Influence of Industry 4.0 on supply chain resilience: The case of chlor-alkali supply chain

A qualitative case study of the chlor-alkali supply chain

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Preface

With the completion of this thesis, I will be winding up my two-year master's program at Delft University. Attending this program has been a wonderful learning experience for me. The variety of subjects I explored enriched my knowledge. I got the opportunity to interact with students from other nationalities and learnt a great deal about their backgrounds and cultures.

As I am previously from an operations background, I developed an affinity towards supply chain electives and ultimately decided to do my thesis in this research area itself. Arriving at this topic itself was an intensive effort. Conducting literature reviews helped with narrowing down on the topic.

The topic of my thesis explores the implementation of Industry 4.0 in the chlor-alkali industry and tries to deduce how this entity affects supply chain resilience. I chose to do this research from the context of the chemical supply chain as I am from a chemical engineering background and had the relevant operational experience.

The thesis was a very challenging task and has contributed to my development in many ways. Planning of activities is a very challenging element. Doing this thesis has helped me in becoming a better time planner. Next, this process has also made me into a critical thinker. It taught me to take any data for granted and to verify all the data that came my way. It also taught me to read between the lines and look for hidden meaning and patterns.

The impact of COVID-19 was quite devastating for the progress of my thesis. First, it affected my productivity and hampered my progress. Then, it blocked off access to companies from whom I could obtain data. It was a test of my self-resilience which is ironical as this is the same topic that I am exploring. Even in such circumstances, I made acquaintance with two professionals who could help me with it. I am very thankful to these anonymous professionals who made mighty contributions to this thesis.

I would like to extend my gratitude to my graduation committee. All three members brought in unique contributions to my thesis. My second supervisor Anneke Zuiderwijk-van Eijk was very supportive and provided extensive review to all my drafts. This made me look at my thesis from outside-the-box and helped me in the report development process. The chairperson Prof Lori Tavasszy gave timely and directional feedback on how to proceed with the thesis at the time that I needed it the most. And last but not the least, my first supervisor Ir. Marcel Ludema, took the time and patience to deal with my queries and to steer my thesis to completion. Having regular Skype calls with him helped with my motivation levels and set subsequent targets.

Lastly, I would like to thank my very supportive family members whose reassurance helped me a great deal to keep myself focussed and to finish the thesis. My wife Dharani was especially very understanding and was always there to support me.

Subbaraman Chittur Ramasubramaniam
Delft, November 2020.

Thesis Summary

Background

This research deals with two active fields in social science research. They are Industry 4.0 and supply chain resilience. The former can be said to be the manifestation of advanced technologies like Internet of Things, Cyber-Physical Systems, Enterprise Resource Planning, Big Data and cloud computing in the manufacturing sector to make the processes more independent and autonomous from human control. The latter is said to be the capacity of the supply chain to mitigate the effects of a disruptive internal/external event and return to acceptable performance levels at the earliest.

Both these concepts are gaining importance in organisations nowadays, but it is not possible to obtain any information linking these two concepts and how one influences the other. Industry 4.0 can be said to be a resource the firm owns and can use it to improve its performance and competitive advantage. These technologies are slowly gaining their way into many organisations. Supply chain resilience is a multidimensional capability and its importance is being recognised by many organisations across all industries.

Problem statement

The influence of Industry 4.0 systems and technologies on supply chain resilience has not been studied in detail yet. This thesis attempts to bridge that knowledge gap in the literature. The implementation of Industry 4.0 brings about many capabilities that affect routine operations within the supply chain. But these changes in capabilities can also affect resilience negatively or positively. This interaction has not been determined yet in literature.

It is now known that Industry 4.0 systems contribute to better efficiency and competitive advantage among many capabilities. Due to the numerous advantages that Industry 4.0 based manufacturing system offer; their usage is only going to increase in manufacturing organisations. I feel it is important to analyse this perspective in scientific literature as any threat to the resilience of the supply chain should be known in advance so that actions can be taken to mitigate its effect. If things are not in place during a disruption, its negative effects can escalate. On the other hand, Industry 4.0 may also have some positive effects on supply chain resilience. This thesis concentrates majorly on these positive aspects and how they can be used to create more resilient supply chains.

Research objective and method

The main objective of this research is to investigate how Industry 4.0 technologies influence the supply chain resilience in a manufacturing context. Continuing from the problem statement, the main research question is formulated as:

> *How can Industry 4.0 be used to improve supply chain resilience, in the context of the chlor-alkali supply chain?*

Due to the explanatory nature of the main research question, the case study is found to be a suitable method for this study. The case being considered here is the Industry 4.0 systems that are being used in chlor-alkali supply chains. The latter is the context in which the case is studied, and details are gathered.

The first step in the research involves literature review to form conceptual models of both Industry 4.0 and supply chain resilience. The knowledge gathered through the literature is used to deepen the understanding of concepts and construct a case study protocol that drives the research work. A semi-structured interview format that is used to collect primary data from (anonymous) respondents who have experience in the chlor-alkali industry. Data obtained from these interviews is also triangulated by collecting secondary data in the form of documents and media published by some chlor-alkali organisations. Secondary data is used to corroborate the primary data and not as an independent source of data.

The interview transcripts are coded, and their results are summarised. Then, with the help of analytical techniques like pattern matching and explanation building, some themes and strategies are drawn from the data. Recommendations are drawn for the chlor-alkali industry for the implementation of Industry 4.0 technologies. These are also applicable to other chemical industries due to the similarities in characteristics with the chlor-alkali industry. They apply to a lesser extent to other manufacturing sectors.

Results

From the data collected for this thesis, it is concluded that Industry 4.0 helps improve resilience with regards to known operational risks within the supply chain. It does not have any effect when it comes to unknown risks that occur outside the scope of the supply chain. Sometimes, it can have negative effects in the latter scenario, but this could not be explored fully in this research due to its randomness.

