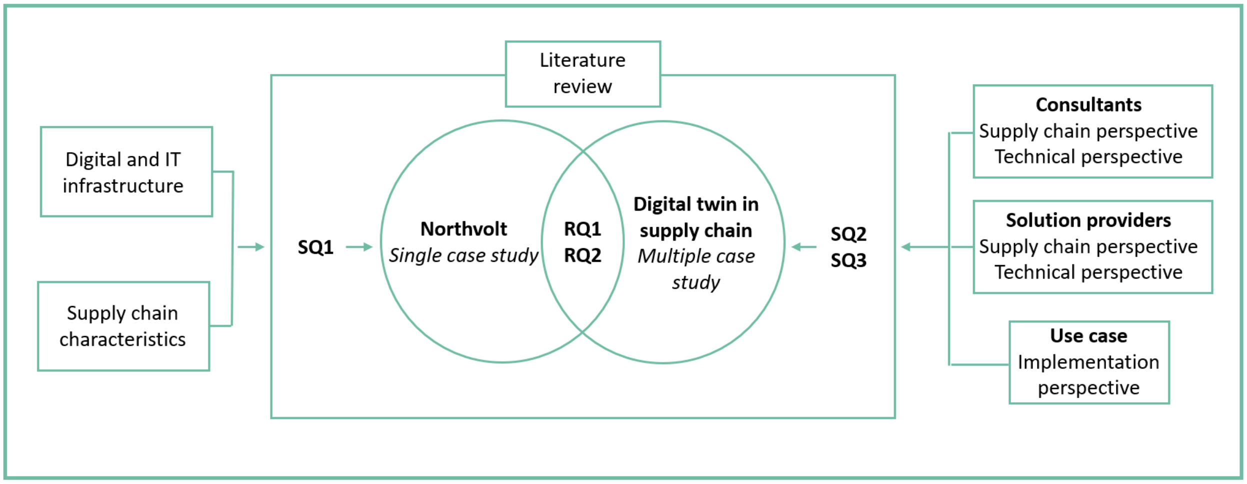

Figure 2.2: Investigation Model

2.2.2 Literature Review

An important part of any research is to build on previous research in the subject field by conducting a literature review (Rowley & Slack, 2004). This provides a summary of the state of the art and allows the researchers to focus their work on areas in the field that have not yet been explored. In this thesis, the literature review was performed on the subject field digital twin.

The database LUBsearch provided by Lund University was used to find relevant literature. Search words that were used were; "digital twin logistic", "digital twin factory", "digital twin manufacturing", "digital twin industry", "digital twin battery", "digital twin warehouse" "digital twin distribution", "digital twin supply chain", "digital twin end-to-end" and "digital twin value chain".

More than 3000 papers were initially found and of these, 1763 papers were screened initially by their title. If the title implied that the article could be relevant, the short description was also read. Out of these, 72 articles were chosen for further screening in regard to their relevance to the supply chain perspective, this by reading their abstract and final conclusions. The relevant sources were then evaluated according to the five criteria given by Höst et al. (2006). These are:

1. Is the material reviewed and if so, by who?
2. Who is listed as guarantee for the credibility?
3. Is the research methodology credible?
4. Have the results been sourced in a context that is relevant for the research questions?
5. Have the results been confirmed and been used in other credible contexts?

With this criteria, the amount of papers were further limited and resulted in that 15 papers were used. The literature review was then performed according to Rowley and Slack's (2004) five stage framework. The framework consists of the following steps:

Stage 1 - Scanning documents: the process of becoming familiar with documents in the subject field and gaining insight into relevant key topics.

Stage 2 - Making notes: annotating the document and highlighting key themes and important texts.

Stage 3 - Structuring the literature review: organising the documents according to the identified key themes into sections.

Stage 4 - Writing the literature review: writing one section at a time according to the structure created in stage 3.

Stage 5 - Building a bibliography: keeping a record of all read documents and their source.

After iterating these steps, the authors became aware that there in general was limited literature available on the subject, a notion also made by Hasan et al. (2020) who claim that this depends on that digital twin still very much is in its infancy. Therefore, the academic papers were complemented with grey literature, namely articles written by business consulting firms. The total amount of such articles included in the literature review is four and the consulting firms were EY, Gartner and DHL Consulting.

2.2.3 Case Studies

As argued by Voss et al. (2002), case study research is one of the most effective research methods in operations management. It is specifically suitable when studying a new phenomenon and to establish new theory in the field. However, there are some challenges while performing case study research and as highlighted by Gammelgaard (2017), there is a lack of knowledge among logistics and supply chain researchers of how the research method actually should be performed. Typical challenges are that it is time consuming, it needs competent interviewers, that it can be difficult to make general conclusions from limited amount of cases and how to form suitable boundaries. Consideration needs to be taken to how predetermined boundaries could impact useful insights, and for that reason a more flexible design is preferrable for explorative research (Voss et al., 2002; Borgström, 2012). This was considered when choosing the methods and research design for the thesis, which have been iterated and developed many times to suit the purpose the best.

In order to answer the research questions two case studies were conducted; a single case study (case study one) and a multiple case study (case study two). To evaluate if the two selected case studies were properly designed, Gammelgaard's (2017) seven guidelines were looked into. The seven guidelines, which can function as check questions when performing case study research, are presented below.

1. Is your study really qualitative?
    - Qualitative research examines real-world problems and incorporates some sort of storytelling.
2. What is the aim of your case study?
    - This needs to be understood as different aims needs different research designs.

3. How did you select your cases?
    - To support the aim of the study, appropriate cases needs to be selected. This should be with consideration to their information thickness rather than there generalisation abilities.
4. What is the quality of your case study research?
    - Quality refers to both case selection and number of cases, as well as the method transparency with the audience. The results and conclusions must be traceable in the research, e.g. visibility of data collection protocols.
5. What is epistemological foundation of your case research?
    - Could for example be to examine closed or open systems.
6. Is an interpretivist or social constructivist approach suitable for your case research?
    - Most commonly is to use a positivistic approach, but as argued by Gammelgaard, an interpretivist or social constructivist approach is very applicable for qualitative case studies.
7. What is the story you want to tell?
    - The results of the case study should be written in a compelling way and in order to do so, it is recommended to have a balance between data, theory and powerful or proofing quotes.

Single case study - case study one

The single case study was used to answer SQ1. The choice of method is motivated by the first of the five single case rationales developed by Yin (2018), namely having a critical case to study. A critical case can be when the case is essential to the theoretical propositions and a single case study can be used to contribute to knowledge by confirming, challenging or extending theory. In this thesis, Northvolt's supply chain is a critical case as RQ1 cannot be answered without it. Northvolt's supply chain will therefore be the subject of case study one.

The scope, i.e. the selection of interviewees, of case study one is presented in Table 2.2 in the following section.

Multiple case study - case study two

The method used to establish knowledge about how digital twin works in practice, i.e. answer SQ2 and SQ3, was a multiple case study. The aim of case study two was to understand the new phenomenon of digital twin in supply chain, and thereby answer RQ1 and RQ2. To do so, three sub-cases were conducted to understand the perspective from the following categories of actors:

- Solution providers
- Consultants
- Use case (company with implemented digital twin in its supply chain)

According to Yin (2018), a multiple case study has considerable analytic benefits compared to a single case study. The selection of cases will be based on the prediction of similar results in order to get enough depth in the data collection to establish some generalisable success factors within industrial supply chains.

The scope, i.e. the selection of sub-case candidates, of case study two is presented in Table 2.3 in the following section.

2.3 Data Collection Techniques

2.3.1 Selection of Techniques

The data collection techniques for the two case studies are presented in Table 2.1 below. The three techniques are derived from the Six Sources of Evidence by Yin (2018). As the design of a case study is flexible, it can be changed during the process. For the remaining part of this thesis, the documentation data collection technique will be categorised as, and referred to, archival analysis.

Table 2.1: Three of Yin's Six Sources of Evidence: Strengths and Weaknesses (Yin, 2018)

Source of Evidence	**Strengths**	**Weaknesses**
Documentation	• Stable – can be reviewed repeatedly • Unobtrusive – not created as a result of the case study • Specific – can contain the exact names, references, and details of an event • Broad – can cover a long span of time, many events and many settings	• Retrievability – can be difficult to find • Biased selectivity, if collection is incomplete • Reporting bias – reflects (unknown) bias of any given document's author • Access – may be deliberately withheld
Archival records	• *[Same as those for documentation]* • Precise and usually quantitative	• *[Same as those for documentation]* • Accessibility due to privacy reasons
Interviews	• Targeted – can focus directly on case study topics • Insightful – provides explanations as well as personal views (e.g. perceptions, attitudes and meanings)	• Biased due to poorly articulated questions • Response bias • Inaccuracies due to poor recall • Reflexivity – e.g. interviewee says what interviewer wants to hear

2.3.2 Interviews

An interview can be structured in different ways depending on its purpose, i.e. structured as an unstructured, semi structured or a fully structured interview. For an explorative study Höst et al.

(2006) suggests using an unstructured interview as it allows the interviewees to reflect and describe on their own experiences with the studied phenomenon.

An unstructured interview should follow an interview guide with various areas of questions, but can be asked and formulated in different ways during the interview (Höst et al., 2006). However, the formulation of questions for the interview guide should be done carefully to avoid any biased answers that are not aligned with the needed inquiry. Yin (2018) mentions that starting a question with why can start a defensiveness, and a how-question can serve the purpose better. The interview guides can be found in Appendix A.

As highlighted in the investigation model, the literature review was used in both case studies. It acted as a foundation for the interview guides so that relevant questions could be asked about digital twin in supply chain.

To ensure that no important information was missed during the interviews, the authors recorded them with the interviewees' permission. The recordings were then transcribed into data collection protocols and summarised into individual case study reports for each interviewee. One case study report was written per interviewee despite the number of interviews performed with the same person.

Case study one interviews

The authors deemed that the following people would be able to provide a complete view of the supply chain characteristics pertaining to Northvolt Ett, see Table 2.2 below. As mentioned in 1.6 Scope, manufacturing operations are not focused on in this thesis. The interviews were performed during the time period 16/11/2020 – 14/01/2021.

Table 2.2: Case Study One Interviews

Interviewee	Role	Department	Scope of interview	Information about the interview
Candidate A	Director	Logistics	Identify Northvolt's supply chain goals and challenges	Two unstructured video calls á 1h
Candidate B	Senior Manager	Digitalisation	Map Northvolt's digital operations	Two unstructured video calls á 1h
Candidate C	Director	Metals and Raw Materials	Understand Northvolt's material flows and sourcing approach	Unstructured video call 40 min
Candidate D	Enterprise Architect	IT	Understand Northvolt's IT architecture and the aspects behind	Unstructured video call 40 min

Candidate E	Enterprise Systems Manager	IT	Understand Northvolt's IT architecture and the aspects behind, systems focused	Unstructured video call 40 min
Candidate F	Logistics Purchasing Manager	Logistics	Understand goals and challenges pertaining to logistics supplier management	Unstructured video call 1h
Candidate G	Manager Material Logistics	Logistics	Understand S&OP processes	Unstructured video call 40 min
Candidate H	Material Logistics Coordinator	Logistics	Map how material planning is conducted	Unstructured video call 1h

Case study two interviews

When performing case study two on digital twin, various actors on the market were interviewed, see Table 2.3. In order to ensure a thorough point of view of digital twin, the selection of actors was based on a triangulation approach where three types of actors were contacted.

Consultants with extensive experience within supply chain and insight into digital twin provided a thorough supply chain perspective. Three consultants from three different consulting firms were selected for interviews. Consultant A has done extensive research regarding digital twin in supply chain, and the authors contacted Consultant A after reading a digital twin article which was found relevant for this thesis. Consultant B has experience working with digital twin solutions in supply chain. Consultant C has extensive experience in supply chain management and an interest in digital twin.

Solution providers of digital twin technology contributed with more detailed technical information. Provider A works for a company that was one of the first to develop digital twin solutions in an industrial setting. Provider B works for another company that provides digital twin solutions with a focus on manufacturing. Provider C is the owner of a company that is a solution partner to the company that Provider A works for. Provider C's company provides digital twin solutions that focus on cost orchestration.

The use case provided comprehensive implementation insights and consisted of interviews with User A and Consultant D. User A works for the company that implemented digital twin in their supply chain and was responsible for the project. Consultant D works for the consultant company that was hired to give advice and consulting to User A's company. It should be noted that Consultant D works at the same company as Consultant B. The use case was chosen for the reason that it has been recognised by Gartner for its successful and innovative implementation of digital twin in supply chain. The authors' ambition was to include three business cases, however, more supply chain use cases could not be identified.

The interviews were performed during the time period 15/10/2020 – 10/12/2020.

Table 2.3: Case Study Two Interviews

Interviewee	Company	Role	Scope of interview	Information about the interview
Consultant A	Global management consulting firm	Partner	Concept, opportunities, challenges and implementation	Unstructured video call 1h
Consultant B	Nordic consulting firm	Senior Business Consultant	Definition, technical aspects and implementation challenges	Unstructured video call 1h
Consultant C	Global management consulting firm	Vice President Value Chain	Common supply chain challenges and the role of digital twin	Unstructured video call 30 min
Provider A	Global technology powerhouse	Country Product Manager, Digital Enterprise	Definition and current state, opportunities and implementation challenges	Unstructured video call 1h
Provider B	Global technology company	Global Product Manager	Definition, specific solutions and reasons for implementation	Unstructured video call 1h
Provider C	Swedish solution partner company	Owner and Managing Partner	Cost and emission focused solutions and technical aspect	Unstructured video call 1h
User A	Global manufacturing company	Business Transformation Manager	Supply chain planning, opportunities, challenges and implementation	Unstructured video call 1h
Consultant D	Nordic consulting firm	Senior Business Consultant	Supply chain planning, opportunities, challenges and implementation	Unstructured video call 1h

Interviewees in relation to investigation model

To visualise how the data obtained from the two case studies aims to answer the research questions, the interviewees have been mapped in the investigation model in Figure 2.3 below.

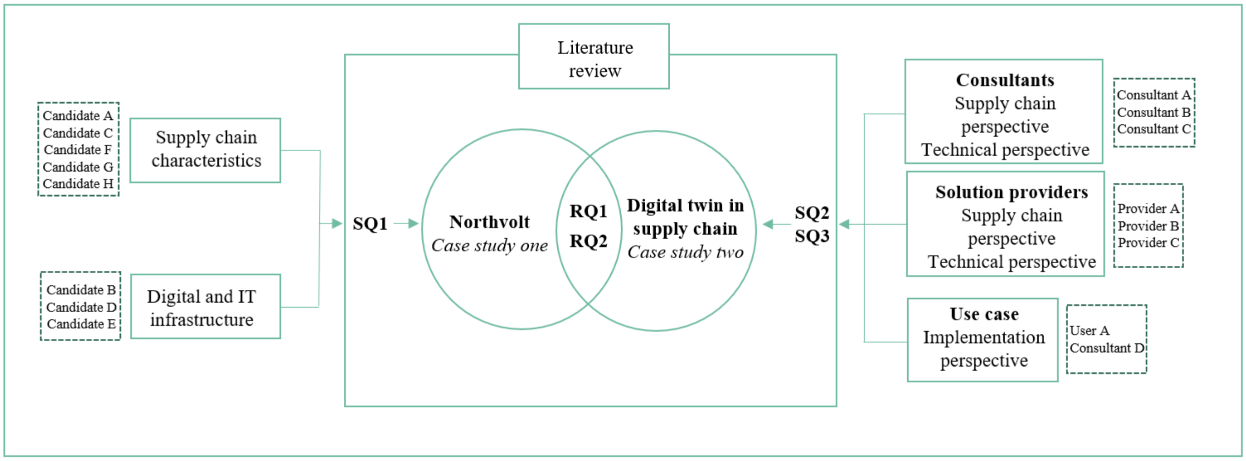

Figure 2.3: Interview Candidates in the Investigation Model

2.3.3 Archival Analysis

To collect further data about Northvolt, an archival analysis was performed. This is a collection technique focused on the extraction of data from company documents and reports (Höst et al., 2006). When using an archival analysis, it is important to keep in mind the origin of the documents and for what purpose they were created.

2.4 Method of Analysis

Gammelgaard (2012) accentuates that qualitative studies are not only about conducting interviews, but how the qualitative data is perceived and analysed. The two chosen methods in this thesis (single and multiple case study) are qualitative and were therefore analysed through a thematic analysis. The purpose of the thematic analysis method is to identify themes in qualitative data such as case study reports (Caulfield, 2020). Thematic analysis is used in many different fields of study for analysing qualitative data and the method most often follows a six-step process designed by Braun and Clarke (2006):

1. Familiarisation
   - Getting an overall view of the data and becoming familiar with it.
2. Coding
   - Highlighting important parts of the text and attributing these to colour coded labels so that main points can be identified and data pertaining to certain areas can easily be found. In order to complete this step, all data must be processed thoroughly.

3. Generating themes
    - Organising and sorting the codes into groups of themes. One theme can include several different codes. In this process, some codes may be discarded if they are no longer deemed relevant or not mentioned often enough.
4. Reviewing themes
    - Comparing the identified themes with the original data in order to make sure that the themes are represented in the data and that the codes have been sorted into the right theme.
5. Defining and naming themes
    - Giving each theme a name and definition.
6. Writing up
    - Writing of the analysis where each theme is discussed in terms of meaning and frequency of occurrence.

The goal of the thematic analysis of case study one was to answer SQ1: *What are the characteristics of Northvolt's supply chain and it's digital infrastructure?* As for case study two, the goal of the thematic analysis was to answer SQ2: *What is digital twin?* and SQ3: *What are the opportunities and challenges with digital twin in supply chain*? Lastly, the results from SQ1, SQ2 and SQ3 were used to perform a cross case analysis with the goal of answering RQ1: *How can digital twin create added value for Northvolt's supply chain* and RQ2: *What factors are important for Northvolt to consider before implementing digital twin?*

2.5 Research Quality

2.5.1 Theory

To ensure high-quality theoretical research, sources were reviewed according to Rowley and Slack's five stage framework mentioned in 2.2.2 Literature Review. Many sources were focused on digital twin in a factory setting, and this was therefore taken into account when writing about digital twin from a supply chain perspective. The authors were able to extract relevant information by keeping this in mind when reading the academic journals. Furthermore, many of the sources were published during the year of 2020, indicating that a lot of the information was new and not as proven as more established information might be.

Grey literature was used to a limited extent to complement the academic journals. This literature was not peer reviewed so the authors instead considered the author's and or publisher's knowledge and presence in the subject field of digital twin.

2.5.2 Data Collection

The quality of the case research was assessed according to four dimensions introduced by Yin (2018).

Construct validity

To ensure a construct validity of the thesis, several different types of sources have been used. In case study one eight internal employees of relevant positions were interviewed. Two employees were interviewed twice and the remaining were interviewed once.

In case study two, eight professionals from various disciplines and companies were interviewed, all selected based on their experience with digital twin and the applicability to Northvolt's supply chain.

To further ensure construct validity, all interviewees have reviewed the case study report pertaining to their interview and corrected any misconceptions.

Internal validity

A cross case analysis was performed on the data to find any relationships between the findings. The thematic analyses identified relevant patterns and explanations of digital twin and how Northvolt could gain from implementing it.

External validity

To make sure that the thesis had an external validity, the ability to draw generalised conclusions in other settings than Northvolt's was examined. This by investigating the replication logic of the findings in case study two.

Reliability

To secure that the same study can be conducted again with the same results, data collection protocols as well as case study reports were made. The data collection protocols were used as a basis for writing the case study reports, and the case study reports were included in Chapter 4. This was to enable method and results traceability, as explained in guideline number four by Gammelgaard, presented in 2.2.3 Case Studies. However, due to confidentiality requirements, the case study one reports have been partly censored in this version of the thesis.

2.6 Research Timeline

The thesis project was divided into four phases; initiation, planning, execution and conclusion stage. This structure enabled a scientific approach to the research project at hand and provided a clear structure to work with. The initiation stage included an onboarding with Northvolt and the reading of literature on how to write a scientific report. The project then moved into the planning stage which entailed formulating a project plan and researching methodology relevant to the subject field. After this was completed, the execution stage was initiated. This was the most extensive part of the project and included the following activities in the given order: literature review, case study one, case study two, analysis and results. Lastly, the conclusion stage was commenced. This entailed presenting the thesis at the Faculty of Engineering at Lund University and at Northvolt, and revising the thesis according to feedback from supervisors and opponents.