When some events occur outside the supply chain, like that of COVID-19 pandemic or economic depression, it is not clear how the usage of Industry 4.0 helps with the resilience to mitigate. In most cases, there is no effect and in some cases the effect is negative. This area has not been explored deeply in this thesis.

This thesis proposes a 3-way framework for implementing Industry 4.0 technologies. It consists of three strategies-mapping critical areas, design of the system, and enhancement of visibility.

In the case studied, the usage of Industry 4.0 was found to be higher near critical areas in the supply chain. An area in the supply chain is said to be critical in the following circumstances-single source of supply, high risk, long lead times and/or poor visibility. When an entity is said to be critical i.e. any change in this entity must be monitored continuously and quickly reacted to, more resilient systems are designed and implemented. Contrarily, when there is not much criticality involved, redundancy is used as a primary strategy with which planning is made.

Next, the design and programming of the system are very critical in the successful implementation of Industry 4.0. This can be done only when the organisation has undergone tremendous learning concerning its processes and knows the extent and depth of the requirements. This thesis proposes the need for flexible systems that can be altered/ upgraded in the future based on the needs.

The last strategy involves using Industry 4.0 technology to improve the communication between supply chain partners and increase visibility with each other. In many instances analysed in this thesis, Industry 4.0 is mainly used to increase visibility to any event that occurs in the supply chain.

This can be attributed to real-time communication systems that give warning about a disruption that can help in planning effective mitigation.

In addition to these strategies, this thesis also conveys two important challenges of using Industry 4.0 systems. The first pertains to organisational challenge that involves employee training for usage of these systems. The knowledge and skills required to operate these systems are not possessed by all employees, hence it is important to update their knowledge and brief them thoroughly about the capabilities of these systems. These systems are also prone to breakdown. In such instances, employees need to be trained in mitigation measures with which the process can be brought to a safe halt.

The second challenge pertains to cyber-security issues like hacking. Many organisations are connected to other organisations in the supply chain by using the internet as a communication platform. But, the risk of using the internet is being hacked and systems being compromised. It costs major operational losses as well. Many companies prefer to use standalone systems that are not connected to the internet to mitigate these risks. Thus, cyber-security planning is a critical challenge in implementing Industry 4.0.

Managerial implications

The three strategies suggested in this thesis are useful for managers who need guidance with implementing Industry 4.0 technologies. The first strategy of mapping the supply chain processes and finding the critical areas is a starting point for implementing Industry 4.0. Ascertaining the critical areas in the supply chain can lead to further probing as to how the risks in these critical areas can be modelled, monitored, and ultimately mitigated.

The second strategy allows the manager to design the Industry 4.0 system. This thesis suggests relying on the learning the supply chain has accumulated and thereby design the system accordingly instead of relying fully on third party designs. It is important to undertake simulations and trials before fully commissioning the system. Also, it is recommended to make the design more flexible and open so that it can be upgraded in the future as well.

Regarding the third strategy, this thesis suggests managers to use Industry 4.0 to improve visibility within the organisation and across the supply chain. A pattern was noticed that in many instances, Industry 4.0 is applied such that it renders better supply chain visibility. Other resilience drivers like supply chain flexibility and velocity were not affected much.

Limitations

The main limitation of this thesis has to do with the primary data collection. All the data was collected from two respondents who previously worked in the chlor-alkali industry. It would have been better to obtain data from a couple of more respondents. Moreover, both the respondents worked for the same organisation effectively making this a single case study.

The next limitation has to do with conducting interviews. Being a good interviewer requires a great deal of skill and practice. I am not experienced with interviewing techniques. It took a few rounds of interviews initially to develop this skill. Due to the limited number of respondents, I could not use and develop this skill further.

Recommendations for future study

The implementation of Industry 4.0 brings about a change in the organisational processes. These changes can also affect resilience positively or negatively. The effect of these changes on resilience can be studied in further research.

Industry 4.0 consists of many underlying technologies. The effect of five of those technologies is studied together in this thesis. These technologies can be considered individually as well and their effect on resilience can be studied. There is a possibility to find useful findings and map the technologies to various resilience enablers.

Data for this thesis has been collected from a single unit of analysis which is the focal chlor-alkali organisation. Data can also be collected from immediate downstream and upstream organisations for better triangulation. It can also be collected from various levels in the organisation. In this thesis, data was collected from higher management representatives. Data can also be collected from lower and middle management. Moreover, this study can be replicated for other industries to discover other themes that are relevant there.

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Chapter 1 INTRODUCTION

1.1 Background

To give the reader some perspective and background knowledge, the various concepts dealt in this research have been discussed in this subsection. First, the concept of supply chain resilience is discussed, followed by Industry 4.0. Lastly, this is followed by discussing the characteristics of the chlor-alkali industry briefly.

1.1.1 Supply chain resilience

A supply chain consists of two or more organisations linked by material, information, and financial flows. These organisations may produce parts, components, end products, provide logistics services and may even be the end customer (Stadtler & Kilger, 2002). The field of supply chain management has become an important area in organisational management as well as scientific research.

In the last few decades, due to globalisation, supply chains have become more complex in nature and longer in length. This led to the introduction of risk management perspective in supply chain management. There has been an increasing interest to manage supply chain risks for companies with global supply chains. This has been reflected in scientific research as well. The field of supply chain risk management (SCRM) has gained widespread attention recently and is now an established research area with several publications in the last two decades (Fan & Stevenson, 2018) in addition to the field of Supply chain management. This research focuses on examining supply chain activities from the risk management perspective.

Building supply chain resilience is a way to mitigate supply chain risks (Christopher & Peck, 2004). Resilience in the context of the supply chain can be defined as its ability to withstand the impact of risks and also to return to an acceptable performance level at the earliest (Christopher & Peck, 2004). The literature indicates many strategies that can be adopted like supply chain flexibility, supply chain agility, supply chain collaboration to position supply chain in a more competitive manner. The concept of resilience is an overarching combination of various key strategies (Christopher & Peck, 2004) that can be adopted by a supply chain and thus it is decided to focus on supply chain resilience in this study.

Risk in the context of the supply chain can be defined as "the distribution of performance outcomes of interest expressed in terms of losses, probability, speed of event, speed of losses, time for detection of events, and frequency" (Manuj & Mentzer, 2008, p. 197). The supply chain of a manufacturing organisation can face different types of risks. They can be broadly categorised as supply risk, demand risk, operational risk and security risk (Manuj & Mentzer, 2008).

There are many ways supply chain resilience can be built, and these are highlighted later in this report. Suffice to say, it includes both proactive and reactive approaches to mitigating risks in the supply chain (Wieland & Wallenburg, 2013). The proactive approach involves assessing the risks the supply chain faces and making strategies to mitigate their negative impacts. It also involves continuous monitoring across various partners in the supply chain to detect any risk occurrence. Then, the reactive approach is mostly used after the occurrence of the risk event. It involves a swift response to the event to mitigate the impact and monitor the status till it is fully recovered. It is essential to carry out both these components to respond to risks effectively and efficiently.

The four pillars of building a resilient supply chain are supply chain reengineering, supply chain collaboration, supply chain agility, and improving the risk management culture in the organisation (Christopher & Peck, 2004). Resilience is improved positively through increased flexibility, visibility, velocity and collaboration in the supply chain (Jüttner & Maklan, 2011). Of these drivers, collaboration with supply chain partners is the antecedent to improving flexibility, visibility and velocity which in turn improves supply chain resilience (Scholten & Schilder, 2015). Supply chain resilience has grown to become an important part of supply chain risk management in an organisation. With the advent of COVID-19, supply chains have recognised the need for resilience, now more than ever.

In this time and age, all companies are taking steps to improve their resilience against potential known and unknown risks that can occur without much notice. And it has also been proposed that developing supply chain resilience also leads to better competitive advantage and financial returns (Abeysekara, Wang, & Kuruppuarachchi, 2019) in the long run.

1.1.2 Industry 4.0

From the beginning of the age of industrialisation in the 1800s, there have been three revolutions that have taken place so far. These are called revolutions because of some radical changes in the production process that enabled the productivity to improve by leaps and bounds. The first revolution was in the 18th century and was powered by the usage of steam-driven machinery with coal as the main fuel. The second revolution was in the 19th century and was powered by the emergence of electricity and better methods of production. The third revolution was in the latter part of the 20th century that was powered by the usage of computers and electronics in the production process to automate part of the processes. The fourth revolution (also called Industry 4.0) is currently underway and is powered by the Internet of Things (IoT) and Cyber-Physical System (CPS) technologies. This helps devices connect and communicate with each other remotely and act without human involvement.

Industry 4.0 is a recent phenomenon that has a huge impact on manufacturing industries through the application of digital connectivity technologies (Lasi, Fettke, Kemper, Feld, & Hoffmann, 2014). This has an impact not only for production management but also for wider entities in the value chain (Haoud & Hasnaoui, 2019). Some of these technologies include big data analytics, advanced manufacturing with sensors, advanced robotics, augmented reality and additive manufacturing (Ivanov, Dolgui, & Sokolov, 2018).

Manufacturing industries across all sectors are adopting Industry 4.0 at an astonishing rate due to the advantages it offers concerning productivity and efficiency. This is true, especially in developed economies. In other words, Industry 4.0 is becoming more and more ubiquitous. An example of Industry 4.0 application can be said to be the track-and-trace technology. Nowadays, it is possible to track consignments on a real-time basis. This helps in improving the planning and communication between buyers and sellers in a logistics chain.

1.1.3 Chlor-alkali industry

This research is focussed on manufacturing supply chains with the chlor-alkali manufacturing industries being the main attention. The primary reason for this is that I am a Chemical Engineer and wanted to carry out this research for the chemical field. The companies that produce chlorine and caustic from salt and water by using an electrolytic cell process come under this classification.

Other than that, the chemical industry also faces the pressure of undertaking their operations safely. According to a large scale survey of multiple industrial sectors reported by Pwc (2016), chemicals companies are planning to invest 5% of their annual revenue in Industry 4.0 transformations in the next five years. This will be done not just internally but also across the supply chain. The report also states that looking forward to five years from 2016, 75% of chemical companies expect to have an advanced level of implementation of these technologies. This is the highest observed amongst many groups of industries. To curtail the length of this chapter, more reasons for choosing this specific group of industries is discussed in Chapter 3. But, suffice to say, the chemical companies and their supply chains are changing with the implementation of Industry 4.0 technologies.

1.2 Problem statement

Supply chains add economic value due to their activities. Any disruption of the activities is very expensive to the whole chain (Kleindorfer & Saad, 2005). Efforts are being taken by organisations to improve the efficiency and effectiveness of their processes so that they can continue their functions despite disruptions (Kleindorfer & Saad, 2005).

The introduction of Industry 4.0 technologies will not only affect supply chain operations and performance but also create new risks (Ivanov et al., 2018). This prompts the need to study the impact of these technologies so that adequate action can be taken to safeguard the supply chain and re-engineer it wherever required. There have been a few studies that focus on the effect of Industry 4.0 on supply chain (risk) management (Ivanov et al., 2018; Müller & Voigt, 2018; Haoud & Hasnaoui, 2019). Recently, a study by Ralston and Blackhurst (2020) examines the influence of Industry 4.0 on the supply chain resilience of logistics and manufacturing organisations.

Many manufacturing-based organisations are adopting Industry 4.0 technologies to digitise and automate their internal processes and thereby improve supply chain performance. Although this has clear advantages, these technologies are still in their infancy and managers do not completely understand the ramifications of this technology and how it can influence supply chain resilience.

Implementing these technologies also involves many changes internally within the organisation. It can render new capabilities and diminish existing ones. These organisational capabilities are in turn responsible for building up resilience in the supply chain. The interaction between the capabilities provided by Industry 4.0 and how it in turn affects supply chain resilience has not been explored in detail in the literature. Thus, in this study, it will be interesting to explore this from the supply chain risk management perspective.