3 Literature Review

In this chapter, the background of digital twin is presented along with its definition and concept. The technological structure of digital twin is also described and supply chain applications and challenges are presented.

3.1 Background

The concept of digital twin first surfaced in 2003 when Michael Grieves proposed an idea of digital twin, inspired by David Gelernter's book Mirror Worlds from 1991 (Neto et al., 2020; Moyne et al., 2020). Grieves described a conceptual model with a virtual equivalent of a physical system, and the data flow between. The vision was that the technology could save physical resources during product development processes and to enable advanced analysis. His whitepaper on the subject marked an important milestone in the history of digital twin and has been used as a foundation for further research. In 2010 the National Aeronautics and Space Administration (NASA) defined the first version of the technology and thanks to them and the Air Force Research Laboratory, digital twin made its first appearance when it was applied on a space vehicle. Qi et al. (2019) describe that digital twin portrays the breakthrough of plenty limitations, such as data acquisition, digital description, and computer performance and algorithms. In 2016, Siemens utilised digital twin in Industry 4.0 and since then, the technology has been implemented by many companies and according to Gartner (2019), 24% of companies with IoT solutions in place or in progress already work with digital twin, and another 42% plan to implement it.

In Figure 3.1 below, important milestones in the history of digitalisation and digital twin have been visualised. The first model of digital twin included three dimensions, namely the virtual space, the physical space and the connectivity between them. To enable the technology to advocate further applications, a five-dimensional model was introduced by Tao and Zhang (2017). The five-dimensional model is based on the three above-mentioned dimensions as well as the two additional ones: data and services. These are further described in subsequent sections.

From the initial applicational area within the military and aerospace industry, the area of digital twin applications has gradually extended into civilian areas. Digital twin technology has been applied on every level from atoms to planets. The smallest digital twin can replicate the behaviour of material or an electrochemical process, and a digital twin could be used for the development of lithium-ion batteries or all-solid-state batteries (Dohrmann et al. 2019; Park et al., 2020). At the larger scale, a digital twin could represent a city or as the UK is currently investigating, the whole country with infrastructure, energy supply, buildings and utilities. Barykin et al. (2020) argues that the need for digital twin in supply chain origins in the overall low reliability and stability in supply chains, as described in the first chapter. A sustainable supply chain needs the right mix of reliability and flexibility, which in turn requires synchronisation of supply chain activities. In the wake of the fourth industrial revolution, conventional supply chains may no longer provide satisfactory results. To build a resilient supply chain, the supply chain design should be transformed from the typical linear, dis-synchronised relations to an interconnected network of trading partners which Barykin et al. further argues should be digitalised and provide on-demand services.

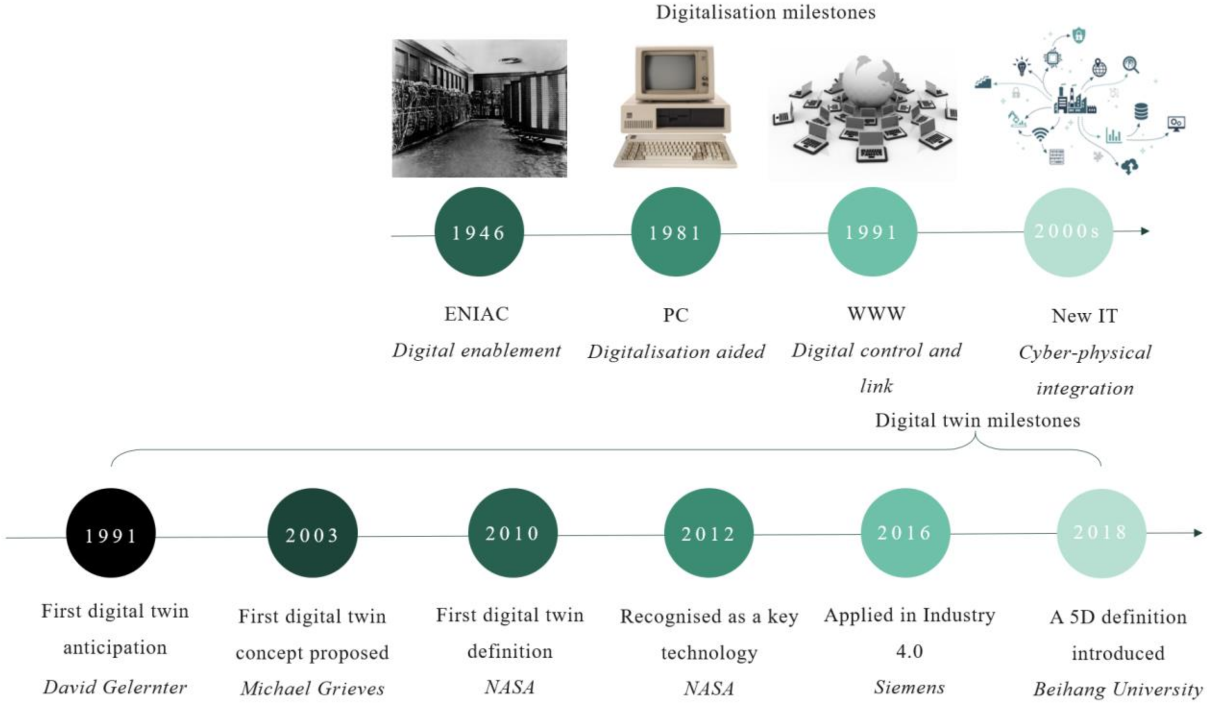

Figure 3.1: A History of Digital Twin, derived from Qi et al. (2019)

3.2 Definition and Concept

Despite the increasing attention towards digital twin in both industry and academia, there is currently no consensus regarding a definition for digital twin (Tao et al., 2019; Yildiz et al., 2020). Some academics state that the main focus of digital twin should be simulation, whereas other scholars claim that the main focus should be on three aspects, physical, virtual and connection (Yildiz et al., 2020). One of the most common definitions is however the one provided by NASA, stating that:

> *"Digital twin is an integrated multi-physics, multi-scale, probabilistic simulation of a product or system that uses the best available physical models, sensor updates, etc., to mirror the life of its corresponding twin" (Zeuxan Zhu et al., 2019).*

Another common way of defining digital twin that reappears in literature is the distinction between Digital Model, Digital Shadow and Digital Twin (Murphy et al., 2019; Fuller et al., 2020; Shao et al. 2019; Kritzinger et al (2018); Yildiz et al. 2020). The different concepts are separated by the level of data integration between the physical and virtual world, see Figure 3.2. To clarify, in this thesis "Digital Twin" (note uppercase letters) refers to this three-way distinction and "digital twin" (note lowercase letters) refers to the general term.

- Digital Model
  Described as a digital representation of a planned physical object, e.g. simulations of product designs or pre-existing processes. The essential aspect of a Digital Model is that there is no automatic data exchange between a physical and virtual space and a change in either of them will not influence the other.
- Digital Shadow
  A digital version of an physical object with data flow in one direction, from the physical object to the virtual. If the physical object is changed, so will the virtual but not the other way around.
- Digital Twin
  Automatic exchange of information between the virtual model and the physical model. The virtual world is constantly updated with real-time information from the physical world. The virtual model is able, if authorised, to make decisions that are directly implemented in the physical world.

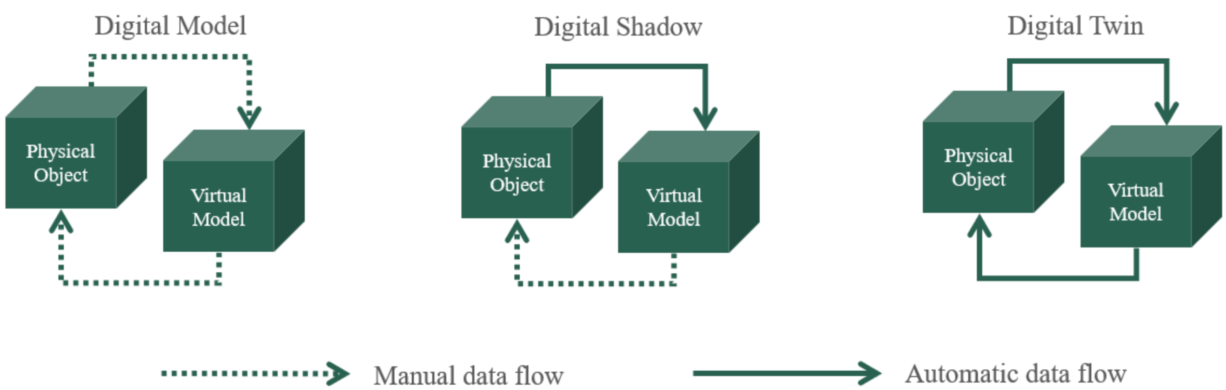

Figure 3.2: Digital Twin Concepts, derived from Fuller et. al. (2020)

The phrasing of the terms can be seen to imply that the Digital Model and Digital Shadow are misconceptions, as implied by Fuller et al. (2020), and that the correct definition of digital twin is the one pertaining to Digital Twin. Qi et al. (2018) emphasise the possibilities with a dynamic system with integrated data flows, and suggest that a digital twin should not just be a mirror of the physical system, i.e. be a Digital Model. Yildiz et al. (2020) support this statement, and claim that the integration of the physical and virtual world is an inevitable trend. However, according to a literature review performed by Kritzinger et al. (2018), the digital twin concept most commonly referred to in literature is the Digital Shadow (35%), followed by the Digital Model (28%) and lastly the Digital Twin (18%). Murphy et al. (2019) commented on this and stated that realisation challenges might be the reason for the shortcoming of Digital Twin classified literature. The availability of valuable real-time data and software and hardware interfaces poses a challenge for the implementation of these more advanced versions with an integrated data flow, thus resulting in few studies on the subject. Kritzinger et al. (2018) instead suggest that the concepts Digital Model, Digital Shadow and Digital Twin should all be viewed as subcategories to digital twin and that Digital Model and Digital Shadow are not misconceptions, but rather simplified versions of Digital Twin as they require less data integration.

The authors decided to adhere to the definition proposed by Kritzinger et al. and let all three terms fall under that of digital twin. This was motivated by the difficulty to distinguish between the terms in academia as well as in the industry. Furthermore, the authors were only able to discover a handful implementations of Digital Model and one of Digital Twin, resulting in that all three terms needed to be included in the study in order to provide a complete point of view.

3.3 Technical Structure

3.3.1 Introduction

Mathematical models of real-world objects have been built and used by researchers and industry during many years (Dohrmann et al,. 2019). These models has become more and more complex and the evolution of smart technology has enabled to link offline physical objects to virtual models. Smart technology has developed exponentially since Grieves initially introduced the concept of digital twin and digital twin solutions have therefore now become much more viable (Tao et al., 2019). The big technology concept breakthroughs for smart technology are identified as IoT, AI, big data analytics, ML, CPS and cloud computing.

As stated by Barykin et al. (2020), there is no unified opinion in which technologies should be used in a digital twin in supply chain. However, most scholars agree that the mix and simultaneous use of simulation, optimisation and data analytics lays the foundation of a digital twin. Barykin et al. (2020) identified that in addition to simulation, optimisation and data analytics, supply chain design and network optimisation are commonly referred as key technologies of digital twin.

As digital twin in supply chain is new territory, the five dimensional model presented by Tao and Zhang (2017) was used to describe the technological structure of a digital twin, see Figure 3.3. The model was created from a manufacturing point of view, but as it is practical as well as scalable it provides a good frame of reference for several areas of application (Qi et al., 2019). As aforementioned, the five dimensions are: physical entity, virtual model, data, smart service and connection.

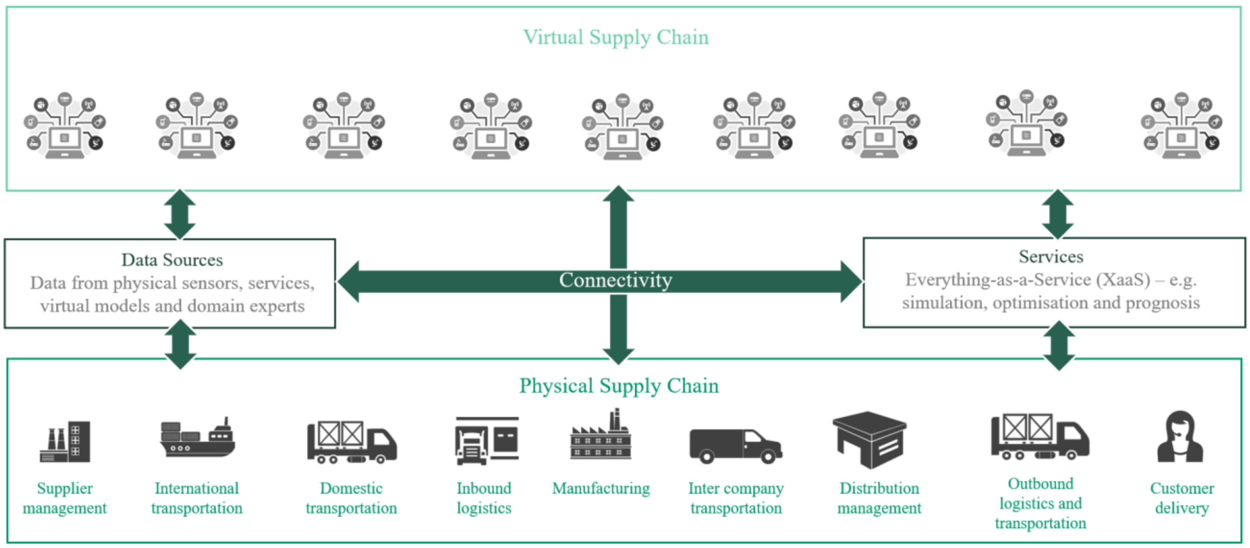

Figure 3.3: The Five Dimensional Model, derived from Tao and Zhang (2017)

3.3.2 Physical Entity

The physical world is often a complex one, characterised by its many attributes and relationships (Qi et al., 2019). Modelling the physical world in a virtual world requires that the internal logic of an entity is mapped, as well as the external connections. One of the first steps in being able to model the physical entity is to measure the parameters that make up the entity or process in question. Furthermore, if the virtual model is to be kept updated, real-time data has to be extracted from the physical world. In an advanced digital twin, such as the Digital Shadow or Digital Twin, the data is pulled on a continuous basis from its source and thus provides a rather accurate current-state of the physical entity or process. One of the main enablers for the perception of the physical world is big data, and big data analytics can in turn make the perception understandable and provide valuable insights.

3.3.3 Virtual Model

A virtual model refers to a digital representation of a physical entity or process that can be analysed and processed through a computer (Qi et al., 2019). One of the cornerstones in achieving a virtual model is modelling, which encompasses modelling of a geometrical, physical and behavioural nature as well as that of rule modelling. The first three aspects are more related to the modelling of an entity and not a process. Rule modelling is however applicable to both and provides the virtual model with the statutes it needs in order to be able to evaluate, judge, optimise and predict situations correctly.

According to Barykin et al. (2020), it is important that the virtual model be constructed through various visualisation technologies i.e. the simultaneous use of simulation and optimisation. The more accurate the virtual model is, the more effective the digital twin is. Two important aspects in reviewing how well the virtual model is made are verification, validation and accreditation technologies in order to validate the model and optimisation algorithms in order to optimise it (Qi et al., 2019). To create this virtual model, it is crucial that detailed descriptions of all processes, facilities, equipment and machinery are in place, as well as the integration of digital twin with business intelligence systems and enterprise resource planning (ERP) systems (Barykin et al., 2020).

3.3.4 Data

The foundation of digital twin is based on data. The data lifecycle of a digital twin consists of 6 steps; collection, transmission, storage, processing, fusion and visualisation (Qi et al., 2019).

Data can be collected from hardware, software and network applications (Qi et al., 2019). Hardware data refers to data collected through foremostly IoT technologies, such as barcodes, RFID, QR codes, sensors and cameras. Software data entails data that is sourced from application programming interfaces (API). Network data refers to data that can be collected from the internet, for example through search engines and APIs accessible by the public.

The second step, data transmission, refers to technologies that enable wire and wireless communication, these are for example fibre optic transmission, Wi-Fi and satellite communication (Qi et al., 2019).

The next step in the data lifecycle, data storage, requires advanced storage technologies (Qi et al., 2019). This is due to that the data is collected from a multitude of sources resulting in the compilation of big data, which is a term used to describe immense amounts of dispersed data. Storage technologies such as cloud storing and distributed file storage enable that these great amounts of data can be stored for analysis and processing.

The fourth step, data processing, refers to the work of sorting through large volumes of raw data and providing actionable information (Qi et al., 2019). The data set is often unstructured, incomplete and inconsistent, requiring data cleaning tools and data transformation tools to structure the data. When the data has been processed, it is then analysed with the help of statistical methods such as distribution analysis and neural network methods such as competitive learning.

Data fusion, the fifth step in the data lifecycle of a digital twin, relies on technologies that enable the fusion of the processed data, for example AI (Qi et al., 2019).

The last step, data visualisation, refers to the presentation of the data in a way so that it can be easily understood (Qi et al., 2019). This can be achieved by using technologies that can display the data in for example dashboards and various charts.

3.3.5 Service

The purpose of a digital twin is to deliver services such as advanced diagnosis, prognosis, simulation and monitoring. In order to achieve this, a digital twin relies on the integration of technologies (Qi et al., 2019). Diagnosis and prognosis can be performed with data analysis technologies such as machine learning and statistical theory. Monitoring is based on image processing, computer graphics, 3D rendering and synchronisation technologies. Simulation services include mechanical and structural simulation for product focused digital twin, and process simulation techniques for process focused digital twin solutions.

3.3.6 Connectivity

The connections between the different parts of digital twin consist of flows of data that ensure interaction between the dimensions (Qi et al., 2019). Furthermore, compatible communication interfaces and protocol technologies are needed to enable a smooth connection between the different dimensions. Furthermore, technologies that can ensure a secure handling of data is crucial as the digital twin, its network, devices and information must be protected as they contain highly sensitive information.

3.4 Supply Chain Applications

3.4.1 Introduction

Digital twin solutions have several applicational areas within the industrial sector. To date, the focus area of digital twin has been on design, production and prognostics and health management. According to Tao et al. (2019), digital twin is a powerful tool for product design, development and improvement. However, as pointed out by Dohrmann et al. (2019), digital twin can create value in many different ways. At an enterprise level, digital twin is a major enabler of improving productivity and efficiency. It can secure high service levels while minimising cost and time, and the dynamic and continuous real-time data collection improves accuracy and predictability (Qi et al., 2019; Wang et al. 2020). Companies that have implemented digital twin solutions have experienced the benefits in following three categories: data-driven decision making and collaboration, streamlined business processes and new business models. Digital twin allows companies to focus on higher-value activities since it can automate error-prone actions, e.g. inspection, testing, analysation and reporting. Dohrmann et al (2019) further argues that digital twin enables remote monitoring, diagnostics and optimisation of manufacturers assets, which helps improve availability and reduction of service costs. Although the value that can be gained from digital twin solutions is application dependant, Dohrmann et al. (2019) have summarised different ways digital twin can create value to the following: descriptive value, analytical value, diagnostic value and predictive value. Further explained in bullet points below:

- Descriptive value
    - Instant visualisation of asset statues, e.g. remote or dangerous assets.
    - Improvement of information accessibility and easier to interpret from a distance.
- Analytical
    - With simulation technologies incorporated in digital twin, data impossible to measure directly in the physical object can be provided.
- Diagnostic
    - If digital twin includes diagnostic systems, measured and derived data can be used to show root causes for states or behaviours.

    - The diagnostic systems can be composed in a way where explicated rules is based on company know-how or ML and data analytics approaches can be used to show root causes based on historical data.
- Predictive
    - Future behaviour and state of the physical entity can be predicted by digital twin.
    - The most complex digital twin solutions can even suggest solutions and actions to the predicted future state.