1.3 Research gap

The study by Ralston and Blackhurst (2020) examines the impact of Industry 4.0 on the supply chain resilience of logistics and manufacturing organisations. This study concludes that the implementation of Industry 4.0 will enhance performance. Some of the limitations of this study are listed below:

i. There were only seven organisations that were studied of which four were manufacturing-based and three were logistics-based companies. The study can be extended to more companies or industries and their validity can be improved.
ii. They were investigated concerning ‘capability loss’ and from operations perspective but not how it affects the supply chain and the interactions between supply chain partners.
iii. The impact of Industry 4.0 on supply chain resilience is not very detailed and can be improved with more descriptions.

According to a study by Ivanov et al. (2018), the authors argue that supply chain resilience is improved by the implementation of Industry 4.0 technologies as there are advantages to digitalisation. But the mechanism of improvement of resilience is not discussed in detail neither are the pitfalls of implementing Industry 4.0.

1.4 Research objective

Deriving from the research gap stated above, *it is the main objective of this research to explore the influence of Industry 4.0 technologies on supply chain resilience in the context of chlor-alkali manufacturing organisations.* It is important to maintain the resilience level of an organisation and understand whether usage of Industry 4.0 technologies will influence supply chain resilience positively or negatively.

1.5 Research questions

The main research question is formulated as “How can Industry 4.0 be used to improve supply chain resilience, in the context of the chlor-alkali supply chain?”

Before answering the main research question, it is necessary to answer the sub-research questions first. The sub-research questions are formulated as shown below:

1. How is Industry 4.0 implemented in manufacturing industries?
2. What capabilities are required to build a resilient supply chain?
3. How does Industry 4.0 implementation influence supply chain resilience, in the context of the chlor-alkali supply chain?

1.6 Relevance

The relevance of this thesis is discussed from three perspectives.

This thesis is relevant to the Management of Technology programme. As the name of the course suggests, the course deals with the design and development of technology to be used in organisations to improve their productivity, financial returns and competitive advantages. In this thesis as well, the usage of Industry 4.0 technologies and its effect on the supply chain resilience of the chlor-alkali supply chain is studied. It is shown in previous studies that supply chain resilience can enhance financial returns as well as a competitive advantage. Moreover, data has been collected and analysed methodically and scientifically to keep up the rigour of the work.

This research is also relevant from a managerial perspective. This research is conducted for managers working in chemical manufacturing organisations. This research will help them to think about Industry 4.0 technologies from the supply chain resilience and risk management perspective. This thesis suggests some strategies that can help managers with Industry 4.0 implementations.

Regarding scientific research, supply chain resilience is still an evolving research area and papers are being published in this area. There are very few papers that connect both Industry 4.0 and supply chain resilience topics. Thus, Industry 4.0 implementation is researched from a risk management perspective. This is a new research area and many recommendations are provided to proceed with future research.

This thesis also has societal relevance. Supply chains form an essential block of society today. It offers numerous jobs and is also responsible for delivering essential household goods to the end consumer regularly. A smooth functioning supply chain is essential for sustenance of society. Disruptions can wreak major havoc by blocking the supply of essential commodities to the customer. This thesis discusses the resilience of the chemical supply chain which is its ability to overcome these disruptions and continue performing at acceptable levels so that the negative effects can be contained.

1.7 Thesis outline

This chapter provided details about the background of the topics. It also stated the research questions and the sub-research questions. The rest of this report is organised as follows.

Chapter 2 discusses the methodology of the research activity. Motivation is also given for choosing methodologies. A research framework is also discussed additionally. Next, Chapter 3 consists of the characteristics of the case considered-Chlor-alkali supply chain. The chemical supply chain is differentiated from other supply chains and the reasons for concentrating on the chemical supply chain are discussed.

Chapter 4 and 5 consists of literature reviews of Industry 4.0 and supply chain resilience respectively. The topics are discussed in depth from the perspective of this research and a framework is designed that helps operationalise the concepts.

Next, Chapter 6 discusses the data collection process and how both primary and secondary data are collected. A semi-structured format is designed for interviewing professionals. Some measures taken to improve the validity of the data is discussed. Then, the methodology followed for conducting the interview and analysing the data is discussed.

Chapter 7 delivers the results of the data collection and analysis. Initially, a summary of the results of the interview is discussed followed by an analysis of the themes that emerge from the data. A framework is proposed that describes how to improve supply chain resilience by implementing Industry 4.0.

Lastly, Chapter 8 consists of the conclusion where the recommendations for the chemical industry are discussed. This is also followed by a discussion of the limitations of the study, recommendations for future research, and a self-reflection on the research process. This is then followed with the bibliography and appendices.

Chapter 2 RESEARCH METHODOLOGY

After narrowing down on the set of research questions, the next main objective is to draft a plan to conduct the research activity. This is called the research design and will be discussed in this chapter.

This chapter is divided into sub-sections. The first section explains the main method chosen in this research. The next section highlights the research framework. In the next section, the methods used to answer individual sub-research questions are stated. This is followed by listing the main contribution made by this study. Lastly, the dynamic capabilities theory is discussed briefly.

2.1 Case study

According to Yin (2018), there are three criteria to check when deciding upon the type of research method to be used. The first is to assess the form of the research question. Second, it is to be assessed if there is a need to interfere in the study to control behavioural characteristics. The last criterion is to check whether the study is focused on current or historical events. Various methods are suggested by Yin (2018) for different combinations of these conditions.

To determine an appropriate method for this research, it is necessary to classify the central research question. In this case, the question is a 'how' type question making it explanatory. To the best of my knowledge, this question has not been taken up previously in scientific research. Moreover, the objective of this study is to explore the concepts involved in a detailed manner and try to come up with an explanation of how one influences the other.