Modern supply chains are constantly on, constantly connected and constantly generating data. Digital twin could enable companies to fully understand the dynamics of their physical supply chain, and to leverage on the information accessibility (Dohrmann et al., 2019). The increasing prevalence of IoT and connectivity has led to that almost anything in supply chains can be real-time tracked and traced. Consequently, companies can continuously collect large amounts of supply chain data. Moreover, data drives information, information drives insight and insights inform decisions that allows for response and new business models (Andersson et al., 2020). All real-world data can be logged by digital twin in real time. This allows for critical hot spot detection and can give proactive warnings about potential disruptions in the supply chain (Barykin et al., 2019; Elliot, 2017). In Table 3.1 below, the value digital twin could create in various supply chain operations is described. The applicational areas of a digital twin in the supply chain operations are presented in the following sections.

Table 3.1: Application Areas of Digital Twin in Supply Chain, derived from Dohrmann et. al. (2019)

	Descriptive	**Analytical**	**Diagnostic**	**Predictive**
Overall	Real time visibility	What-if scenario planning	Main drivers for cost and emissions	Disruption prediction
Supply chain planning	-	Improves decision making Increases synchronisation of flows of goods and materials Supply to factory plan Distribution plan	Root-causes for inefficiency	Inventory management based on accurate forecasts
Logistics	Describe weather, traffic or macro level conditions and risks	-	-	Determine supply failure probabilities
Supplier management	-	-	-	Sourcing prices based of future market
Manufacturing	-	Making autonomous decisions about what, how and what to make to maximise profitability	Root causes for bottlenecks	Prediction of machine failure Predict bottlenecks

3.4.2 Supply Chain Planning

A fundamental component of global manufacturing is supply chain planning. The need for a digital, analytical and responsive supply chain planning approach is driven by the interest of reliability, efficiency and productivity (Wang et al., 2020). To maximise product value, supply chains needs to be orchestrated with a holistic approach. Planning has a major impact on the overall cost, productivity and quality. Summarised, planning comprises of three essential elements, i.e. what the concerned items are, quantity of purchased, delivered and produced goods, products and materials and the start and finish of the involved planning subjectivities, such as demand forecasting, aggregated planning and inventory planning. With forecasting as the base of supply chain planning, the dynamic and extensive data gathering done by digital twin substantially improves the planning activities. Moreover, if a company implements several digital twin solutions or integrates various systems used for different supply chain functions, the tremendous data collection allows for long-term forecasting and counteracts any silo-planning.

Wang et al. (2020) continues that digital twin will bring deeper understanding of how to plan, design, operate and optimise supply chains, all the way from individual assets and shipments to complete global networks. Digital twin will, by having an enormous data access, optimise the balance availability, inventory costs and lead times across supply chain networks. Complete supply chain visibility will give an overview of location and availability of material and products in inventory as well as suppliers, distribution partners and in sales channels. Furthermore, the supply chain set up could be optimised regarding aspects as supplier and manufacturing footprints, logistics lanes and configured stock locations to meet requested service levels, and ensure the response time promised to customers (Dohrmann et al., 2019).

3.4.3 Logistics

In logistics, digital twin solutions have so far not reached widespread implementation (Dohrmann et al., 2019). However, most of the enabling technologies are ready. IoT has been used for some years now as well as geographical information systems and the benefits of this can be extended by applying digital twin. Sensors are used in the industry today to trace shipments as well as machinery and equipment. There is also an increasing use of open API strategies and data migration to cloud-based systems. The design, operation and optimisation of logistics infrastructure could be substantially improved by digital twin, and it could also optimise the performance of automation systems.

One of the key elements of why digital twin would be suitable for warehouses and comparable facilities would be its contribution to continuous performance improvement (Dohrmann et al., 2019). The identification of waste will be easily detected by gathering data of the movement of inventory, equipment and personnel. Any potential set up changes could be tested in the digital twin. However, warehouses are just a small portion of the logistical operations. The goods and material flows depend on the orchestration of various activities, such as ships, trucks and aircraft, order and information systems and people.

3.4.4 Supplier Management

Supplier selection and management is known to have a substantial impact on competitive advantage in supply chain management. To successfully obtain a performance advantage compared to competitors when comparable suppliers are exposed to disruptions, supplier selection and management should be resilient. Thanks to modern technologies, as abovementioned, intelligent decision-making principles could also be used for supplier selection. Research made by Cavalcante et al. (2019) show that instead of focusing on estimating the probability of erratic events and disruptions, the focus should be on using data to forecast the supplier tendency to have, or to be exposed to major disruptions. This by gathering data of their financial state, their capacity and information about their suppliers.

3.4.5 Manufacturing

In production, digital twin could improve the predictability, resilience and reliability (Dohrmann et al., 2019). Digital twin in manufacturing is the most common digital twin, this since factories are data-rich environments with extensive use of automation and robotics systems, as well as IoT technologies and data-driven optimisation of performance. The slightest improvement of performance could in production be worth millions of dollars. Companies could use digital twin to predict component or machinery failure, bottlenecks, product quality or any hazards or production risks. It allows for running of complex what-if scenarios or to improve on-time delivery.

3.5 Supply Chain Challenges

In 2018, Gartner placed digital twin at the peak of inflated expectations in the Hype Cycle for Emerging Technologies, see Figure 3.4 (Panetta, 2018). This phase entails that there are many success cases of digital twin implementation, but that they are followed by a majority of failed attempts. At the peak of inflated expectations, some companies implement the technology, but most do not. Gartner anticipated digital twin to reach the plateau of productivity and become a mainstream technology in business in the next five to ten years, i.e. between 2023 and 2028 (Shetty, 2018).

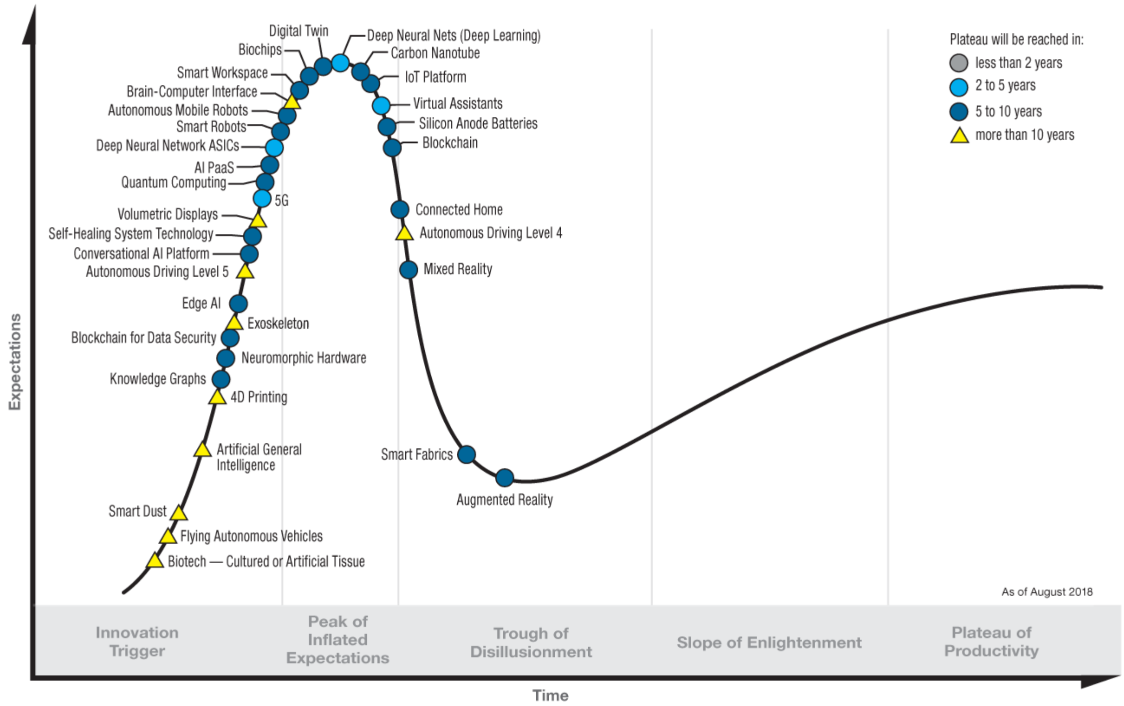

Figure 3.4: Gartner Hype Cycle for Emerging Technologies, 2018 (Panetta, 2018)

However, there are many challenges concerning digital twin, and some enabling technologies are still evolving. Dohrmann et al. (2019) summarised the key challenges of digital twin into seven major categories. These are further explained as:

- Cost
  The foundation of digital twin lies within a scalable, digital ecosystem comprising technology platforms, continuous development of models and maintenance. Most of these costs decreases as the technologies reaches wide-spread application but the decision of implementing digital twin must be in comparison to other solutions with the same value at lower cost.
- Precise Representation
  A major challenge will be to overcome any data gaps or inconsistencies in data streams that occurs where digital twin lacks precision. It is an immense challenge to match the physical, chemical, electrical, and thermal state of a complex asset. With the modern technology this must be complemented with assumptions and simplifications to have an economic viable digital twin.
- Data Quality
  The digital twin will be as good as the data is. To collect data from thousands of IoT applications, operating remotely or in complex conditions or over unreliable networks is an extreme challenge. This in combination with accessing data from systems generating various data types. To overcome these issues, companies needs to have methods in place to identify and remove bad data and to manage the data gaps.

- Interoperability
  There are commercial and technical data exchange challenges that remain despite essential progress in openness and standardisation. Using digital twin solutions from a certain supplier could make it difficult, or even impossible, to reproduce the same functionality with other suppliers. Companies are likely to be locked into long-term single-provider relationships.
- Education
  Employees, customers and suppliers all need to be onboard with the new way of working that follows by implementing a digital twin. This requires change management and capability building.
- IP Protection
  The most sophisticated and advanced digital twin includes business critical information and know-how about the product, suppliers, customers and operational processes. This is followed by challenges in data ownership, identity protection, data control, and governance of data access by different user groups.
- Cyber Security
  As follows by the abovementioned challenge with IP Protection, digital twin will be a target for cyber criminals. By being able to control the physical entity with the virtual entity of digital twin, devastating real-world impact could be a fact if a digital twin would be exposed to a cyber-attack.

4 Case Studies

This chapter consists of two case studies; case study one and case study two. Case study one presents the reader with general knowledge about Northvolt's product as well as in-depth interview reports with eight Northvolt employees. The second case study contains interview reports from three different actors; consultants, solution providers and a use case. The consultant and solution provider groups consist of three candidates each, and the use case of two candidates.

4.1 Case Study One: Northvolt

The scope of case study one was to identify Northvolt's supply chain characteristics and to look into its digital and IT infrastructure. In Figure 4.1 below, case study one has been highlighted in the investigation model of the thesis.

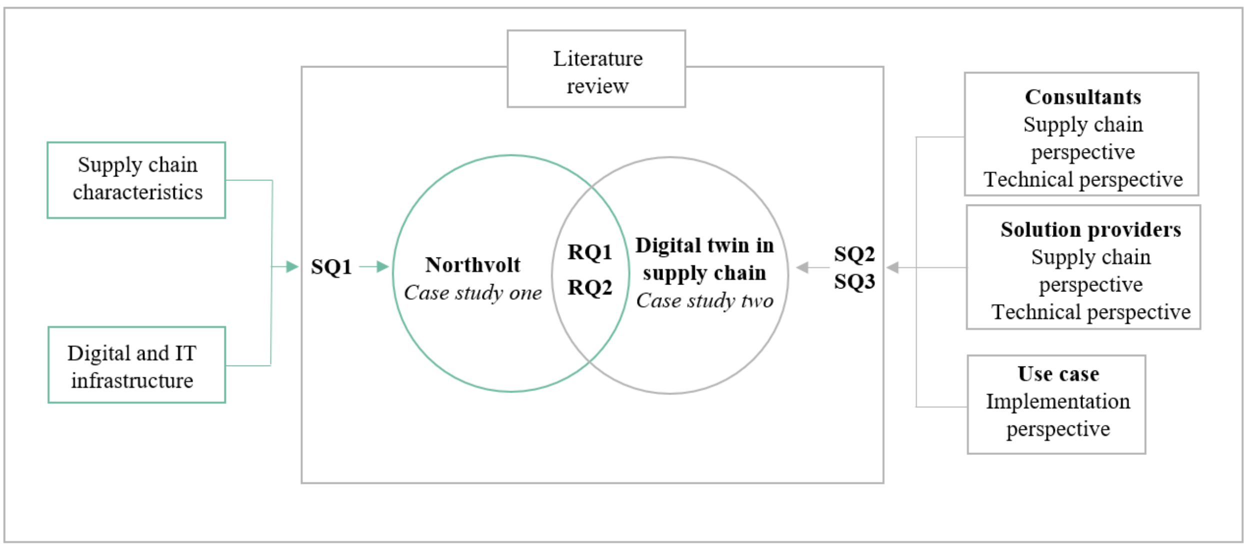

Figure 4.1: Case Study One Highlighted in Investigation Model

4.1.1 Archival Data: Northvolt's Product

One important characteristic of Northvolt's manufacturing, compared to other battery manufacturers today, is the focus on deep vertical integration. The ambition is to manufacture the majority of the parts in-house. The product portfolio produced at Northvolt Ett consists of two formats of lithium-ion battery cells, namely prismatic cells and cylindrical cells. It is in the battery cell the electrochemical reactions occur and is therefore the central part of a battery, which consists of several cells put together in modules and packs. The battery cells are placed in series or parallel combinations, and the two methods makes it possible to get any desired rating of voltage and capacity. In Figure 4.1 below, the two cell formats produced at Northvolt Ett are shown.

Figure 4.2: Prismatic Cell (to the left) and Cylindrical Cell (to the right)

A cylindrical cell has great mechanical stability, high specific energy and tolerates added safety features that are not achievable with other formats. This cell format is commonly used for portable appliances. A down-side with cylindrical cells is that they have less than the ideal packing density. A prismatic cell is space-efficient but typically more expensive to manufacture than the cylindrical cell. A case of aluminium or steel safeguards structural stability, mechanical robustness and humidity protection. The application area of prismatic cells are electric powertrain and energy storage systems. The main components of a battery cell, irrespective of format, are cathode, anode, electrolyte, separator, and a case. The total lithium-ion battery cell material cost is approximately distributed as per follows:

- Cathode 41%
- Anode 28%
- Electrolyte 9%
- Separator 16%
- Case 6%

In Figure 4.3 below, the five largest reserves of raw materials that are included in the battery cell components are illustrated. The figure shows that battery supply chains are highly dependent on global sourcing.

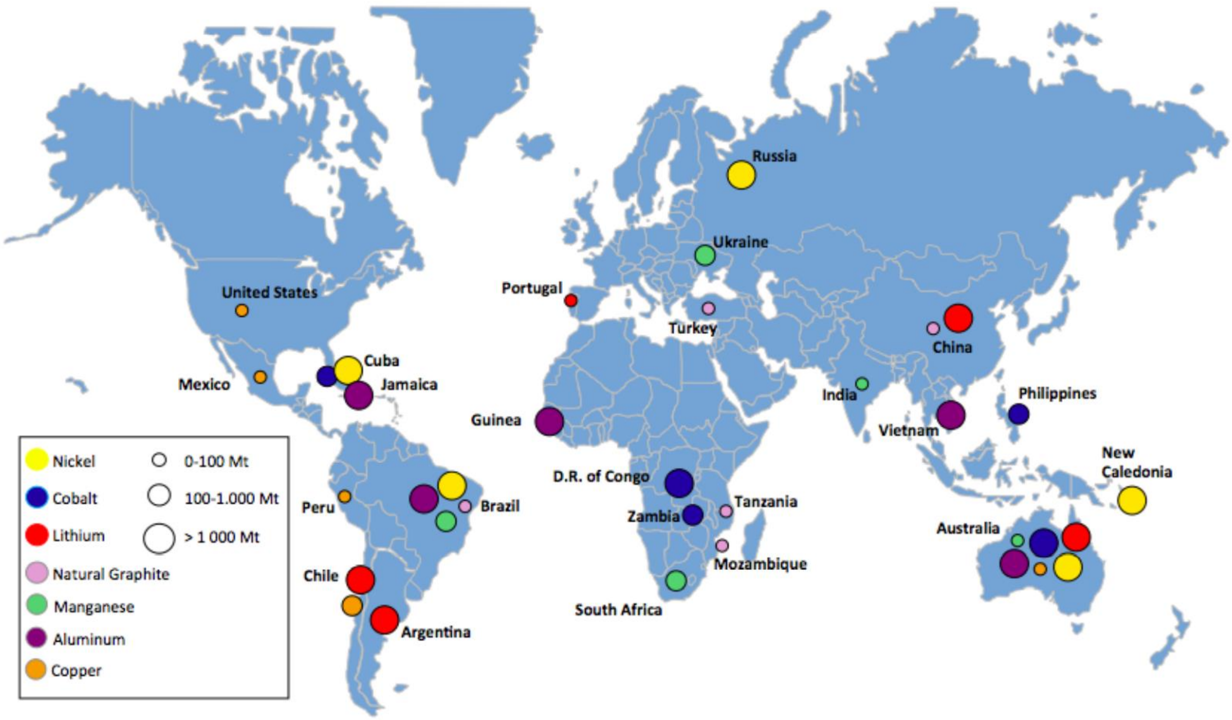

Figure 4.3: Battery Raw Material Reserves

4.1.2 Interview Data: Northvolt's Supply Chain

Case study one consists of the interviews in Table 4.1 below. In this public version of the report, confidential information has been excluded. This entails that some interview reports presented here can come across as short, compared to the length and scope of it as presented in Table 2.2. All information regarding specific strategies and external parties has been removed.

Table 4.1: Overview of Case Study One Interviews

Interviewee	Role	Department
Candidate A	Director	Logistics
Candidate B	Senior Manager	Digitalisation
Candidate C	Director	Metals and Raw Materials
Candidate D	Enterprise Architect	IT
Candidate E	Enterprise Systems Manager	IT
Candidate F	Logistics Purchasing Manager	Logistics
Candidate G	Manager Material Logistics	Logistics
Candidate H	Material Logistics Coordinator	Logistics

Candidate A - Director of Logistics

When discussing the characteristics of Northvolt supply chain, Candidate A explained that the different types of direct material used in production are not that many. The battery cell manufacturing will require approximately 40-50 different types of materials, where some stock keeping units (SKUs) will be purchased from one supplier and some SKUs will be purchased from several suppliers, depending on quality and type. Consequently, Candidate A estimated that the supply chain for direct material will include approximately 50-70 suppliers.

According to Candidate A, the most important aspect to consider when designing the supply chain, is lead time stability. The entire supply chain will be driven by Northvolt's manufacturing capabilities wherefore, in order to secure the lowest price possible of Northvolt's products, there is a particular need for optimising the manufacturing operations. Candidate A explained that this means that the factory must run at full speed at the maximum stable pace and highlighted that to ensure an optimised manufacturing, while keeping costs down, the stock levels must be at the minimal level possible to still satisfy the production. Candidate A pointed out that an advantage of the factory operating at a stable pace, with negligible volatility, is that the stock planning will be easier than if consideration was to be taken to fluctuations in demand. In addition to a high lead time stability, Candidate A explained that the supply chain solutions must have a good balance between price, cost of freight and short transit times. The reason for this is that the materials, products and Northvolt's finished goods are expensive. Consequently, it is important that the products and materials reach the warehouses in as short time as possible to minimise the tied up capital. Nonetheless, Candidate A accentuated that it is crucial to have some level of flexibility in the warehouse stocks for the ability to cope with any disruptions.

Candidate A is optimistic about using digital twin for the logistical operations. An example of a use case for digital twin suggested by Candidate A is if it could improve the sustainability and provide basis for decisions based on correct emission calculations. Candidate A accentuated the importance for Northvolt, having sustainability as the company backbone, to ensure that the most sustainable option is always chosen. Moreover, Candidate A believes that it would be of value for Northvolt to have digital twin, or advanced simulation program, to run what-if scenarios to plan the optimal way of producing a specific demand from a specific customer. However, this would be applicable in the long term, when the operations of multiple factories and material flows need to be coordinated. By knowing the exact capabilities and costs required to produce specific orders, which are predicted to be of large scale, transparency towards customers as well as strategic decision making processes can be improved.