In the current research, the nature of the research question has been ascertained to be explanatory. The researcher cannot interfere or control any of the events within the chemical supply chain. This makes the research setting non-contrived and no ability to interfere in the supply chain processes for the research. Moreover, the study concentrates around contemporary events. Thus, according to the guidelines provided by Yin (2018), a case study is the most appropriate method for this thesis.

A case study is a practical research method that is used to explore a current phenomenon occurring within a particular context especially when the phenomenon and the context cannot be distinguished (Yin, 2018). The latter point mentioned by Yin is especially important in this research. The relationship between the two entities is being investigated in this research. The first is the usage of Industry 4.0 technologies in the chlor-alkali supply chain and the next is supply chain resilience. The former is the context of the research and the latter is the phenomena that are being investigated. It is not possible to easily envision a boundary between the phenomena and the context which makes a case study a more apt choice for this research.

Researchers choose a case study to explore the topic of Industry 4.0 and supply chain resilience. Industry 4.0 is a very broad topic that makes scoping and narrowing down quite tricky, thus cast study is a good method for exploring the implementation and usage of Industry 4.0 (Yin, Stecke, and Li (2018) cited from Ralston & Blackhurst, 2020). Similarly, case-based research is also recommended by researchers to investigate ways to develop resilience in the supply chain (Bhamra, Dani, and Burnard (2011) cited from Ralston & Blackhurst, 2020). Some studies that follow a case-study approach are the papers by Scholten, Scott, and Fynes (2014), Scholten and Schilder (2015), and Scholten, Scott, and Fynes (2019). Details about these papers will be discussed in the literature review of supply chain resilience.

According to Yin (2018), there are two types of case studies: single and multiple. Both are further subdivided into holistic and embedded. This research will use multiple holistic case study. This is mainly due to the reason that data across the cases can be cross-analysed and conclusions can be drawn. With multiple cases leading to the same conclusion, the validity of the results will be rendered more strength. The external validity is also better in this case as there is room for 'analytic generalisation'.

The main difference between holistic and embedded case study is that there is only a single unit of analysis in the holistic type whereas there are multiple units of analysis (within a single case) in the embedded type design.

This research is also qualitative. The major reason for this is that the way Industry 4.0 affects supply chain resilience has not been explored in-depth so far. Thus, in this initial research on this field, I wanted to investigate and conclude on a set of themes that can be used for further (qualitative and quantitative) research in the future. Also, trying to add quantitative research elements into this study would make the research more intensive and cause a time constraint, so it was not considered. The main method of data gathering would be through interview of professionals working in the chemical supply chain. In addition to the dialogue, their expression, emotion and reaction would also help in steering the data collection process.

Secondary data will also be collected through documents from chlor-alkali companies. These documents can consist of reports, blogs, and videos that showcase the use of Industry 4.0 technologies in the chlor-alkali supply chain.

Throughout this thesis, frequent references have been made to the case study textbook by Yin (2018) as many of the techniques mentioned therein are suitable for a case study and hence are applicable in this thesis as well.

2.1.1 Case definition

According to Yin (2018), it is an important requirement to define and bound the case before undertaking case study research. Yin (2018) suggests that this can be seen from the way the research questions are framed. The main research question is reiterated herein - "How can Industry 4.0 be used to improve supply chain resilience, in the context of the chlor-alkali supply chain?"

As discussed earlier, the question is explanatory, and it seeks about how the organisation/supply chain uses Industry 4.0 technology and ultimately how this usage affects the resilience of the organisation/supply chain. In this case study, the unit of analysis is the usage of Industry 4.0 in the supply chain of chlor-alkali industries.

Now that the case is defined, their boundaries need to be scoped. Not all the characteristics regarding the focal organisation/supply chain need to be included. The implementations of Industry 4.0 systems, how they are used, their advantages and limitations are the focus of the study. That too, the usage of these technologies in undertaking manufacturing and supply chain processes are considered. In other words, the phenomenon being considered is the usage of Industry 4.0 system and the context is the chlor-alkali supply chain. The length of the supply chain is also to be scoped due to practical limitations for collecting data. Thus, the chlor-alkali industry and their immediate downstream customer is considered. The downstream customer is chlorine and caustic consumer.

2.2 Research framework

The research framework is shown in Figure 2.1 below. The research process is distinctly divided into six major parts. The first part consists of performing a literature review. The second part consists of desk research to analyse the concepts and build a model that helps answer the research questions. The third part consists of the actual data collection through interviews of experienced professionals. The fourth part consists of conducting interviews with respondents and collecting data that can be useful to answer the research questions posed in this thesis. The fifth part consists of analysing the qualitative data obtained. The final part consists of reflection to provide recommendations for the industry. Each of these parts is explained in the following subsections.

2.2.1 Literature review

This is one of the key steps that is used in every research work. This helps in the formation of a theoretical framework. For this thesis, new frameworks are made for both industry 4.0 as well as supply chain resilience.

Thus, the literature about these two distinct topics is to be reviewed from the perspective of what is required for this thesis. It involves finding the appropriate keywords and searching the online databases available to look for relevant articles. Once these articles are downloaded, they are scanned and checked for any relevant content. These contents are summarised and presented in categories that make reading and interpretation easier.

The literature review introduces the many frameworks that are being used in this theory. The downside of the literature review is that the search process is very intensive, and a general search procedure is to be adopted. The quality of the sources is also critical and peer-reviewed articles are preferred in this scenario.

2.2.2 Conceptualisation

The literature review conducted for Industry 4.0 and supply chain resilience is used to construct a conceptual framework involving terms that are important to understand the concept effectively from the perspective of this thesis. This involves desk research by consolidating all the details from the literature and synthesising it to create a framework.

Since data will be primarily gathered through interviews, it is necessary to 'translate' the views and comments of the respondents into variables being investigated in this thesis. Thus, the conceptual frameworks created also help to 'translate' the views of the respondent. This helps in the data collection and interpretation that follows subsequently.

Carrying out step 1 and 2 will enable to answer sub-research questions 1 and 2. These are discussed in Chapter 4 and 5 respectively.

2.2.3 Planning

According to Yin (2018), planning of activities is a crucial step in conducting the research activity. Its importance is emphasised in conducting interviews for collecting data. With all the theoretical data that has been collected so far, the protocols used for data collection need to be finalised. In this thesis, a semi-structured interview was used for collecting primary data and company documents published online was used as secondary data.

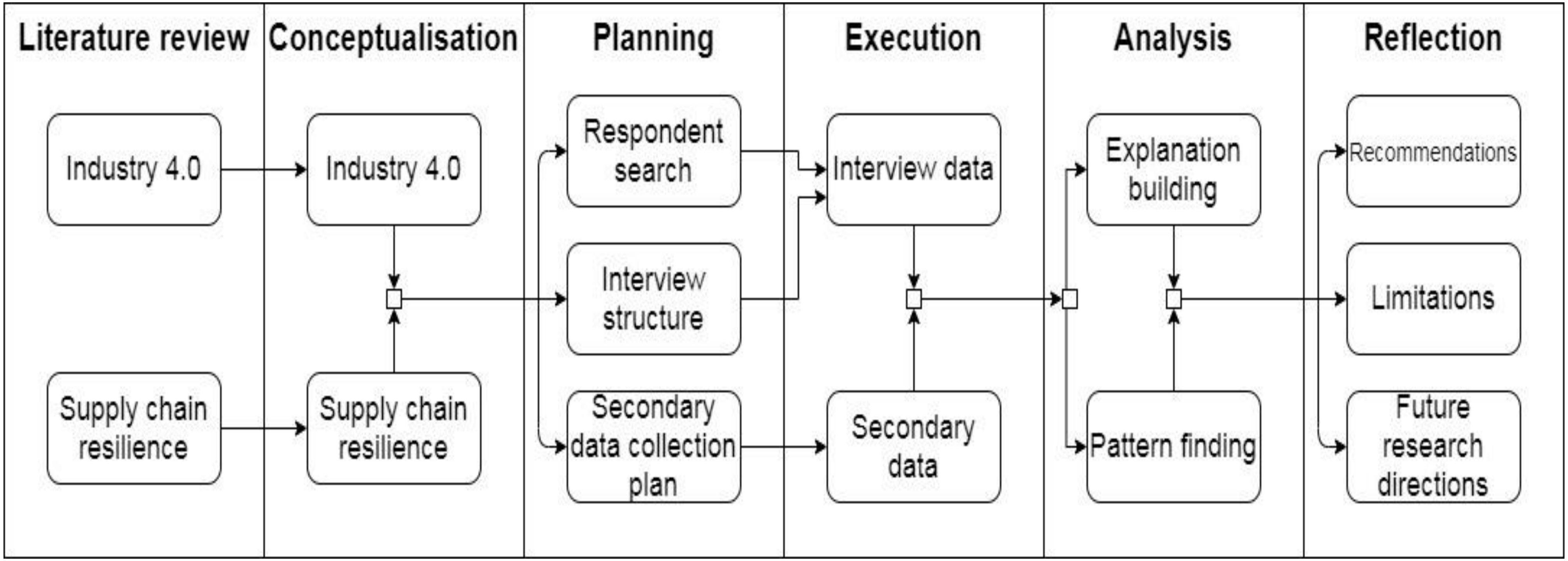

Figure 2.1: Research framework and flow diagram

2.2.4 Execution

In this step, the data collection window opens, and the gathered respondents are interviewed, and qualitative data is recorded and transcribed. While collecting this data, the procedures followed are upgraded each time with new data that is available.

Although the interview is the primary source of data collected, it is also the necessity of the case study to try to obtain data from different sources and try to triangulate the findings. Thus, wherever possible, secondary data from company reports, consultancy reports, and company blogs have also been cited in this study.

Step 3 and 4 are discussed in Chapter 6.

2.2.5 Analysis

This is a critical step involved in this thesis as the collected data is analysed from the viewpoint of this research and meaningful conclusions are drawn that can be used to give recommendations for the industry at large. Some strategies suggested by Yin (2018) are used in this step to analyse the data. A framework is made for analysing the data collected from the interviews and reports. There is software available for analysing qualitative data. But in this research, the data dealt with is limited and a regular word processing software is used for data analysis. The main strategy used for analysing data is to analyse the data from 'ground-up' and try to identify useful patterns and relations from the perspective of the thesis.

The analytical procedures used in this thesis are discussed in Chapter 6.

2.2.6 Reflection

The last part of the study is important to reflect on the findings of the previous parts and the methodologies used to carry them out. The findings are summarised at the end of the study. Also, there are further discussions regarding the limitations and recommendations for future research.

The results of the interview and thereby answers to sub-research question 3 and the main research question are discussed in Chapter 7. Chapter 8 summarises the research process and the results. It also contains limitations, self-reflection, and recommendations for future study.

2.3 Contribution

This thesis aims to make the following contribution to existing literature. The first involves a guiding framework that relates to the implementation of Industry 4.0 to improve supply chain resilience. This is useful for managers in the chemical supply chain to analyse how implementing Industry 4.0 can influence their supply chain resilience and in what ways a positive influence can be established. To the best of my knowledge, this will be the first analytical framework relating Industry 4.0 to supply chain resilience.

Chapter 3 THESIS DOMAIN

In this chapter, the case that is being analysed is described. This is the chlor-alkali industry which is a subset of the chemical industry. In the first section, motivation is given for choosing the chemical industry. In the second section, a unique character of the chemical supply chain is described. In the third section, the chlor-alkali industry is discussed along with the method of production used. Then, some characteristics of the chlor-alkali supply chain are also discussed. Data for writing this chapter are obtained through internet searches and partly from the interviews with professionals in the chlor-alkali industry.

3.1 Reasons for choosing the chemical industry

It is interesting to explore this research from the viewpoint of chemical industries due to three main reasons. The first reason is that I am from a Chemical engineering background and I am familiar with the terms and general working conditions in the chemical industry. This will facilitate me in exploring this problem from the chemical supply chain perspective.