Candidate B – Senior Manager, Digitalisation

According to Candidate B, Northvolt aims to become a fully digitalised company. As for the initial set-up, a major focus has been on the production environment. The term digital twin is not officially used in Northvolt's digitalisation strategy. However, Candidate B mentioned that two of their strategies incorporate a similar approach to that of digital twin.

One of the strategies, referred to as digital twin of products, is used to ensure complete traceability of the battery cells. Candidate B explained that the complete history of each state the cell has been in will be tracked, as well as the performance and behaviour of the cell when it is used by a customer. Consequently, Northvolt will have the complete cell life cycle traceable and can therefore use that information to predict and increase the product quality. To improve the quality prediction, ML will be applied in the programs. Candidate B pointed out that the real value would be if Northvolt could become the best in the world to predict cell duration by determining how many cycles each will last, since that is the major factor impacting each customer's total cost of ownership of Northvolt's products.

Candidate C – Director of Metals and Raw Materials

The material used in the upstream production of Northvolt Ett includes nickel, cobalt, lithium and manganese. Candidate C described that this is used for the precursors and cathodes of the cells. When talking about the purchasing strategy used for the sourcing of this material, Candidate C explained that life cycle analysis are done on all materials to ensure that the most sustainable option is always chosen. Candidate C accentuated that working with minerals like cobalt, where there is a substantial risk for sourcing the mineral from mines where child labour, or forced labour occurs, it is particularly important to include all sustainability impact categories when deciding the most sustainable option. Candidate C explained with an example related to the sourcing of nickel, where there are great reserves in south east Asia that is used by many companies. In the area it is legal to dispose residual products in the sea, referred to as deep sea storage. However, although this generates a minor CO_2 footprint it is not sustainable. Moreover, when continuing the discussion about sustainability, Candidate C described that the transport of the mined materials is a minor contributor to the complete footprint per material unit. This means that a mine in Australia could be more sustainable than a geographically closer mine.

Furthermore, Candidate C explained that complete traceability down to mine-level is an important aspect to consider when selecting suppliers. This is easier to ensure when the suppliers have all the material processes integrated inhouse, i.e. owning the mine, the smeltery and the refinery. In such cases, there is only one company to assess. When the suppliers are only responsible for the refinery, the assessment process is more complex.

As a consequence of the thorough inspection of potential new suppliers, Candidate C described that it is hard to achieve automatic data collection of this process, as the assessment is done manually. With the traceability requirements in mind, Candidate C can see many opportunities with digital twin solutions. Reflecting about the potential with such solutions, Candidate C thinks that there could be an opportunity to use digital twin for improving stock planning, risk prevention of the material shipments and full visibility of the material flows. As some materials are purchased in a salt format, the material is often sensitive to humidity, temperature and in some cases even light. To trace the various states of the material until its used in the production, Candidate C believes that transponders and sensors could be a good solution. By gaining control of the states of the materials shipped to Northvolt, any potential production delays, due to the pre-treatment that needs to be done in case of any damaged material, could be reduced.

Talking about the various challenges with digital twin, Candidate C stressed the difficulties with getting the suppliers onboard with sharing the necessary data. As explained by Candidate C, the digitalisation maturity of material suppliers varies. With suppliers of minerals like lithium, implementing certain data and information sharing requirements is not an issue. Lithium suppliers are mostly serving the battery industry which compared to many other mineral markets is quite young, wherefore the digitalisation maturity and openness is relatively high. However, with minerals like nickel, Candidate C pointed out that the battery industry is only a subcategory of customers for the suppliers which mostly are serving the steel industry, where the majority of the companies are based in China. Consequently, the buying power of battery companies is limited, and implementing data and information sharing requirements in the contracts can be difficult.

Candidate D – Enterprise Architect

According to Candidate D, an important aspect to consider when investigating the applicability of digital twin in a company is knowing if you want to look at the full end-to-end supply chain or if you want to use it for a specific operation. It is also crucial that every domain is digitalised, integrated and able to interoperate with other systems. When working with end-to-end supply chain digital twin, Candidate D pointed out the importance of end-to-end data exchange, used for improving decision making and predictive analysis. Only by having integrated systems, a closed decision making loop for continuous improvements and optimisation processes can be achieved. Candidate D explained that in comparison to simulation solutions, there is a challenge for the users of digital twin solutions to ensure that the data fed into the model is actually real data and not simulated data. Simplistically explained, Candidate D said that the real data is the difference between digital twin of an operation and a simulation of an operation.

In Candidate D's view, there are several challenges to overcome in order to reach a successful digital twin solution. A major challenge is data. Master data must be cleaned in order for the production system to perform well. Furthermore, reference data must be accurate and provided with integrity. Network security is critical to protect the industrial IP from external attacks, such as the stealing of process information or ideas pertaining to the digital factory. To reach a fully intelligent industrial communications network, all data exchange must be standardised. Another challenge highlighted by Candidate D, is that the IT structure and systems are GDPR compliant and to ensure that information is relatively role- or client based and that IP sharing is controlled.

According to Candidate D, there are many possibilities to gain from digital twin. An opportunity that Candidate D pointed out is automatic stock replenishment. Continuing the discussion about digital twin opportunities, Candidate D shared some thoughts made while doing own research about the concept, as presented in the list below:

- Circular economy: built-to-last, built-to-repair and/or built-to-recycle products, made from homogeneous materials to facilitate full recycling at end of life.
- Genealogy and traceability of production materials.
- Environmental impacts: increasing productivity, energy and resource efficiency.

- Predict new product quality in the manufacturing process while minimizing waste and energy consumption.
- Failure detection and prevention before actual operation begins.
- Time to market: save time and money for foundation work to scale manufacturing.
- Minimal cost and effort to development and test for complicated production recipes or routes.
- Flexibility and agility.
- Improved efficiencies by providing the opportunity to respond to volatility and diversity of global markets.
- Rapid development of innovative products and services in a collaborative fashion.
- Circular economy benefits from collaboration of suppliers, customers and relevant stakeholders.
- Rapidly simulate the impact of new regulatory policies and laws on sales in certain regions or countries.

When reflecting about how to implement digital twin in a company or on a larger scale, Candidate D described that a proof of concept of digital twin on a specific operation could be made and integrated with the team centre. Moreover, as Northvolt Ett will be a Gigafactory in need of complete and robust processes, Candidate D mentioned that a digital twin of the miniature production in Northvolt Labs has been used. Furthermore, since the concept of digital twin is relatively new, and there are not that many previous use cases to learn and compare with, Candidate D sees a challenge with education and highlights that it could be best to start with smaller projects. Another aspect in regards to implementation that is highlighted by Candidate D is to ensure that the operations and processes to be included in digital twin incorporates a digital thread. With a digital thread all the handshakes and interactions between systems and departments are traced, and the information generated by each can be used to improve visibility of the full chain. Another aspect highlighted by Candidate D is time studies; a digital twin could work with time series information and to track how long it takes to manufacture one battery and how the process could be streamlined. To know what handshakes is given from one system to another and where any stage gates are.

Candidate E – Enterprise Systems Manager

When discussing possibilities with digital twin, Candidate E mentioned Northvolt's Blueprint team, working on mapping all business processes in order to have a blueprint for future factories and operations. Candidate E thinks that probably, Northvolt needs to have a digital twin in the future since there will be many potential use cases. Candidate E also stated that having data is not an issue, since all data possible about the batteries will be collected, however, there will be a challenge sorting out relevant data. When asked about other potential challenges with digital twin, Candidate E answered that the right conditions are in place, since the complete IT structure is built from scratch currently. However, the challenge is the company maturity and process establishment, as well as the data challenge. There are many possibilities to reach a synergy in a digital twin solution, but to fully understand what kind of digital twin Northvolt needs will not be possible until all processes are in place.

Candidate F – Logistics Purchasing Manager

According to Candidate F, the current focus of the logistics team is on business intelligence and to understand the different possibilities of designing the logistics system. The major streamlining is not made in procurement but in how the systems are designed. However, as a part of designing the logistics network and system, various actors need to be contacted and in the end selected for supplying logistical services.

Candidate F further stated that one goal is to reach full control of the supply chain, and that this includes strong cooperation with suppliers. Candidate F believes there are many synergies between Northvolt and the suppliers in the transport solutions which could be achieved if ensuring a strong collaboration.

When discussing challenges with data, Candidate F explained that there are many uncertainties with the information received from the distributors. An example is when the distributor does not own the equipment used, in such cases there is an extra step in the process as the equipment suppliers need to be involved as well in order to get any information from e.g. the transponders on containers. Candidate F further described that for the logistics team, deviation management is important and will influence the setup of KPIs for the suppliers. It is critical to identify any deviations or non-conformities as soon as they happen, since that increases the chances to reduce delays or ripple effects.

From a logistics perspective, Candidate F thinks that digital twin could be of high value. In regards of planning, Candidate F sees a great opportunity to use digital twin for planning activities. By optimising planning as far as possible, tied up capital in safety stock could be reduced and the collaboration with logistical suppliers would be improved since the forecasts are communicated with them.

Candidate G – Material Logistics Manager

In recent months, Candidate G's team has been supporting Northvolt Labs with material planning, defining how much material is needed in order to keep the line running. Candidate G described that Northvolt Labs will function as a prototype factory, where both commercial volumes will be produced, but also testing, prototyping and planning activities. The support from Candidate G's team is a short-term solution until a sales and operations planning (S&OP) manager is hired. The goal for the team, in regards to S&OP planning, has been to align functions related to the production, i.e. aligning production planning, capacity planning and material planning. As for the demand planning, Candidate G pointed out that customer product managers are assigned.

When discussing the possibilities for the logistics department with cloud-based solutions, Candidate G’s view was that it is not relevant until the current systems are up and running, and that it is identified that using a cloud-based database and optimisation solution would mean a significant improvement. However, when ready, moving to the cloud could definitely be the next step. Furthermore, when discussing the possibilities with digital twin, Candidate G thinks that it would be interesting to see what it can offer compared to the systems implemented today. As implementing such advanced, cross-company tools is difficult and expensive, the current system limitations need to be identified.

From Candidate G’s point of view, the near-term challenges for Northvolt will be to determine all ramp-up processes and how to achieve a successful commissioning phase. From a long term perspective, Candidate G stated that since the demand will be stable, the biggest challenge will be that the manufacturing volumes will be huge. With huge volumes, the impact of production stops, or any other delays and even the small variations, can be very critical and a solution to the problem must be realised quickly. Material-wise, the challenges are also limited to the volumes as the different types of material used are not that many, but the volumes will be large. Therefore, as pointed out by Candidate G, Northvolt must make sure to adopt successful first-in, first-out processes.

Candidate H – Material Logistics Coordinator

When discussing opportunities with cloud-based solutions, Candidate H stated that if everything was available on the cloud, the data could communicate there and it would be possible to slice, dice and plan for stakeholders. Candidate H agreed that the term digital twin could be used for this approach. Candidate H further went on to discuss the opportunities with such a solution. If all the data could be integrated on the cloud then for example, data from the factories and different stakeholders could be used as input for simulation. If the factory simulators could get a hold of this, they could then come up with a better simulating model that can perform different real life scenarios and give advice on how to be more ready. From a pure logistics perspective, digital twin could facilitate the investigation and simulation of greener transport alternatives.

However, Candidate H explained that there are challenges for Northvolt in regards to how to handle digital twin. It needs to be decided at what level the data communication should be kept, for example, should digital twin be used only inhouse or should it also include forwarders and suppliers? The last aspect is difficult as suppliers might not want to share this information. Also, each supplier works with different software and the information is therefore not going to be uniform. Furthermore, if focused on an end-to-end digital twin implementation, there will be challenges from a logistics point of view. For example, getting accurate estimated time of arrivals is not a simple task, especially when it comes to sea freight. In general however, the data will probably be accessible and the challenge will rather be how to integrate the data from the different stakeholders, and how accurate that data is. To succeed with digital twin at Northvolt, Candidate H added that processes would need to be standardised.

4.2 Case Study Two: Digital Twin in Supply Chain

The scope of case study two has been to gather qualitative data which forms the foundation of the digital twin point of view. In Figure 4.4 below, case study two has been marked in the investigation model of the thesis.

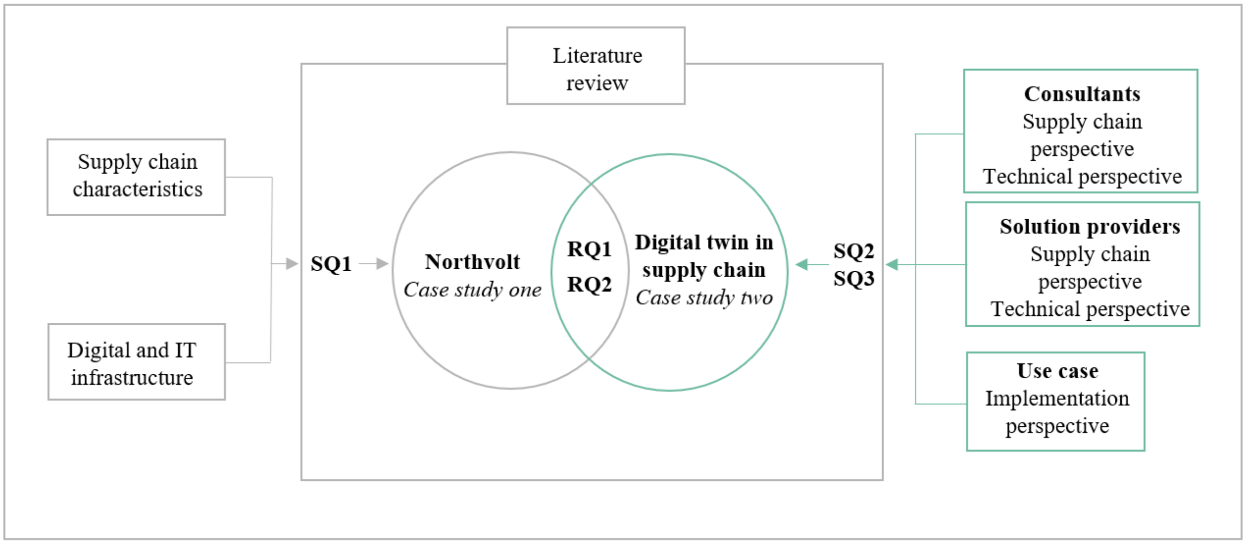

Figure 4.4: Case Study Two Highlighted in Investigation Model

4.2.1 Consultant Cases

In Figure 4.5 below, the consultant cases can be seen in the investigation model.

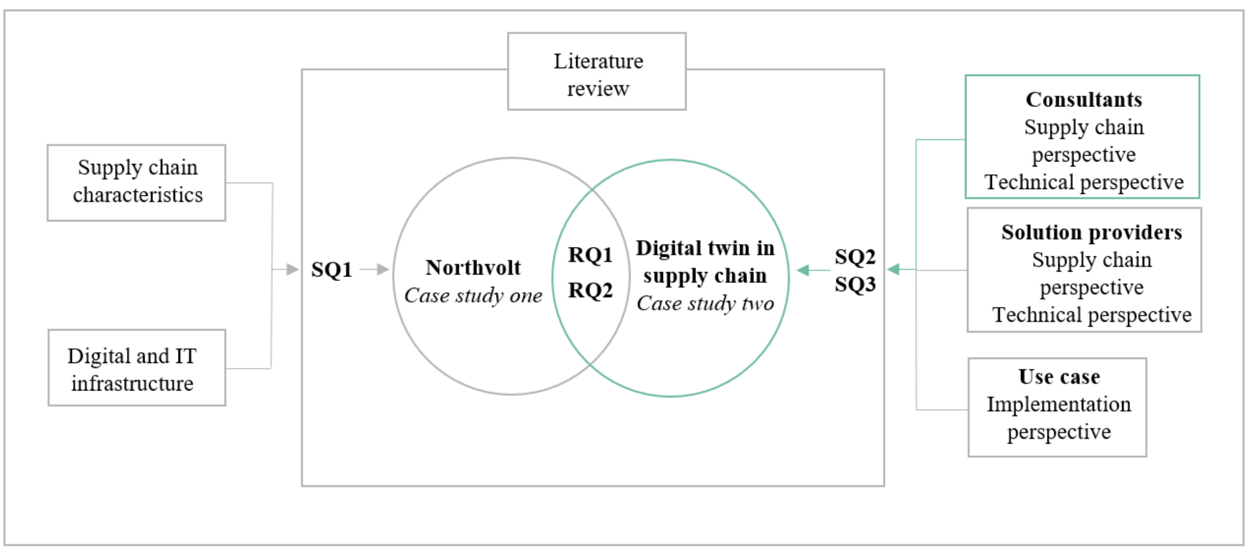

Figure 4.5: Consultants in Investigation Model

Consultant A

Consultant A is Partner at a global consultancy firm and has worked in supply chain for over 25 years, with a focus on delivering end-to-end supply chain strategy. During this time Consultant A has worked in several industries, from automotive to retail and life sciences to manufacturing. The interview with Consultant A focused on the concept of digital twin, opportunities and challenges with digital twin in supply chain and recommendations for implementation.

According to Consultant A, digital twin allows companies to see what is happening in their supply chain, ideally as live as possible. Digital twin provides companies actionable information, sometimes even the actions themselves that should be taken to make sure the supply chain works in the most efficient way. In other words, digital twin can be used as a decision's portal for operational, tactical and strategical operations in a supply chain. Digital twin can help mitigate risks in operational operations, for example delays in production caused by logistical disruptions such as weather impacts. By doing a forecast demand on the delayed material, a digital twin can project if there will be a shortage in production and if so how to mitigate it, for example by changing the production schedule. From the tactical perspective, digital twin can help companies look three to six months ahead and identify capacity issues and supplier risks. Digital twin can also through design and simulation improve strategical operations by for example helping companies become more cost and risk effective. Consultant A pointed out that during the COVID-19 pandemic it has been made clear that many companies have only designed their supply chain for cost and not risk.

When asked about the three concepts of digital twin, Consultant A stated that the Digital Model has been used for many years and models focused on supply chain have been around for a long time. The Digital Shadow is also considered to be relatively common but not in the end-to-end supply chain regard as it requires a manual decision regarding what to do with the information. A Digital Twin on the other hand is the automation of a reaction to the data. Consultant A specified that a Digital Model is best suited for strategical decisions and not for operational ones. A Digital Shadow however is good for operational decisions, but is limited as human interaction is needed. A Digital Twin is not useful for strategical decisions as certain information is hard to reflect in the data, for example the political stability of a country. However, a Digital Twin is exceptionally useful for operational and tactical decisions.

In Consultant A's experience, one of the challenges with digital twin today is that it is currently used externally to all the individual systems in the supply chain. Digital twin does not run the supply chain, it merely models and influences it, resulting in the risk that by the time information has been fed into the execution systems, it becomes a local optimised solution in that particular execution system. Whether this is a warehouse management system (WMS) or a manufacturing execution system for a factory, it is the same problem.

Consultant A further stated that another major challenge with digital twin is that data does not often come in an accessible format. In many companies, the underlying data quality is poor, resulting in that services such as analytics and AI cannot be used to their full extent. For example, around 60% of Consultant A's customers do not have accurate dimension data for their products. The biggest issue with the data is that of the data creation. Most systems Consultant A has come in to contact with have become really good at data entry capability and data usage. The fundamental problem is that the data has to be put in to the system somewhere. This is typically a manual interaction and at that point it is a question of "does the person inputting the data see the value of that data"? Quite often, there are certain bits of information they see as critical and that data comes through relatively accurate. Some data is just required by the system but is not critical for the user, resulting in that the data quality drops off quickly. In order to mitigate this, a certain level of standardisation regarding how data is collected, processed and shared is needed according to Consultant A.

In order to implement an end-to-end digital twin solution, suppliers need to be integrated in the digital twin. Consultant A explained that this poses another big challenge as it is difficult to find the commercial balance between what the suppliers want to disclose versus what they do not want their customers to know. One way to work around this is to put in the agreements with the suppliers that they need to share certain data. However, this can be anti-competitive as the suppliers might deal with some of the company's competitors. Legal challenges might also play a part in this.