The second reason pertains to the complexities faced within the chemical supply chain. Chemical manufacturing differs from other manufacturing sectors (like electronics, automobiles, appliances). It can be run in batches or continuously where processes are carried out in strict recipes that require constant scrutiny. The chemicals can be produced by either make-to-stock or make-to-order basis by utilising different equipment. In this scenario, equipment planning and utilisation pose a challenge for operations management (Infor, 2019). Additionally, there is high competition due to a globalised market which puts downward pressure on the cost (Deloitte, 2017). Increasing customer demand with importance to customisation and high service levels also puts pressure on the chemical supply chain (Deloitte, 2017). It is claimed that the aforementioned risks to the supply chain can be mitigated with the implementation of Industry 4.0 in the manufacturing process (BCG, 2017).

The third reason is a gap in the recent study by Ralston and Blackhurst (2020) which explores the impact of Industry 4.0 on the supply chain resilience. This study was done qualitatively by interviewing many professionals working majorly in logistics and manufacturing and not explored for chemical manufacturing. Thus, in this thesis, the same is explored in the chemical industry sector.

In addition to the above-cited reasons, the chemical producing sector is also one of the largest contributors to the European economy. The European chemical sector is the second largest worldwide by revenue. In 2018, the total revenue contributed was €565 billion of which €160 billion was generated from exports outside Europe. Despite being a major contributor to the economy, it is less researched than other industries (Ho, Zheng, Yildiz, & Talluri, 2015). This makes it even more interesting to research from chemical supply chain perspective.

3.2 Characteristics of the chemical supply chain

Chemical industries consist of a complex set of sub-industries which depend on each other for materials. In other words, the product of one organisation will be utilised as raw material by another organisation within the same industrial group and/or another group. Majority of the products are traded between different organisations (B2B). A schematic diagram of the network complexity is shown in Figure 3.1. Unlike the traditional manufacturing organisation where the downstream supply chain is converging, in the chemical supply chain, the same is said to be diverging (Kannegiesser, 2008; Banker, 2017).

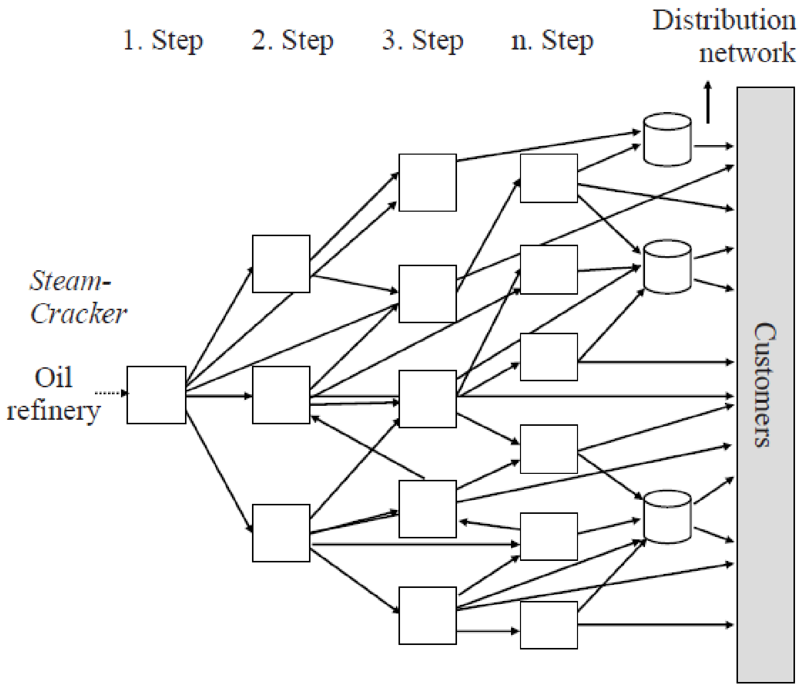

Figure 3.1: Schematic of the chemical supply chain (Kannegiesser, 2008)

3.3 Chlor-alkali industry

Chlor-alkali industry comprises those that produce chlorine, caustic soda and hydrogen. It is present all over the world and it is a highly geographically localised industry. The products produced in this industry are used for a wide variety of applications and it drives many industries downstream. The main raw materials for this production process are salt (sodium chloride), water and electricity. The process is the electrolytic decomposition of salt (Killheffer & Standen, 2019).

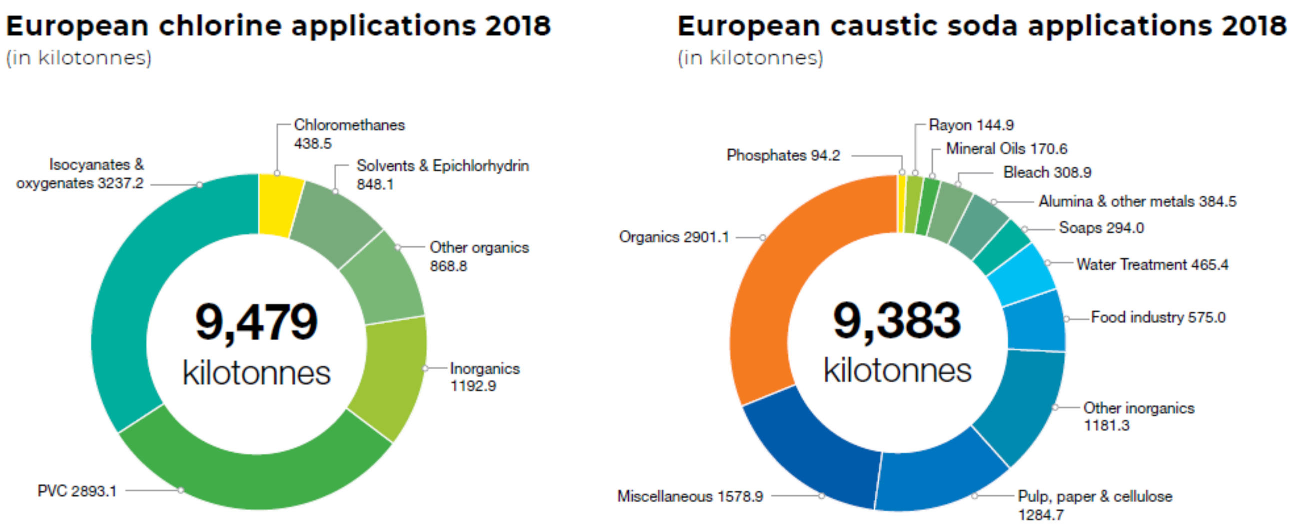

Figure 3.2: European consumption of Chlorine and Caustic soda in 2018 (Euro Chlor, 2019a)