Consultant A pointed out another complexity regarding suppliers, and that is the risk of sub optimised supply chains. Depending on who owns the digital twin, the supply chain in question will vary. If one company optimises their supply chain they might actually disturb the supply chain that belongs to one of their partners. This results in individually optimised supply chains and the loss of the end-to-end perspective.

In regards to digital twin implementation strategies, Consultant A recommended companies to first map out their entire supply chain. Mapping a supply chain is however by no means easy and if a company can create a digital twin that deals with 90% of the supply chain, that is a lot better than having no digital twin at all. If companies attempt to map everything perfectly there is a risk that they will never get anywhere. It can therefore be wise to apply a level of pragmatism. By starting off with a solution that is 20% on day one, 30% after 6 months, 40% after a year and then keep adding up capability, companies can get value out of the solution even though it is not complete. If a company instead waits with implementation until everything is completely mapped, they risk finishing the mapping when it is already out of date as supply chains are dynamic and not static. Consultant A also stated that companies need to focus on the fact that they are able to collect the data and not so much how they are collecting it. By making everything connectable, companies can make sure they have the capability of transferring data, even if they are not collecting the data today. A good idea is to mandate a system that says that data has to be able to be made consistent rather than saying the data has to be consistent in every system everywhere as that is not possible. Consultant A pointed out that companies that are able to set up their systems and data collection strategies from scratch have an advantage when it comes to digital twin implementation compared to companies whose systems have been up and running for quite some time.

Consultant A further stressed the importance of openness and trust with supply chain partners when implementing digital twin. Here a mandate is also needed that says that as part of the way we do business we will share information with you and we expect you to share information with your suppliers and for that information to be visible to us. It is a two way system that requires a certain way of contracting in order for the information exchange to be made viable.

Consultant B

Consultant B is a Senior Business Consultant at a Nordic consulting firm focused on optimising supply chains with the help of technological solutions such as digital twin. Consultant B co-founded the firm 15 years ago and has a lot of experience in working with business systems, manufacturing execution systems and advanced production systems. The interview with Consultant B focused on the definition of digital twin, the technical aspects and challenges in regard to implementation.

In relation to the five dimensional model presented in *3.3 Technical Structure*, Consultant B viewed the model's virtual supply chain dimension as the whole digital twin. As the virtual supply chain contains all of the data from the physical supply chain it is therefore in essence the true digital twin. Consultant B viewed the model's service dimension as the solution that their company offers to customers and described it as tools that analyse the data in digital twin. Consultant B referred to these tools as solvers and explained that they are software programs that perform various calculations in order to solve the problem at hand. Different solvers are used for different areas, for example, one solver can be used for inventory planning and another for capacity planning of the factory.

Working with an external solver has many advantages according to Consultant B. In a business case Consultant B worked on, the case company had several business systems that were used as the main source of data which required that the virtual supply chain was able to reflect data from all the systems. By adding a planning layer over these systems, information could be easily extracted from and inserted into the systems. Consultant B stated that this provides an advantage when companies make acquisitions as they sometimes also acquire new business systems and instead of forcing a new business system on the acquired party, the planning layer can bridge any eventual gaps and provide transparency.

If a company however only has one business system, in some cases that can become the digital twin, as digital twin must not necessarily be separated. However, in regards to the execution, Consultant B claimed that a business system is not able to receive and carry all the information that is needed. Databases, tables and other ways of saving all that information, all that traceability, would be required. The business system is simply not interested or capable of keeping track of certain information that is necessary for the solution to work properly.

Another advantage of keeping all the data integrated in an external layer, is that it provides security when a business or transaction system might need to be replaced. It also opens up for the possibility to work with best in breed systems, meaning that a company can cherry-pick the best systems, despite them coming from different suppliers. However, many different systems might result in integration difficulties which can be perceived as a disadvantage, but Consultant B claimed that working in a setting where all systems are the same will prevent flexibility and agility.

According to Consultant B, one of the main challenges when implementing digital twin is to decide what level of detail is needed in order to solve the problem at hand. The solution has to be detailed enough to provide a good result but at the same time not too detailed so that it becomes complex, unmanageable and unnecessary expensive. If the digital twin is however built in greater detail, this can be used as a basis for other solvers that might be needed to solve other problems.

In addition to understanding the level of detail that is required, it is also important to understand how often the digital twin needs to be updated and how connected it needs to be. Consultant B mentioned as an example that some operations only need daily updates, like production planning. There is no added value in becoming more connected as the complexity and the cost increases at the same time. However, a warehouse storage location needs to be updated more often so that there is no risk of someone receiving instructions to place something in a position that became occupied five minutes before.

In regards to integrating digital twin backwards and forwards in the supply chain, to for example suppliers and customers, Consultant B recognised several benefits. For example, an integrated planning network could synchronise material flows between supply chain entities, thus improving overall operations. However, there are many challenges in this area, and therefore not something that Consultant B currently works with. Consultant B stated that data security is one aspect, especially when it comes to a product switching hands. Getting access to data from customers, distributors and suppliers is very difficult, as there is a risk of exposing sensitive data such as prices. However, if the product is merely being transported by a service provider, accessing data is usually easier.

Consultant C

Consultant C is Vice President of Value Chain at a global consulting firm and has more than 30 years of experience in end-to-end supply chain planning and optimisation. Consultant C has worked with many global companies and helped them change the way they operate through integrated work systems and performance behaviours. The interview with Consultant C focused on common supply chain challenges and the role of digital twin.

According to Consultant C, one of the most common issues in supply chains is that of silo mentality. One way this has been clear is through all the many different systems companies use in order to control operations, such as transport management systems (TMS), WMSs, customer relationship management systems, integrated management solutions, planning systems, scheduling systems and purchasing systems. There exists systems for every department in the company and none of them are joined up. However, Consultant C stated that recently two things have happened.

Firstly, people have found ways of overcoming interface problems and data can now easily be collected from various systems. This has resulted in that significantly more data is now accessible compared to when it was all stored in silos. Secondly, by applying tools, for example advanced mathematics, artificial intelligence or machine learning to this collected data, companies can now do something that before was not possible.

However, in the end, the tools are just a means to an end. It is what is done with the tools that determines how successful the operation, or in other words the digital twin, becomes according to Consultant C. By using the tools correctly and in the right place, companies can work out what the strategy and the tactic of the company should be. For example, instead of using digital twin to react intelligently, companies can start responding intelligently. Having a digital twin that merely tracks what is going on in operations provides no competitive advantage. Digital twin needs to be used in the correct way and with the proper parameters to be of use, as stated by Consultant C:

"If I go back a lot of years, there was a software that came on to the marketplace and it was called shopfloor data capture. This was a system that would monitor… [analogy]… where all the bits are in the factory. You could find out exactly where things are. Okay why do you want to find out where things are, why do you want to know that? While a customer comes in and says where's my order you can see exactly where it is. But why is the customer asking that? Well we're late with delivery. Okay what's the problem here, are we trying to find out where these bits are to respond to a request because our performance is poor? Or are we doing it to try and get better control of what we're doing and put a different strategy in place? What most people buy it for [refers to shopfloor data capture] is the former not the latter. Very smart tool, you can see where everything is. Okay so what? What are you going to do with it? So for me the same thing, the digital twin can replicate it, what now are you going to do? It's the parameters that drive the model, whether that's the way you think, how you want to flow it, the tactics you're going to have, whether you're going to have a pull system or push system, a pull-push system, you know whether you're going to have a manufactured to order all the way through you know make to stock. All those are the parameters that will drive the model"

Furthermore, if looking to implement digital twin on an end-to-end basis, Consultant C stated that it is very important that people understand why they should look end-to-end and what it actually means. There are several software houses that are probably 20 years ahead of the physical world and are inventing solutions that are not yet being the adopted. The reason for this is that people in supply chain do not fully understand what the software houses are selling. Consultant C mentioned an example:

"One of the processes I get involved with is called sales and operations planning and it's really all about end to end planning. It's been around in its current form for probably as long as I've been doing it, 35 years. People are looking into it more now than they ever have done, that's 35 years later. So software houses called it supply chain back in the 90s, so it's been around for 30

years but we are still struggling with it. That's the human being part, the technology will move fast. How broadly we embrace it is a different question."

Consultant C explained that currently, digital twin solutions have foremostly been embraced in the factory setting. For Consultant C's customers it is probably still 60% about the factory, with the supply chain coming second.

4.2.2 Solution Provider Cases

In Figure 4.6 below, the solution provider cases can be seen in the investigation model.

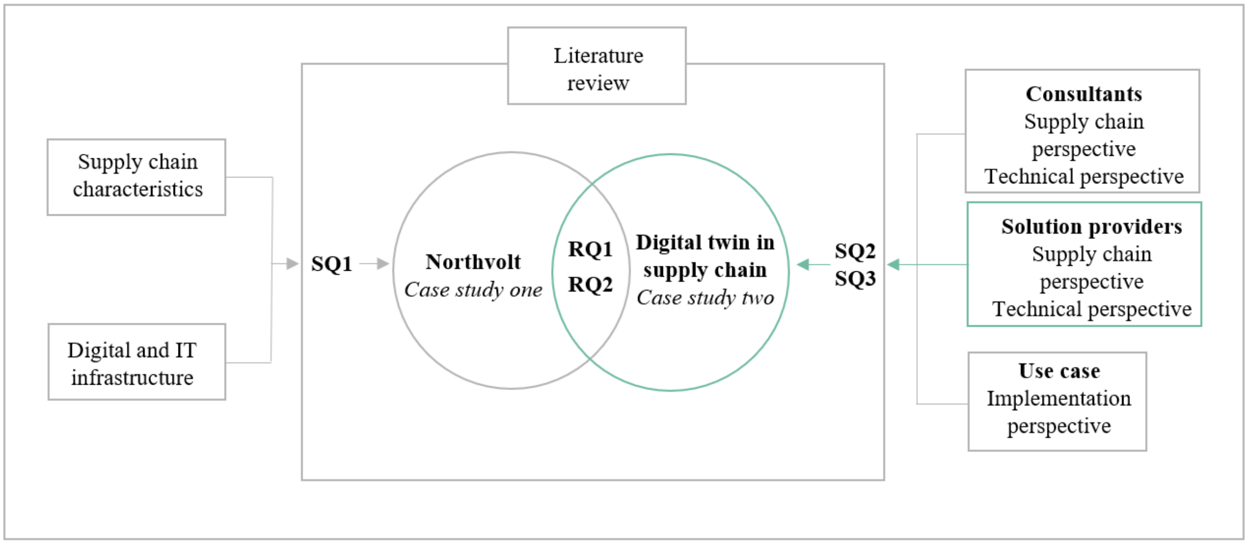

Figure 4.6: Solution Providers in Investigation Model

Solution provider A

Provider A works as a product manager at a global technology powerhouse. Provider A sells solutions within digitalisation in industry, with a focus on the vertical supply chain, aiming to connect the virtual and physical world. The interview with Provider A focused on the definition and current state of digital twin, its opportunities and implementation challenges.

According to Provider A, up until three years ago (i.e. 2017), there was little talk about digital twin solutions in the industry. Since then, the word has appeared more frequently but there are still different understandings of what it actually is. In Provider A's experience, digital twin means so many different things depending on who you talk to, what they work with, where they live and to what extent their nearby universities use the term. For some people it is more or less a simulation that is connected to a real process. For Provider A, digital twin is more about having a representation of a reality. It can be just data, it is not necessary to have a visual representation. It can also be a compilation of data that is used in order to make decisions. If it is used to make decisions automatically or if it is looked at in order to make decisions, that does not matter. It should be a tool that is used to reach certain goals, and that can look very different depending on what it is supposed to achieve. The overall purpose of digital twin is to be able to ask hypothetical questions like "if we do it like this, what happens then?" without having to do it in reality. According to Provider A, digital twin is in other words used to test things before they are done in reality.

In Provider A's opinion, Gartner made the right call in placing digital twin at the top of the Hype Curve. There are a lot of inflated expectations regarding what digital twin can solve, and Provider A stated that soon more articles will most likely be published on the challenges and downsides of digital twin, resulting in that the hype will go down. However, Provider A believes that even though, and perhaps because of the hype going down, the real values of digital twin will emerge. The industry will be talking about digital twin in the future, but with a narrower definition and a clearer sense of the value digital twin can contribute with. To support this belief, Provider A compared digital twin with CPS:

> *"A digital twin lives on the border between having a simulation and a reality that collects data, all these systems together create a digital twin. CPS and digital twin basically have the same definition, but CPS is not as hyped any more. CPS has become narrower, but they overlap."*

However, Provider A also mentioned that there are areas where it is relevant to use digital twin, but there are also areas where it is not needed.

When implementing digital twin in supply chain, it is important according to Provider A to think about what data there is in the supply chain and what the digital twin should be created of. Another important consideration is to understand what the digital twin will be used for. There is a risk that the digital twin ends up being too big, or too small. When building too big, it might cost too much. It might also result in the collection of unnecessary data and the connection of things that are not part of the issue. Provider A pointed out that a good starting point is defining a question that answers if something is not living up to its potential, or is posing a challenge. This should then be boiled down to a purpose from a business perspective so that value can be created with the help of the technology. As there is no out of the box solution for digital twin, it is of very high importance that companies get this right so that suppliers can provide something viable.

Provider A explained that there are many challenges associated with implementing digital twin in supply chain. For example, there is an enormous complexity in the data that the company does not own. Suppliers need to be on board, they need to be aware that they are required to share data and find solutions for data collection where they are missing data. Provider A further mentioned that blockchain can be used to mitigate these challenges, as it offers a solution where different actors can input their data and have it verified. This entails that no one is the owner, and the burden of collecting the right data is shared.

When implementing digital twin, Provider A recommended that companies make sure that their systems use the most common protocols, for example MQTT. Any system that requires communication in its own protocols will lead to difficulties in integration. These cases require data brokers which are expensive and complex. Even if two systems are using the same protocols, the data might not be structured in the same way. Therefore, it is important to demand the right data structure, as well as protocols, from the suppliers and make sure that the collected data exists in one format. Also, the data should be collected in a readable way in open formats that can be sent on. Lastly, as aforementioned, it is crucial that the company knows why it wants to implement digital twin. In some cases, there might be several things that need to be solved, then several solutions are needed. Digital twin needs to be created for its purpose, but there is an advantage in doing this openly so that it can be expanded into other digital twin solutions if there is a need for it. This can be achieved by using standards and even though there is no specific digital twin standard, there are standards for security and communication etc., which are the building blocks of the system.

Solution provider B

Provider B works with Digital Strategy and Architectures at a global technology company. The interview with Provider B focused on the definition of digital twin, specific solutions and reasons for implementing digital twin.

According to Provider B, a digital twin is a representation in a digital system of something that is not digital. For example, a drawing of a production facility in PowerPoint is a digital twin, but with limited functionality. Provider B pointed out that it is important not to let the term twin be misleading and let it imply that there is only one twin. Almost all digital systems that are used today have a digital representation of something that is not digital, resulting in that there exists countless digital twin solutions. A good example that many do not think about is that a taking a picture of an object actually results in a digital twin. If the camera can pick up on heat then the picture can be analysed to see if the object is overheated in any area.

The company Provider B works for sells systems that connect digital twins that exist in different systems. The solution is capable of connecting all the systems that have a digital twin. By reading the information from these systems, it is possible to draw conclusions, partly about what is happening but also about what will happen and what is wanted to happen. The solution is mostly used for facilities and is often referred to as automation systems.

Provider B stated that the most common problem for why customers turn to them for their solution is that they have a hard time getting people, systems and equipment to work together in a good way. By using their system the people are provided a virtual digital representation of the facility that they can understand. It makes it easier for the people to understand what is going on in the digital systems and foremostly gain access to the information. Also the systems can access each other via this connection. Provider B indicated that this is the whole point, that it allows people, systems and equipment to work better together. The users of the systems are also digitally represented. As soon as an employee logs on, there is a digital twin of that employee, or more precisely, his or her actions.

In regards to how to handle data, Provider B explained that they are not focused on extracting data, but rather let the data remain where it is. Instead, they put requirements on the systems that create the data to make sure that the data is clean. Provider B claimed that this is one of the most important ways to create the right type of information. If the one that creates data does not have an incentive to create good data, everything fails.

The risk of extracting data instead of letting it remain in place, is that if one system is changed, then all digital twins that have been created are ruined. A new system provides new, different data, resulting in that the new digital twin becomes different than the old one. In a facility for example that contains thousands of small objects, things are changed on more or less a daily basis which makes a database digital twin very difficult to handle. Provider B instead recommended to let the data remain in the system up until there is a need to use it. A temporary data model can then be created for one specific and maybe even time limited reason.

Solution provider C

Provider C is Owner and Managing Partner of a company that provides cost orchestration solutions. Provider C previously worked for a software house provider and has a lot of experience within digitalisation and cost management. The interview with Provider C focused on digital twin solutions in regard to cost and CO2 footprint and the importance of digital thread and digital strategy.

Provider C's company works with a digital twin of cost that allows companies to know where they are positioned from a cost perspective at every moment along the supply chain. New technologies have enabled this way of working, and Provider C mentioned that historically these calculations have been performed in Excel, which is not connected to a system and therefore hard to keep correctly updated.

In addition to tracing cost, Provider C explained that digital twin can also keep track of the CO2 footprint of products. This can be valuable to the purchasing department as they can see the effects on the CO2 footprint when choosing material. It becomes a trade-off between product cost and CO2 footprint, where the choice of material is based on these two parameters. When a supplier has been selected, transport can be added to the CO2 total. The calculations are based on databases that possess information on how much CO2 certain materials cost, as well as the energy consumption and type of energy that is used in the processing of the material. Provider C expressed a belief that soon there will be laws enforced that require manufacturers to display the CO2 footprint of their products. Provider C furthers stated that measuring CO2 from bought material has always been a black box and companies will need to become better at this in the future.

According to Provider C, one of the most important aspects of implementing digital twin across processes is that there needs to be a digital thread. This entails having digital records of all operations in the supply chain, from receiving an order from a customer with certain specifics, to that it is registered in the ERP system. The digital thread requires that no manual handling is involved and that it is implemented end-to-end. It is also important to have a digital strategy in place, and that not too many different software programs are used within the company. The digital thread plays a role here as well. Gaps between software programs need to be bridged, for example with the help of APIs. Provider C explained that there is an advantage in using a software house as all the systems are then already talking to each other.

In Provider C's experience, the manufacturing industry is very driven by technology and not as much by value. Many companies have very advanced manufacturing software systems, but are at the same time performing planning and doing calculations in Excel. This poses a challenge as here the digital thread is broken. In Provider C's opinion, people working in digitalisation are technicians and do not often have the supply chain mindset. Their main focus is on R&D and manufacturing, resulting in that there is a risk that a silo situation occurs, further hindering the digital thread. It is in other words according to Provider C just as important that purchasing and logistics are part of the digital strategy as R&D and manufacturing are in order to achieve a consistent digital thread.

Provider C reckoned that one of the biggest challenges with digital twin is that of master data. The technology behind digital twin in itself is not difficult, but providing the right data for the technology to act on is. When looking to apply digital twin on an end-to-end approach, there are also challenges in terms of information sharing between companies, for example between supplier and customer. However, Provider C claims that transparency is increasing, but the maturity is still low and companies are not yet inclined to give away their cost structure.

4.2.3 Use Case

In Figure 4.7 below, the use case can be seen in the investigation model.

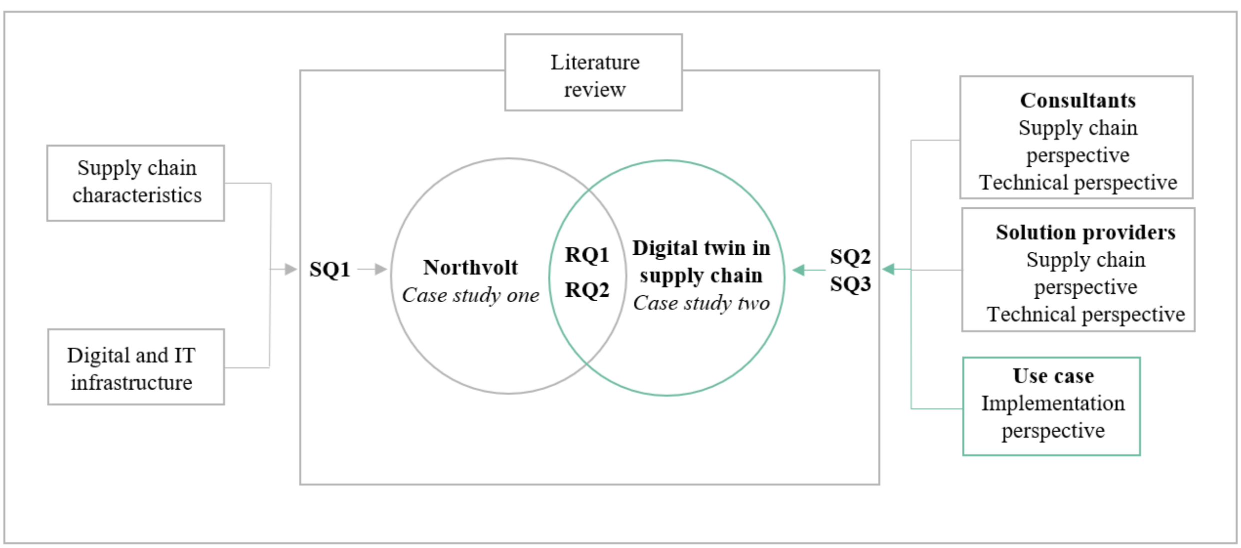

Figure 4.7: Use Case in Investigation Model

The use case section is structured into seven parts; introduction, solution, implementation and results, next phase, opportunities, challenges and critical success factors.

Introduction

Company A is a Swedish manufacturer that has been officially recognised for its innovative work with digital twin solutions in integrated planning. The digital twin journey began in 2015 when Company A management decided that they needed to reinvent their supply chain in order to minimise the risk that their business model might be disrupted by external players in the future. Company A had at that time a traditional supply chain, where several suppliers supplied one factory which in turn delivered to one factory warehouse. That factory warehouse then in turn delivered to regional and local warehouses all over the world, which in turn delivered to distributors and customers, see Figure 4.8. The problem with this set up was that the supply chain included a high product variety, manufacturing plants in over 100 locations around the world and over 15 000 distributors and resellers. As it grew too large, and too many people with their own specific scope were involved, Company A experienced problems achieving service level targets, high networking capital and bullwhip effects. To solve this, Company A decided to make one person responsible for planning the end-to-end supply chain for a specific product assortment from customer order all the way up to where purchase orders were placed to suppliers, see Figure 4.9. This entailed that this person was responsible for deciding what to produce, how much to stock where and how much to ship and distribute. However, in order to make this solution viable, Company A needed to eliminate the manual handling involved and increase the automation efforts. It was decided that a digital twin was the best option to enable this automation transition.

User A and Consultant D were both directly involved with the implementation of the digital twin solution at Company A. User A is the Business Transformation Manager in Demand Chain at Company A, and was responsible for the internal IT core team that worked on the project. Consultant D is a Senior Business Consultant at the consulting firm, Company B, that was hired to give advice and consulting to Company A in their creation and structuring of the digital twin. Company B also delivered the software program, program A, that was used to handle the output of the digital twin.

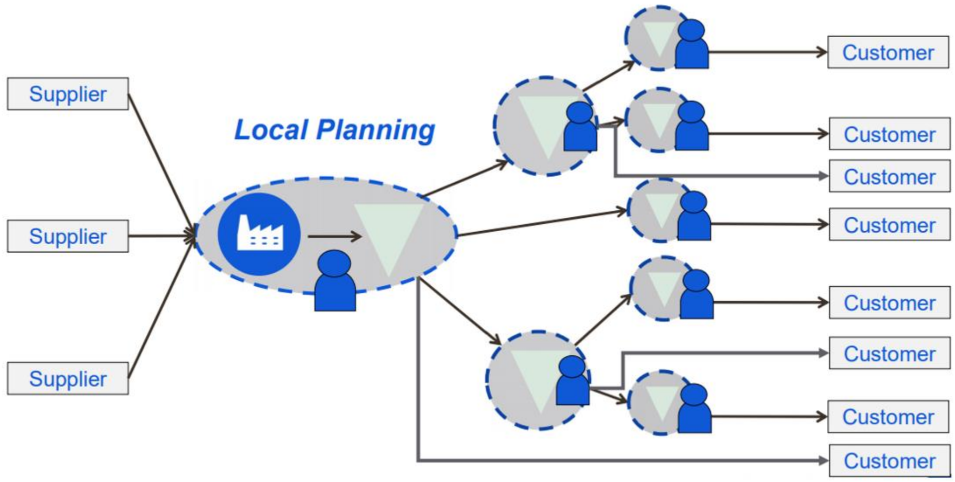

Figure 4.8: The Demand Chain Set-Up Before the Project (provided by Consultant D)

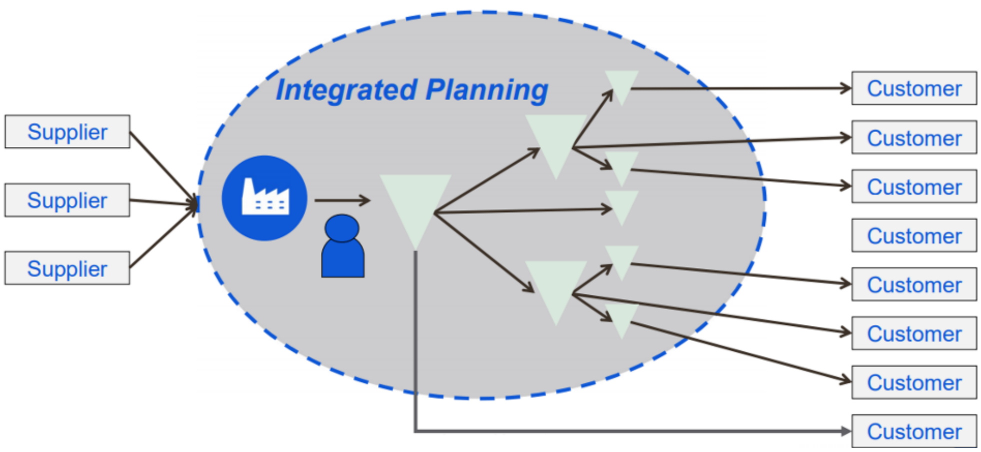

Figure 4.9: The Demand Chain Set-Up after the Project (provided by Consultant D)

The solution

As aforementioned, Company A had come to the conclusion that they needed to go in the direction of global planning in order to improve operations. They determined that they wanted to do this in a cost efficient and automatic way and according to User A, it was clear from the start that there really was no other way of achieving this than with a digital twin. User A described digital twin as a digital representation of the real world, or in other words, a bits and bytes representation of that which in the world is happening in atoms and molecules. User A further added:

"The digital twin is for us really more a concept and a mindset, how you technically realise it, there are a lot of different options. I mean in our case the digital twin is you could say, in the end it's just a very big database."

Consultant D referred to the digital twin as a platform and structure that is used to collect and transform data into structured, valuable business insights in a single format and sees digital twin as a way to gather competence in one place. In this case it is realised with an SQL database.

As for the scope of the project, Company A decided to launch it on their in house operations first as this was deemed most viable. This entailed consolidating data from all Company A’s factories and warehouses around the world in the digital twin. For example, all the material in stock around the world, all the customer orders, all the material in transit between warehouses, the warehouses themselves and the production machines were represented in a digital way within the digital twin.

User A explained that the process of consolidating the data can be structured into steps, where the first step is to collect all the information in the digital twin and the second step is to normalise and harmonise the data within the digital twin. Sometimes the data also needs a bit of massaging so that it is in a good shape or format. The data is then used by program A that contains the business logic. This is done on a continuous basis, but Consultant D clarified that this does not necessarily entail that it is done every minute or even every hour. The frequency of the data upload depends on the planning process in question and what is required to fulfil the purpose. In the case of Company A, a daily basis is sufficient to enable integrated planning and Program A therefore runs every night. Program A includes a lot of processes with a focus on demand planning, inventory optimisation and replenishment to secure target service levels of Company A, resulting in information about for example what safety stocks to keep, what production orders to prioritise, what stock replenishment orders to fulfil and when and where to do this. This information is then sent to Company A’s ERP systems where it is executed. In other words, the information flow is bi-directional, with data being collected from warehouses, factories, sales and distribution units into the digital twin and Program A, and data flowing back to these entities via the execution system.

User A further explained that the global planners’ responsibility in this process is to keep track of alerts from the system that notifies them on deviations. Planners can for example be alerted to an unusually large order and can then intervene to determine if it is an onetime event. If so, they can then inform the system to not plan for it in the future and to consider it an exception.

Implementation and results

The implementation of the project was divided into three stages; i) proof of concept, ii) pilot and iii) deployment and continuous improvement, where Company A and Company B were continuously cooperating. In retrospect the implementation has been divided into six different stages for the sake of explanation, see Figure 4.10. The proof of concept was initiated in 2017, where User A, Consultant D and their teams implemented the solution on one production site. This then grew continuously, and the project was rolled out on more sites. According to User A, the forecast quality was comparable or better from day one and since then, the quality and forecast methods have improved further. The payback was very clear from the beginning, but it took two or three years to make the payback visible on the bottom line of Company A. Company A was further able to decrease inventory with 14%, maintain a stable service level and decrease manual work with 20%.

The implementation part of the project took three years from start to finish line. According to Consultant D, this was largely due to that they were transforming an old organisation with many structures and different business systems.

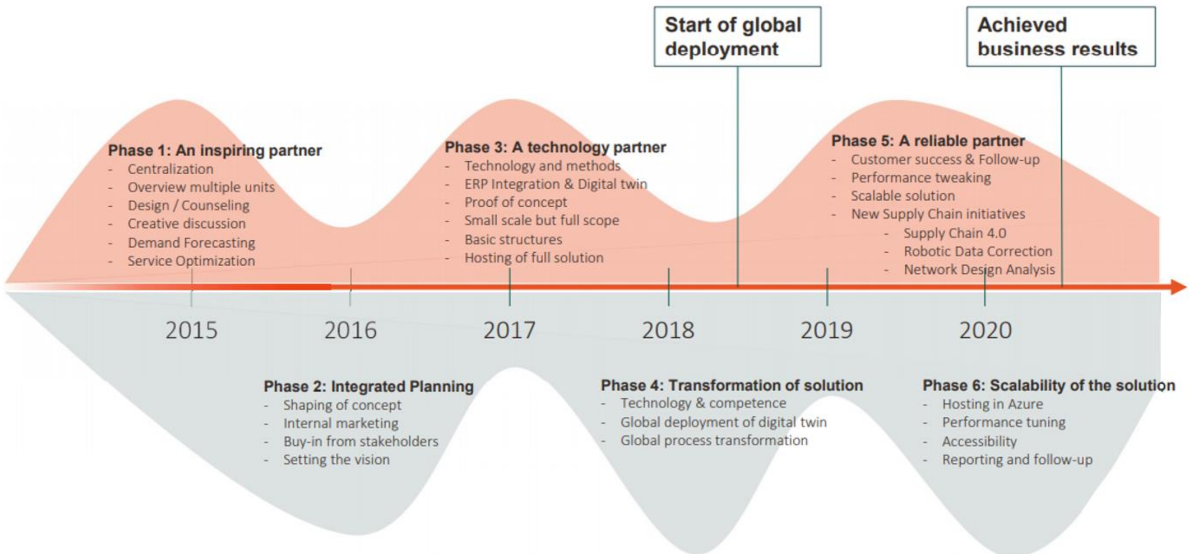

Figure 4.10: Implementation Timeline for Integrated Planning (provided by Consultant D)

Next phase

The next step for Company A is to forward integrate and include distributors in the integrated planning solution, see Figure 4.11. Consultant D explained that this will be achieved by offering to take over the planning for the distributors in exchange for insights into their sales. User A further elaborated that the warehouses of their distributors will be made visible in their digital twin and thereby be included into integrated planning. This will allow Company A to not only see what the distributor orders from them, but see what the customers are ordering from the distributor and their inventory. This entails that Company A's planning responsibility can be extended to the distributor which, according to User A, will help distributors achieve benefits such as a higher customer service levels, decreased inventory levels and lower costs.

According to User A, there is also a plan to integrate backwards and add information about suppliers. User A mentioned that in the big scheme of things, integrated planning and the digital twin were just the first step but that they overall see that the journey will be a much bigger one.

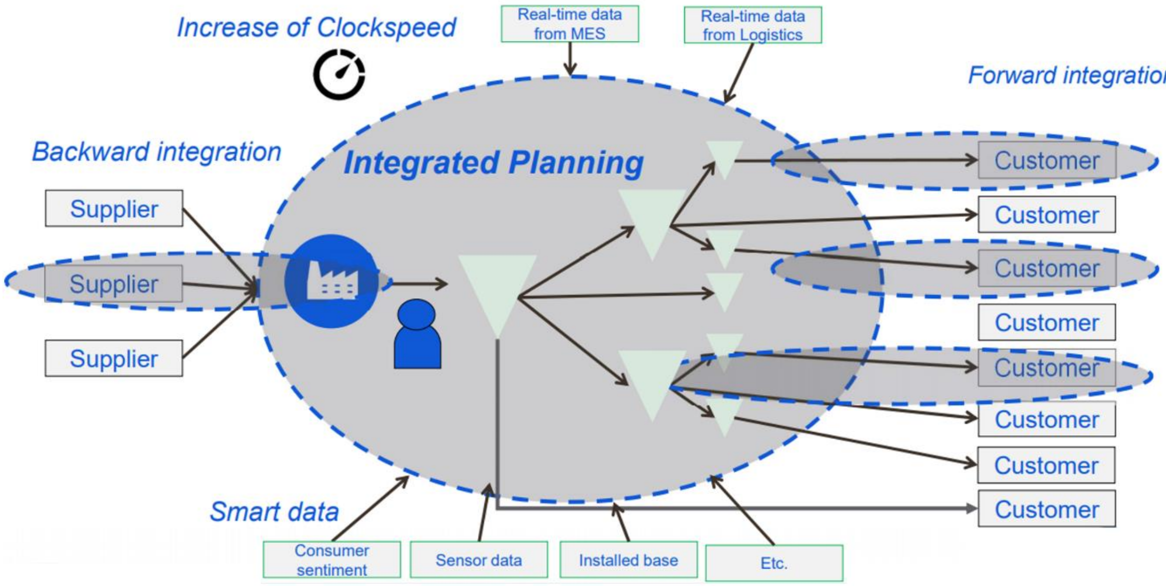

Figure 4.11: The Next Steps for Company A (provided by Consultant D)

Opportunities

According to Consultant D, digital twin can provide visibility and insights into data, both from a financial and logistical perspective that before was not possible. Furthermore, by applying advanced analysis on the data, business critical insights can be gained from digital twin.

User A found that a great opportunity with digital twin is that management decisions can be brought into operational planning automatically with basically immediate effect. There is in other words no need to rely on email communication and management meeting handovers to put decisions into effect.

User A further stated that digital twin can also mitigate the effects of disruptions in the supply chain. During the COVID-19 pandemic of 2020, the digital twin helped Company A to see from a global as well as graphical perspective what was happening around the world, allowing them to understand the impact and even more importantly, react quicker to those events than had been possible before. User A also added that even though the planning process was their focus, there are many other use cases of digital twin and more opportunities to be gained.

Challenges

According to both User A and Consultant D, one of the major challenges with implementing the digital twin was the data, or rather the pure lack of it and lack of good quality data. User A mentioned that they had to invest quite some effort in making sure that all the data that was needed was actually available, or that it was updated at least daily or more frequently. To mitigate this, data quality check reports were implemented at Company A. This entailed that the data quality was checked continuously, initial cleaning efforts were performed and sales units and warehouses around the world were instructed on how certain data fields needed to be maintained. Technical adjustments were also made to certain data fields so that they could only be populated in a certain way and wrong information could not be entered.

Critical success factors

Consultant D explained that one of the most critical success factors when implementing digital twin is to have a digital thread or system of records of everything that is going on in the company. Everything has to be digitalised if it is to be of use. Another important aspect is that of buy in from stakeholders, e.g. that the CEO is all in and sponsors the project. Furthermore, good data quality is very important as it is not possible to get anywhere without the correct data. Consultant D also highlighted the importance of organisation and accountability. In supply chain, dependent flows need to be planned together, entailing that one person should be responsible for inventory and service end-to-end. Lastly, Consultant D added that it is important at an early stage to bring on a partner that has done the journey before, and that the partner is chosen based on the scope of the project.

User A agreed on the importance of a digital thread and transactional workflow and further specified three main points. Firstly, in situations concerning green or brown field operations and where companies can start from scratch, it is highly advantageous to have a harmonised or standardised underlying ERP layer and only one WMS system, planning system and transactional system etc. This will save a lot of money and painful workarounds. Secondly, it is critical to build digital twin competence in house. Competence can be partly bought from consultants, but it is important to build the competence in house as well as the digital twin becomes business critical. If buying the service from a supplier, you risk becoming very dependent on the competence that sits outside. Lastly, when the digital twin has been implemented, even if it is just at an early stage, it is key to get management interest and get their mindset moving in the right direction. By starting with small use cases early, even if they are just 95% operational, people become exposed and can start to see how it works. It is important to get into the learning curve as soon as possible, not when everything is perfect, but when things are good enough.

5 Analysis and Results

In the following chapter findings from the case studies are presented and analysed together with the literature review. The first two sections focus on summarising the two case studies and answering SQ1: What are the characteristics of Northvolt's supply chain? SQ2: What is digital twin? and SQ3: What are the opportunities and challenges with digital twin in supply chain? The third section consists of a cross case analysis and aims to answer RQ1: How can digital twin create added value for Northvolt's supply chain? Finally, the last section focuses on RQ2: What factors are important for Northvolt to consider before implementing digital twin?

5.1 Northvolt Characteristics

Northvolt's supply chain is characterised by deep vertical integration, where the majority of the battery components will be manufactured in-house. Consequently, most inbound material flows will consist of raw materials, which constitutes for the largest share of total cell cost. To date there are approximately 40-50 suppliers for the total amount of direct material, as estimated by Candidate A. Considering that, and the stable, predicted demand for Northvolt's products, Candidate A and Candidate G considered that Northvolt's supply chain will be of low complexity. To ensure stable lead-times, sustainable operations and cost efficiency, Northvolt puts high demands on their suppliers to reach full control. Strong collaborations could lead to important synergies between Northvolt and suppliers. Cross-company planning is another aspect considered with high priority by most candidates, this with regards to both the aspect of minimising tied up capital, but also to improve the collaboration with suppliers.

According to all candidates, Northvolt's product solutions will offer deep product traceability, which as well will be used for predictive quality. This has also contributed to Northvolt's high digital ambitions. As for the digital supply chain infrastructure, Northvolt is currently laying the foundation. To date, the major focus has been on securing the digital capabilities for Northvolt's manufacturing. The key focus is on cloud-based solutions and systems that are compatible with cloud-based solutions and can interoperate with other systems. However, according to Candidate B the ambition is to become a fully digitalised company. As agreed by most candidates, the current set up, with the ability to coordinate and interoperate the current systems and solutions, will be enough at least short term.

However, although the supply chain flows will be uncomplicated, there are some aspects that could be risk factors in the long term. One important fact to take into consideration is the fact that Northvolt is a young company. The fact that the factory, Northvolt Ett, is still being built means that any challenges related to the actual production and it's supply chain are not yet discovered. According to Candidate C and Candidate G, the necessary materials are supplied from industries from various maturity levels, impacting Northvolt's influence and ability to demand data sharing.

In Table 5.1 below, Northvolt's supply chain characteristics and challenges have been summarised.

Table 5.1: Northvolt Supply Chain Characteristics and Challenges

Northvolt Supply Chain in the Commissioning Phase	**Northvolt Supply Chain in the Operational Phase**
Established characteristics - Expensive finished goods - Dangerous goods - One factory - Deep vertical integration - Sustainable, circular approach - Deep product traceability - Digital factory Challenges - Fluctuations and uncertainty - Tied up capital - Maturity level	Aspiring characteristics - High lead time stability - Stable demand flow - Full control - Cross-company planning - Material flow visibility Challenges - Large manufacturing volumes - Lowest possible amount of tied up capital - Full control - Identification of deviations - Suppliers of various maturity levels

5.2 Digital Twin in Supply Chain

5.2.1 Concept

Case study two showed that there are many different views and interpretations of what digital twin is. Provider B explained that digital twin can be as simple as a photo of an object, whereas User A described it as an bits and bytes representation of what in the world is happening in atoms and molecules. Consultant D referred to digital twin as a platform and structure that is used to collect and transform data in a single format. These interpretations can all be viewed as digital representations of reality but to a varying complexity. Provider A explained that the many different understandings of digital twin depend on the person you talk to and their background as well as to what extent nearby universities use the term. For some it can be a simulation of real process and for others, including Provider A, it is more a representation of a reality, a collection of data. This representation can be used to ask hypothetical questions and test situations before they are implemented in reality. Digital twin can therefore be used as a tool for decision making.

Provider A further added that it does not matter if the decisions are made automatically or not but Consultant A stressed the fact that the digital twin should at least provide actionable intel. Digital twin should allow companies to see what is happening in their supply chain, ideally as live as possible, added Consultant A.

User A shifted the focus of digital twin from simply being a technology to that of it being a concept and a mindset, a way of working. This was in line with the thoughts of Consultant C, who stated that *“the tools are just a means to an end”* and stressed the importance of using the tools in the correct way so that companies can improve their strategies and tactics.

Provider A stressed the fact that digital twin is at the "hype of inflated expectations" on Gartner's hype curve and that soon a more narrow definition of the term will emerge, as well as the real values of the it.

5.2.2 Technical Structure

The case study showed that there is no consensus regarding how to technically realise digital twin. User A stated that there in fact are a lot of different options of how to go about it, but that for Company A it ended up being a very big database. Consultant B pointed out that a database digital twin can be used as a source, and that different solvers can be applied to it to solve different problems. This was the case of Company A, where an external program was used on the digital twin in order to enable integrated planning.

By using the five dimensional model by Tao and Zhang (2017) presented in 3.3 Technical Structure, Candidate B clarified this point of view. The digital twin, or the database, reflects the virtual supply chain dimension as it consists of data that mirrors real operations. The solver on the other hand corresponds to the model's service dimension, as it contains the services used to analyse the data in the digital twin. Consultant A however described that the analytical services are a part of the digital twin, i.e. in line with the five dimensional model approach.

As for the connectivity dimension of the five dimensional model, Consultant B and Consultant D stated that the level of connectivity needed is highly dependent on the task at hand. For example, Consultant D mentioned that daily updates are sufficient for Company A to achieve integrated planning. On the other hand, as stated by Consultant B, daily updates are not sufficient for warehouse picking and replenishment, this requires much more frequent updates. Consultant B also stressed that there is no added value in becoming too connected if it is not needed to solve the problem, instead it increases the cost and complexity.

Consultant B further explained that using an external solver on digital twin is a good approach, especially if a company operates in many different business systems as it bridges gaps and provides transparency. An external layer can also provide security as the data is saved in more locations and that it allows companies to work with best in breed systems. Provider B however explained that there are many risks involved with an external layer as it entails that data needs to be extracted from the systems. If a system is changed, the cooperation of all the digital twins in the facility would be disrupted. However, as Consultant B and Provider B work with considerably different digital twin solutions, it does not entail that either approach is wrong, rather that the technical construction depends on the purpose of the digital twin.

5.2.3 Applications

Many of the interviewees in the study agreed that digital twin is a tool that can be used to reach certain goals and that it should not be implemented without a clear purpose. Provider C works with digital twin that allows companies to track where they are positioned from a cost as well as CO_2 footprint perspective along the supply chain. Provider B offers a digital twin solution that enables people, systems and equipment to work together in a more efficient way. User A and Consultant D implemented digital twin in order to enable integrated planning for Company A on a global scale.

Supply chain planning is according to Wang et al. (2020) a very promising application of digital twin. Planning activities have a major impact on the overall cost, productivity and quality of the supply chain. By integrating several supply chain functions in the digital twin, planning activities can be improved and silo-planning can be counteracted.

The case study further showed that digital twin can be used to provide visibility and insight into data, e.g. from a financial or logistical perspective, as stated by Consultant D. This is supported by Wang et al. (2020), who further stated that a digital twin can give can an overview of location and availability of material and products in inventory, as well as optimise inventory costs and lead times across supply chain networks. According to Wang et al. (2020), digital twin can also bring deeper understanding of how to plan, design, operate and optimise supply chains, all the way from individual assets and shipments to complete global networks.

According to Dohrmann et al. (2019) the adopters of digital twin in supply chain can benefit from descriptive, analytical, diagnostic and predictive insights about their supply chain operations on a regular basis. Consultant C and Consultant D agreed that by combining digital twin with advanced analytics, business critical insights can be gained and companies can work out what the strategy and tactic of the company should be. This is supported by Qi et al. (2019) and Wang et al. (2020) who stated that companies that have implemented digital twin have experienced benefits in terms of new business models.

Another application of digital twin is that of risk mitigation. User A explained that the digital twin provides Company A with a global as well as graphical perspective of what is happening around the world, something that was very useful during the COVID-19 pandemic. With this visibility, Company A was able to react quicker to disruptive events, thus mitigating effects on the supply chain. Consultant A agreed that digital twin is a valuable tool for risk mitigation and added that during the pandemic, many companies realised they had not optimised the supply chain for risk, but for cost. Barykin et al. (2019) and Elliot (2017) also supported that digital twin can be used for risk mitigation and explained that it can give proactive warnings about potential disruptions in the supply chain. Candidate C added that digital twin can help companies respond intelligently, instead of react intelligently.

User A mentioned that one clear opportunity with digital twin is the ability to directly incorporate management decisions into operational planning, resulting in that decisions can be put into effect immediately, without handovers and emails.

In summary, many application areas of digital twin were touched upon during case study two and the literature review. When asked to put these in relation to the concepts Digital Model, Digital Shadow and Digital Twin mentioned in 3.2 Definition and Concept, Consultant A provided insight that resulted in the creation of a digital twin application framework, see Table 5.2 below. The framework is based on the three digital twin concepts and the three business levels. It specifies which digital twin concept is most appropriate to employ depending on the level it is to operate on. The framework shows that a Digital Twin is best suited for tactical and operational decisions, whereas a Digital Model is most appropriate for a strategic decisions. A Digital Shadow operates in between and can be used for all types of decisions, however with some limitations. Text in cursive reflect the authors' input and is the result of extensive interviews, and the remaining text is input from Consultant A.

Table 5.2: Digital Twin Concept Framework

	Digital Model	**Digital Shadow**	**Digital Twin**
Strategic	Yes + design and simulation can give strategic insights	*Yes/No* + *can accumulate real-time data into long term insights* - *could be too advanced and expensive*	No - certain aspects hard to reflect in the data - *too advanced and expensive solution*
Tactical	*No* - *time consuming to perform manual simulations*	*Yes* + *what if scenario planning*	Yes + can look 3-6 months ahead and identify future risks
Operational	No - requires real-time updated information	*Yes/No* + *identify inefficiencies* - *limited as human interaction is needed*	Yes + can provide real-time visibility and actionable intel for operations + *increase synchronisation of supply chain flows*

5.2.4 Challenges

The case study showed that the major challenges with implementing digital twin are those regarding the third dimension in the five dimensional model, namely the data. All candidates agreed on that data is the most difficult and critical element to focus on, an aspect also highlighted in the literature review by Dohrmann et al. (2019). However, various aspects have been emphasised. During the implementation and construction of the digital twin at Company A, both the lack of, and the quality of the data, was indisputably the biggest challenge as stated by User A and Consultant D. Difficulties of providing the right data was also an aspect mentioned by Provider C, Consultant A and Dohrmann et al. (2019), who stated that data does not often come in accessible formats. Moreover, Provider A pointed out that digital twin implementors must consider which data is necessary and where in the supply chain it is generated. Additionally, Provider C concluded that without the right data, the technology and systems used in the digital twin cannot act correctly. A way to ensure clean data mentioned by Provider B was to instead of laying all focus on data extraction, focus on specifying requirements on the systems that generate the data. An additional challenge with data is that of the master data. Master data is often inserted manually into the systems and if the person inserting the data does not understand its true value, some critical data could be missed.

Apart from the technical challenges with data, there are challenges with involving external parties when implementing a forward or backward integrated digital twin. When optimising a supply chain, Consultant A pressed on the fact that considerations must be taken to the risk of sub-optimising the supply chain network, involving the external parties. Supply chains are complex networks involving multiple stakeholders wherefore the end-to-end perspective must involve the complete network to achieve the greatest benefits. Moreover, the tendency to share data varies. This was highlighted by Consultant B, who said that data security is an important aspect to consider when integrating with external partners. This was also supported by Dohrmann et al. (2019), who further stated that as digital twin contain business critical information they risk being the target of hacks. To achieve a high level of data security, Provider A mentioned blockchain solutions as an example.

Dohrmann et al. (2019) also highlighted the challenge with educating employees, customers and suppliers and getting them onboard with the new ways of working that follow the implementation of digital twin. This was also implied by User A who mentioned how important it is to get into the learning curve as soon as possible.

Furthermore, Dohrmann et al. (2019) stated that the cost aspect of digital twin can also pose a challenge. The cost of most technologies, including digital twin, decrease when they reach wide-spread application, but the decision of implementing digital twin must be in comparison to other solutions with the same value at lower cost.

A summary of the challenges with digital twin provided by the case study two and literature review can be found in Table 5.3 below.

Table 5.3: Digital Twin Challenges

Technical Challenges	**Other Challenges**
- Data accessibility - Precise representation - Data quality - Master data - Interoperability - Cyber and data security	- Involving external parties - Education - IP protection - Sub-optimisation - Cost

5.2.5 Implementation

Although the case studies, as well as the literature study, showed that there are many different perceptions among both industry experts and academia, the subject of implementation marks more of a consensus. First of all, the purpose of the digital twin must be specified, both in order to implement the right sized digital twin and to achieve the right level of detail in the digital twin

(Provider A, Consultant B). In Table 5.4 below, the authors have consolidated the most critical steps when implementing a digital twin, which have been derived from case study two.

Table 5.4: Implementation Elements

Implementation Elements	**Description**	**Source**
Define purpose	Identify a challenge or a goal that cannot be achieved with current digital capabilities	Provider A
Map supply chain	Start with 20% and scale up, value can be achieved even though the solution is not complete	Consultant A, User A, Consultant D
Determine necessary size	Vertically and horizontally	Consultant B
Ensure connectivity and digital thread	System of records Transactional workflow. Connect node-to-node, mindset	Consultant A, User A, Consultant D, Provider C, Candidate D
Start small	Identify a first use case and scale up	Consultant A, User A, Consultant D

As for the system set-up in the company, most interviewees stated that the difficulties are not within the systems themselves but in, as stated above, the data. However, as explained by Provider A, the selected systems within the company that are to be included in the digital twin should use common protocols, such as MQTT. If the systems use non-standard protocols, the integration with other systems will be more expensive. Moreover, it can be a good idea to ensure that the data is collected in open formats so that it can be sent on to various systems. Further on, it must be considered what happens if a system is exchanged, so that the digital twin is not too dependent on one specific system, as highlighted Provider B.

An additional important aspect is to ensure that the company has a digital strategy in place (Provider C). To overcome the integration challenges described above, not to many systems should be selected and the selection of a software house is preferred according to Provider C. In the digital strategy, a digital thread should be incorporated (Provider C, User A, Consultant D). As pointed out by Provider C, some companies still perform tasks manually in Excel even though they possess expensive and complex systems. Provider C stated clearly that it is important that purchasing and logistics are included in the digital thread, and not only manufacturing. According to Consultant D, a digital thread is one of the most critical success factors when implementing a digital twin. Lastly, Candidate D stated that to reach a fully intelligent industrial communications network, all data exchange must be standardised.

5.2.6 Summary

Below, in Table 5.5, the key take-aways from the market insights have been summarised.

Table 5.5: Summary of Key Take-Aways from Case Study Two

	Concept	Structure	Applications	Challenges	Implementation
Consultant A	Decisions' portal for operational, tactical and strategical operations	-	Risk mitigation on operational level. Identify capacity issues and supplier risks on tactical level. Improve strategical decisions through simulation	Local optimised solutions. Poor underlying data quality, due to issues in data creation. Accessing supplier data. Sub-optimised supply chains	Map out the supply chain, does not have to be 100% accurate. Focus on being able to collect data and transfer data. Maintain openness and trust with suppliers
Consultant B	Collection of data representing the physical supply chain	Digital twin is a database. External solver analyses the data in the digital twin	Synchronise material flows between supply chain entities	Data security. Getting access to data from customers, distributors and suppliers	Important to decide what level of detail is needed and how often the digital twin needs to be updated
Consultant C	Data collected in one place, not silos, that is analysed with tools, e.g. AI and ML	-	Overcome silo effects that are the result of every department working in different systems. Respond instead of react intelligently	-	Important to understand the need for implementing a digital twin
Provider A	Digital representation of reality. A tool that is used to reach certain goals, to test things before they are done in reality	-	-	Complexity in accessing external data. Integration of systems with different protocols and structures	Understand the purpose behind implementing the digital twin from a business perspective, and scale it accordingly. Common protocols in systems, data in one format
Provider B	Digital representation of something that is not digital	Varies, but focus on getting many digital twins working together	Synchronise between people, systems and equipment	Creating the right type of information and ensuring clean data	-
Provider C	-	-	Cost and CO2 traceability and optimisation	Include logistics and purchasing in the digital thread. Manufacturing/ technicians lack supply chain mindset	Need of a digital thread across all supply chain entities. Digital strategy in place, no too many different software programs
Use Case	A digital representation of the real world. A platform that gathers competence in one place	Digital twin is a database. External solver used for calculations, ERP systems used for execution	Improve forecasts, mitigate risks of disruptions, increase visibility and transparency and thereby reduce costs, e.g. inventory and manual labour	Lack of data and good quality data. Digital thread that tracks everything that is happening in operations	Buy in from stakeholders. Bring on an experienced partner at an early stage. Standardised ERP layer good. Build competence inhouse

5.3 Cross Case Analysis

5.3.1 How can digital twin create added value for Northvolt's supply chain?

One of the most important questions to consider when investigating if digital twin could be of value for Northvolt is if the application areas of digital twin are in line with the needs and characteristics of Northvolt's supply chain. The summarising table above, Table 5.5, shows that one big strength of digital twin is that it helps companies gain visibility of their supply chain. This was especially relevant in the use case of Company A, as its supply chain was complex with many interconnected global flows between multiple factories, warehouses and distribution centres. The visibility digital twin provided helped Company A reduce inventory levels, maintain a stable service level and minimise manual labour. When it comes to Northvolt, Table 5.1 shows that there are few characteristics that point to visibility being one of the company's main challenges as the supply chain is still relatively small-scale. However, as Candidate A and C stated, visibility of material flows could benefit Northvolt in the long term when the operations of multiple factories and material flows need to be coordinated.

Consequently, this indicates that one digital twin solution might suit one company, but not another. As stated by the interviewees in case study two, a digital twin is a tool that can be used to reach certain goals and that it should not be implemented without a clear purpose. Since every company has its own unique objectives and challenges, it entails that digital twin solutions are company unique. In the case of Northvolt, a clear goal for digital twin could be to improve operations affecting the two most important aspects of Northvolt's value offering, namely sustainable and competitively priced batteries. It is important that Northvolt cut costs wherever they can, as long as it does not result in an unacceptable trade-off when it comes to sustainability. There are digital twin solutions on the market that focus on precisely this. As Northvolt has a lot of tied up capital a digital twin focused on automatic stock replenishment or stock planning could further decrease costs. There is also the potential application of risk prevention which could help mitigate impacts that disruptions in the supply chain could have on the large manufacturing volumes. Digital twin could provide effective and insightful analysis automatically, without the need for gathering and extracting data which is necessary for an ad hoc analysis of the supply chain.

As Northvolt is still in the commissioning phase it is challenging to identify more specific business cases and also to evaluate the actual potential of digital twin solutions focused on decreasing costs and improving sustainability. It is crucial that Northvolt identifies and evaluates such a business case before implementing a digital twin. However, the authors believe that the aforementioned business cases have promising potential and should be looked further into.

Additionally, it is also important to consider the cost-benefit perspective of implementing a digital twin. As each digital twin solution is unique and tailored for the company and challenge at hand, there is no out of the box solution which poses a challenge when estimating the cost-benefit aspect. In order to evaluate the cost perspective, Northvolt must first fully understand what it is they want to achieve and analyse if their existing systems/resources can solve it in a sufficient way. If not, the first step for Northvolt would be to clarify what type of digital twin solution is required, e.g. if it is of an operational, tactical or strategical nature. The *Digital Twin Application Framework* (see Table 5.2) can be used to determine this and thereby the scope of the project, resulting in a starting point for a cost estimation.

Furthermore, the authors believe that digital twin should not be seen as just merely a tool, but as a strategic investment. Companies do not buy ERP systems or TMS for the mere purpose of decreasing costs, but rather for the fact that they cannot operate without them. These systems are strategic investments that allow companies to gain access to data that can help them make better decisions. An important characteristic of Northvolt's supply chain is that it is expanding at a rapid pace. This entails that there are many strategic decisions to be taken regarding operations, and digital twin could provide the necessary insight to make the most optimal ones. Furthermore, the battery market is still emerging and new players are continuously establishing themselves on the market. In this regards, digital twin could contribute to a competitive edge.

5.3.2 What factors are important for Northvolt to consider before implementing digital twin?

When implementing digital twin in supply chain, there are several factors that need to be considered before a potential implementation. In Table 5.6 below, the prerequisites and challenges of digital twin have been listed along with Northvolt's capabilities and challenges.

Table 5.6: Supply Chain Digital Twin Prerequisites and Northvolt Capabilities and Challenges

Supply Chain Digital Twin	**Northvolt**
Prerequisites • Digital thread • Digital strategy • High quality data • Data accessibility • Management support • Digital twin mindset • Education • System interoperability Challenges • Involve external parties • Cyber security • Supplier maturity and proneness to share info • IP Protection • Sub-optimised supply chain networks • Education	Capabilities • Competent digitalisation team, skill inhouse • Enterprise architecture focused on system integration • Key focus on cloud-based solutions and system integration • Master data quality manager • Vertical integration Challenges • Company maturity* • Lack of clear intangible problem for digital twin*

* short term challenges, due to commissioning phase

From Table 5.6 above, it is clear that Northvolt possesses many capabilities that give them a strong head start when it comes to implementing digital twin. They have a competent digitalisation team, entailing that they have lot of competence inhouse, with a major focus on integration of systems. In general they have a good data structure and are currently hiring a master data quality manager that will continue to work with this. These capabilities facilitate the establishment of a digital thread which is one of the most important prerequisites for a successful implementation of digital twin. A digital twin can simply not be built without a digital thread in place as all data needed for the digital twin must be digitally traceable. To secure a digital thread, a digital strategy that covers all supply chain entities must be in place. Furthermore, some digital twin solutions can make decisions that are automatically implemented in the physical supply chain and it is therefore critical to incorporate cyber security aspects in the digital strategy. This is also relevant for simpler types of digital twin solutions as they contain sensitive information.

Another significant characteristic of Northvolt's supply chain is the high degree of vertical integration. This means that Northvolt controls a large part of the supply chain themselves, resulting in that they can create a digital twin for a large part of operations without including external parties. However, in order to implement an end-to-end supply chain digital twin, external parties must be incorporated. When backward integrating, this poses a big challenge as it requires trust and data sharing, but many suppliers of raw materials needed for battery manufacturing are not digitally mature or willing to share data. An important factor to consider is therefore how to make sure that this type of data exchange is made viable. When forward integrating, external parties such as logistic service providers and customers also need to be included in the digital thread. One way to realise this is to focus on partnership relations with the external parties.

Lastly, as Northvolt is in its commissioning phase, the supply chain is evolving rapidly and constantly growing. Digital twin types Digital Shadow and Digital Twin build on that data for all processes is accessible and tangible. This is not the current case for Northvolt, thus indicating that it is reasonable to wait with these types of digital twin until processes and their data flows have been stabilised. The Digital Model on the other hand is not restricted to the completion of the commissioning phase and could be used to facilitate strategic decisions through simulation, e.g. where to locate new warehouses/factories. Moreover, as pressed on in the previous section, it is essential that a digital twin is implemented with a specific business case in mind. Until the commissioning phase is completed, it will be challenging to identify and evaluate the right business case for Northvolt.

6 Conclusions

In this chapter, the two research questions, RQ1 and RQ2, are answered and recommendations for Northvolt are presented.

6.1 Answers to Research Questions

To investigate the concept of digital twin and to evaluate its opportunities and challenges in relation to Northvolt's supply chain, two research question were formulated in the beginning of the thesis. Each chapter was then created with the ambition to answer these research questions. Moreover, it was deemed necessary to support these two research questions with three sub-questions, which have been answered in Chapter 5. To answer RQ1 and RQ2, it was necessary to collect insights on digital twin from industry professionals and a practical use case and to compare these findings against a literature review. The outcome was mapped against Northvolt's supply chain to identify the specific potential value of digital twin for Northvolt's supply chain and important factors to consider before implementing it.

6.1.1 Research Question 1

RQ1: How can digital twin create added value for Northvolt's supply chain?

This study has that shown a digital twin can create added value for Northvolt's supply chain by *ensuring that the supply chain operates at the lowest possible cost, and with a minimal emissions footprint.* As stated in the problem formulation, high demands are placed on Northvolt's supply chain performance to deliver the greenest battery at the most competitive price. Digital twin can support this goal and thus create added value for Northvolt's supply chain.

6.1.2 Research Question 2

RQ2: What factors are important for Northvolt to consider before implementing digital twin?

As a result of this study, three important factors for Northvolt to consider before implementing a digital twin have been identified. The first factor is *preparing with the right digital supply chain strategy and infrastructure.* This includes securing a digital thread of all data that needs to be included in the digital twin as well as supporting the digital thread with a digital strategy that covers all supply chain entities.

Secondly it is important to consider *how to include external parties in the digital thread.* Raw material suppliers have different digital maturity levels and have a varied willingness to share data. This challenge must be overcome before implementing an end-to-end supply chain digital twin.

The last factor is that *each digital twin solution is uniquely developed to fit a specific business case*. Therefore, the authors want to stress the importance of *identifying a business case*, where no other solution can fulfil its purpose at a lower cost than digital twin. As Northvolt and its supply chain are rapidly developing, the authors want to highlight the potential of business cases not yet existing.

6.2 Recommendation for Northvolt

Based on the results and analysis of this study, it is recommended that Northvolt initiates an internal discussion between supply chain entities regarding potential business case(s) for a supply chain digital twin, with this thesis as a foundation.

If a business case is found, it is suggested that Northvolt in the short term, i.e. until Northvolt Ett is up and running, keep building up the strong digital infrastructure currently being constructed. The current approach with the clear focus on system integration and cloud-based solutions is a perfect growing ground for digital twin. However, to ensure that the strong digital infrastructure supports the end-to-end of Northvolt's supply chain, it should be noted that a digital strategy is necessary for all supply chain entities. It is recommended to strive for a connected company, where all supply chain operations are digitally traceable and where operations outside the factory walls are managed with the end-to-end supply chain in mind. In bullet points below, the authors have summarised three short term recommendations for Northvolt:

- Set up a cross-functional workshop to discuss potential business case(s) for Northvolt's supply chain and appoint one person as concept owner to ensure that the discussion is driven forward. If a business case is found:
    - Focus on making all supply chain operations digitally traceable so that a digital thread is achieved throughout all operations and between all supply chain entities.
    - Continue building up the strong digital infrastructure that is currently being constructed and ensure that it supports the end-to-end supply chain. A digital supply chain strategy needs to be in place that covers all supply chain entities, and not just manufacturing.

7 Discussion

This chapter discusses the generalisation of results and the contribution to research. Lastly, limitations and future research recommendations are presented.

7.1 Generalisation of Results

Even though the thesis was written for Northvolt, the findings made are relevant to any company looking to understand digital twin, as a large part of the thesis focuses on breaking down the concept of digital twin. The thesis furthermore investigates two companies with very different supply chain characteristics, resulting in that the results covered a wide spectrum. This entails that many companies will be able to identify with at least some part of the thesis.

Furthermore, the thesis presents the *Digital Twin Concept Framework*, that aims to explain how the different digital twin types can be used in relation to the business level they are to operate on. This framework can be useful for companies that are looking to implement digital twin.

7.2 Contribution to Research

Limited research has been conducted in the field of digital twin from a supply chain perspective, as was apparent when the authors conducted the literature review, with the majority of papers focused on manufacturing. Furthermore, many of the papers were published in 2020, indicating how recently academics have begun investigating digital twin. This paper builds on academic literature, but also on insights from industry and thus bridges the gap between academia and industry. This was achieved through an extensive literature review and a multiple case study (case study two) with professionals from different disciplines. Furthermore, case study two can be used as a benchmark for defining the concept of digital twin.

The results from this thesis are relevant to academics looking for insights on digital twin that are rooted in the industry, and who want to understand how theory presented in academia can be applied in a supply chain setting.

7.3 Limitations and Future Research

Even though this thesis contributes to bridging the gap in literature on digital twin in supply chain, several gaps remain.

The scope of the thesis was to investigate the opportunities and challenges with digital twin for Northvolt, wherefore Northvolt's supply chain has been the focus of the thesis. As a supply chain digital twin can potentially be applicable for most companies that have a supply chain, additional research can be performed on supply chains with other characteristics. Moreover, the study was limited to being of a qualitative nature as Northvolt's supply chain still is in its commissioning phase. Further research is therefore suggested to include quantitative data as well so that practical benefits can be analysed further.

Due to the lack of standardised processes in Northvolt's supply chain, the study was to some extent limited. By investigating digital twin in relation to a company with an established supply chain, the authors are convinced that more insights into digital twin could be gained. Future research is therefore encouraged to be performed on an ongoing digital twin implementation.

Furthermore, as digital twin is an emerging technology, it is critical at this stage to highlight all sides of the topic. The authors attempted this by focusing on both opportunities and challenges, but believe it would be valuable to also investigate companies that have implemented digital twin without success. However, the authors experienced difficulty in finding such a case, but are convinced they exist.

Lastly, future research is also encouraged to apply the *Digital Twin Concept Framework* to practical cases and test its validity.

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Appendix A

In Appendix A, the interview guides used for both case studies are presented. As all interviews were performed as video calls, the original interview guides were in the format of a PowerPoint presentation. To make it more accessible in the thesis' report format they have been summarised into text and bullet points.

Case Study One: Interview Guides

This section presents the interview guides used in case study one at Northvolt. The performed interviews are shown in Table A.1 below. All candidates were presented with the background of our thesis i.e. a summary of the problem description and the purpose, as well as a brief explanation of digital twin using the information learnt from the literature review. In the beginning of the interview the authors' expectations for the interview were stated.

The interviewees that were interviewed after the use case interviews were provided with an introduction to the case at Company A, in order to facilitate the understanding of digital twin with a tangible example. This was applicable for Candidate A's and B's second interviews, and the interviews with Candidate F, Candidate G and Candidate H.

Table A.1: Repetition of Table 2.2 - Case Study One Interviews

Interviewee	Role	Department	Scope of interview	Information about the interview
Candidate A	Director	Logistics	Identify Northvolt's supply chain goals and challenges	Two unstructured video calls á 1h
Candidate B	Senior Manager	Digitalisation	Map Northvolt's digital operations	Two unstructured video calls á 1h
Candidate C	Director	Metals and Raw Materials	Understand Northvolt's material flows and sourcing approach	Unstructured video call 40 min
Candidate D	Enterprise Architect	IT	Understand Northvolt's IT architecture and the aspects behind	Unstructured video call 40 min
Candidate E	Enterprise Systems Manager	IT	Understand Northvolt's IT architecture and the aspects behind, systems focused	Unstructured video call 40 min
Candidate F	Logistics Purchasing Manager	Logistics	Understand goals and challenges pertaining	Unstructured video call 1h

			to logistics supplier management	
Candidate G	Manager Material Logistics	Logistics	Understand S&OP processes	Unstructured video call 40 min
Candidate H	Material Logistics Coordinator	Logistics	Map how material planning is conducted	Unstructured video call 1h

Candidate A

Questions asked during the first interview:

- How would you map the supply chain?
- How would you describe Northvolt's supply chain characteristics, i.e. a robust supply chain vs. a resilient/flexible supply chain?
- We have understood that sustainability is the core of Northvolt's operations, but more specifically what are the main strategic goals/targets for the supply chain?
- What will be the main challenges when it's up and running?
- What is done inhouse and what is outsourced?
- To stay competitive on the battery cells market, what is Northvolt aiming for?
- Connected to the overall supply chain goals/challenges:
- What are the main strategic goals for Northvolt's logistics operations?
- What are/will be the main challenges for logistics?
- If Northvolt would implement a digital twin on a larger part of the supply chain, what would you think is important to include or what would you want to be able to do, e.g. regarding
    - Sustainability
    - Visibility
    - Cost control
    - Other?

Questions asked during the second interview:

- How will Northvolt's S&OP look like in the future?
- Current open position for S&OP: what will be the scope of the role?
- What is the strategy for these operations? (e.g. local or company-wide integrated planning)
- What will be the S&OP working conditions? (e.g. challenges in planning operations between recycling, purchasing, manufacturing and transport a.s.o.)
- What digital strategies will be in place to support S&OP?

Candidate B

Questions asked during the first interview:

- We have understood that sustainability is the core of Northvolt's operations, but more specifically what are the main strategic goals/targets for the supply chain?
- What will be the main challenges when it's up and running?
- What are the main strategic goals for Northvolt's digitalisation department?
- System/software house?
- What are/will be the main challenges for digitalisation?
- If Northvolt would implement a digital twin on a larger part of the supply chain, what would you think is important to include or what would you want to be able to do?

Questions asked during the second interview:

- Northvolt's digital thread:
  - Are there any areas where the digital thread is missing, e.g. operations that are handled through email/requires manual input?
  - Is there a strategy in place for a digital thread on a supply chain level (last meeting we talked about the digital thread in the factory, with automated data flows and digitalised tasks, i.e. related to CoA)?
- How do you ensure that you have clean and relevant master data?
- Are you working towards collecting all operational data?
- Regarding the complexity with integrating systems (e.g. PLM, TMS), how is Northvolt selecting system suppliers and how much of the system solutions are developed in-house? What's your take on this?
- If Northvolt would implement a digital twin on a larger part of the supply chain to Northvolt Ett, what would you think is important to include or what would you want to be able to do?

Candidate C

Questions asked during the interview:

- Tell us more about your role!
- What is your and Northvolt's approach and strategy for selecting and sourcing raw material?
- Are there any digitalisation strategies incorporated in the raw material operations/activities (e.g. to ensure traceability/visibility or sustainability)?
- What are your thoughts about supply chain digital twin regarding
  - the challenges for Northvolt?
  - the opportunities for Northvolt?
  - the applicability for Northvolt's future operations (i.e. when Northvolt Ett is up and running)?

Candidate D

Questions asked during the interview:

- Tell us more about your role!
- What is your and Northvolt's approach and strategy for selecting systems, software or other IT related products?
- How familiar are you with digital twin solutions?
- What are your thoughts about supply chain digital twin regarding:
    - the challenges for Northvolt?
    - the opportunities for Northvolt?
    - the applicability for Northvolt's future operations (i.e. when Northvolt Ett is up and running)?

Candidate E

Questions asked during the interview:

- Tell us more about your role!
- What is your and Northvolt's approach and strategy for selecting systems, software or other IT related products?
- How familiar are you with digital twin solutions?
- What are your thoughts about supply chain digital twin regarding:
    - the challenges for Northvolt?
    - the opportunities for Northvolt?
    - the applicability for Northvolt's future operations (i.e. when Northvolt Ett is up and running)?

Candidate F

Questions asked during the interview:

- Tell us more about your role!
- What is your and Northvolt's approach and strategy for purchasing?
- Are there any digitalisation strategies incorporated in your operations/activities?
- What are your thoughts about supply chain digital twin regarding:
    - the challenges for Northvolt?
    - the opportunities for Northvolt?
    - the applicability for Northvolt's future operations (i.e. when Northvolt Ett is up and running)?

Candidate G

Questions asked during the interview:

- Tell us more about your role!
- How do you work with S&OP?
- How do you plan the inventory levels?
- Are any other departments involved?
- What digital strategies do you work with?
- Is there a digital thread throughout operations? In other words, are all decisions/activities digitally traceable and accessible (e.g. not stored in local excel files or similar)

Candidate H

Questions asked during the interview:

- Tell us more about your role!
- What digital strategies/digital threads have you implemented or will implement?
- What are your thoughts about supply chain digital twin regarding:
    - the challenges for Northvolt?
    - the opportunities for Northvolt?
    - the applicability for Northvolt's future operations (i.e. when Northvolt Ett is up and running)?

Case Study Two: Interview Guides

This section presents the interview guides used in case study two with industry professionals. The performed interviews are shown in Table A.2 below. All candidates were presented with the background of our thesis i.e. a summary of the problem description and the purpose. In the beginning of the interview the authors' expectations for the interview were stated.

Table A.1: Repetition of Table 2.3 - Case Study Two Interviews

Interviewee	Company	Role	Scope of interview	Information about the interview
Consultant A	Global management consulting firm	Partner	Concept, opportunities, challenges and implementation	Unstructured video call 1h
Consultant B	Nordic consulting firm	Senior Business Consultant	Definition, technical aspects and implementation challenges	Unstructured video call 1h
Consultant C	Global management	Vice President Value Chain	Common supply chain challenges and	Unstructured video call 30 min

	consulting firm		the role of digital twin	
Provider A	Global technology powerhouse	Country Product Manager, Digital Enterprise	Definition and current state, opportunities and implementation challenges	Unstructured video call 1h
Provider B	Global technology company	Global Product Manager	Definition, specific solutions and reasons for implementation	Unstructured video call 1h
Provider C	Swedish solution partner company	Owner and Managing Partner	Cost and emission focused solutions and technical aspect	Unstructured video call 1h
User A	Global manufacturing company	Business Transformation Manager	Supply chain planning, opportunities, challenges and implementation	Unstructured video call 1h
Consultant D	Nordic consulting firm	Senior Business Consultant	Supply chain planning, opportunities, challenges and implementation	Unstructured video call 1h

Consultant A

Background questions:

- What is your background?
- How do you define digital twin?

Questions in regard to the article:

- Are there any requirements on the raw data from the physical & device layer, e.g. data format, data language?
- How can this be handled in regards to suppliers?
- Is there a risk of sub optimisation if data is collected from Enterprise Data Systems?
- How do you ensure clean data?
- Do you have any examples of a digital twin solving a supply chain problem?
- What are important parts to trace in the supply chain that might easily be forgotten?

Questions with regards to Northvolt:

- What would you recommend them to keep in mind at such an early stage of their supply chain organisation in regards to a future implementation of digital twin?
- Any system configurations that should be avoided etc?

Other questions:

- As concluded in the article, there is much to be gained from implementing a digital twin, but with such a new and complex technology, there are many challenges that need to be considered. What would you say are the greatest challenges with this technology (today/future)?

Consultant B

Background questions:

- What is your background?

Project related questions (the interview focused on one of their biggest projects):

- What was your company's role in the project?
- What was your role?
- What did the collaboration look like?

Technical questions:

- What did the solution look like?
- What systems did you use?
- What technologies were needed?
- What were the technical challenges?

Questions in regards to other projects:

- What other digital twin projects have you worked with?
- What practical problems did they aim to solve?
  - Why was digital twin the right solution?
  - Did you consider other solutions?
- How did these projects differ from the aforementioned project you worked on in regards to
  - implementation?
  - technical details such as what systems and what data was used?
  - the construction of the digital twin?

Questions with regards to Northvolt:

- If Northvolt had wanted to implement digital twin, how would you have gone about it?

    - What is important to consider when initiating the project?
    - Which structures/technologies/systems need to be in place?
    - What are the critical success factors for a successful implementation?

Consultant C

The interview with Consultant C did not have an interview guide as it was unstructured to the point that it was a pure discussion rather than a questioning interview.

Provider A

Background questions:

- What is your background?
- What is your role at the company?

Questions in regard to the company's digital twin solution:

- How long have you worked with digital twin technology?
- How far has the development of digital twin technology come today?
    - In general?
    - In supply chain?
- What digital twin solutions do you offer?
    - Within supply chain?
    - Within separate entities?
- Can you describe what different kinds of intelligence levels there are of digital twin? (refer to digital model, digital shadow, digital twin)

Questions on digital twin set up in supply chain

- An end-to-end supply chain digital twin, does it consists of several integrated digital twins or just one?

Questions on opportunities and challenges:

- What challenges do you see with implementing a digital twin on a supply chain?
- What opportunities do you see with implementing a digital twin on a supply chain?

Questions with regards to Northvolt:

- How had you gone about implementing a digital twin at Northvolt?
    - Several separate digital twins or one whole from the start?

Provider B

Background questions:

- What is your background within digital twin solutions?

Questions in regard to the company's digital twin solution:

- What supply chain, or logistical, digital twin solutions have you implemented so far?
- Any planned projects?
- What practical problems did/will the digital twin solve in these examples?
- What systems did you/the companies have to have in place in order for them to work together with your solution?
- Has you implemented any digital twin solutions on internal operations?
- What problem did it solve in that/those case(s)?

Questions on challenges:

- What have you identified as main challenges with digital twin in regard to
    - implementation?
    - maintenance?
    - utilisation?
    - human dynamics?

Questions with regards to Northvolt:

- If Northvolt had wanted to implement this technology on their end-to-end supply chain, how would you have gone about it?
- What structures/technologies/systems need to be in place?
- What are the critical success factors for implementation?
- When in time do you find it reasonable to implement an end-to-end supply chain digital twin solution?

Provider C

Background questions:

- What is your background within digital twin solutions?

Questions in regard to the company's digital twin solution:

- How do you work with digital twin solutions within supply chain?
- Do you have any end-to-end solutions?
    - If not, what does the future look like in that area?
    - An end-to-end digital twin, does it/would it consist of several digital twins that are integrated or just one?

Questions on challenges:

- What challenges are there currently in regards to supply chain digital twin?
- What future challenges are there?

- Other challenges with the technology itself?

Questions with regards to Northvolt:

- If Northvolt had wanted to implement this technology on their end-to-end supply chain, how would you have gone about it?
- What are important aspects they need to consider?

User A

Background questions:

- What is your background?

Questions on the project:

- Why did you implement digital twin?
- What systems/platforms did you have to have in place?
- What were/are your main challenges in regard to
    - in regard to implementation? implementation?
    - in regard to maintenance? maintenance?
    - in regard to utilisation? utilisation?
- What is the result? Are you satisfied?

Questions with regards to Northvolt:

- What structures/technologies/systems need to be in place for a successful implementation of digital twin?
- What are the critical success factors for implementing a digital twin?

Consultant D

Background questions:

- What is your background?

General questions:

- What was your company's role in the project?
- What was your role?
- What did the collaboration look like?

Technical questions:

- How was the digital twin solution constructed?
- Which systems did you use?
- What technologies were needed?

- What were the technical challenges?

Questions in regards to other projects:

- What other digital twin projects have you worked with?
- What practical problems did they aim to solve?
    - Why was digital twin the right solution?
    - Did you consider other solutions?
- How did these projects differ from the project you worked on with User A in regard to
    - implementation?
    - technical details such as what systems and what data was used?
    - the construction of the digital twin?

Questions with regards to Northvolt:

- If Northvolt had wanted to implement digital twin, how would you have gone about it?
    - What is important to consider when initiating the project?
    - Which structures/technologies/systems need to be in place?
    - What are the critical success factors for a successful implementation?