Chlorine is the main product of this industry and sodium hydroxide (caustic soda lye) and hydrogen are the by-products. The total consumption of chlorine and caustic soda are shown in Figure 3.2. In 2018, 9.47 million tonnes of chlorine and 9.38 million tonnes of caustic soda were produced in Europe alone (Euro Chlor, 2019a). The Chlor-alkali industry directly provides 6600 jobs in Europe (Euro Chlor, 2019b) and is indirectly accountable for millions of jobs as many other industries rely on these two products (Euro Chlor, 2019a). Thus, it is essential to maintain and improve the supply chain resilience to provide security to the many industries that are dependent on this industry.

According to Euro Chlor (2019a) (European association of Chlorine producers), there are three Chlor-alkali production units in the Netherlands. Two of them are operated by Nouryon and the third by Sabic.

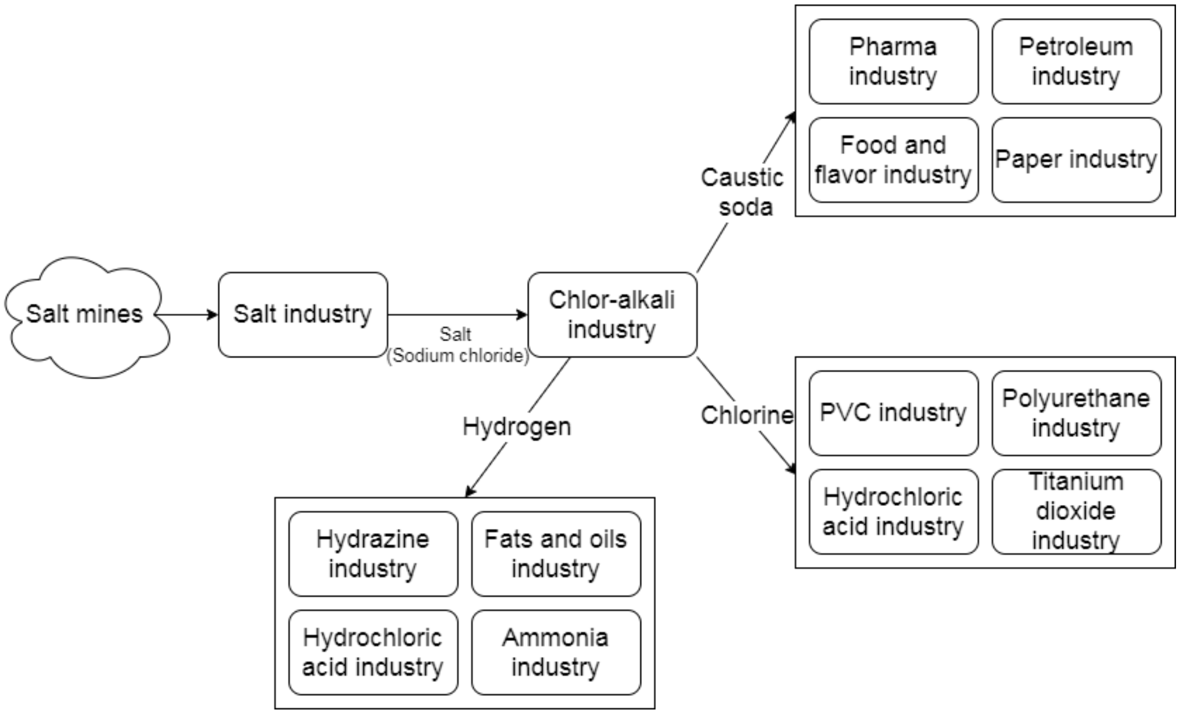

Figure 3.3: Schematic of the Chlor-alkali supply chain (Own representation)

A schematic of the Chlor alkali supply chain is given in Figure 3.3. The salt industry is upstream of the Chlor-alkali industry. The salt industry produces salt (Sodium chloride) from natural sources like underground salt mines that have rich salt deposits. The salt is majorly used by the Chlor-alkali industry to produce sodium hydroxide (caustic soda lye) and chlorine. The operations of many critical industries depend on the availability of these products and any interruption can have costly impacts. Thus, it is essential to maintain the supply chain resilience of the Chlor-alkali industries for the smooth functioning of many other chemical industries. The supply chain is narrow upstream of Chlor-alkali industry, but it broadens downstream as it caters to a wide range of industries.

3.3.1 Production process

There are three types of processes involved in chlor-alkali production. They are mercury cell process, diaphragm cell process and membrane cell process. Mercury cell process is the oldest and it has been phased out in Europe as of 2017. This was done due to the toxic nature of mercury and the availability of much lesser toxic alternative processes. Of these two processes, the membrane cell process is the latest and is majorly used by all chlor-alkali manufacturers across Europe.

For illustration and understanding, the membrane cell process is explained briefly here. The electrolytic cell consists of two separate chambers separated by a membrane. Each chamber has different electrodes, one has an anode and the other cathode. Saltwater is fed on the anode side of the membrane. Chlorine bubbles up and gas is released. This is collected and purified to remove oxygen before using further downstream. The brine that leaves the chamber can be further purified and reused in the process.

The membrane selectively allows sodium ions and some water to pass through to the cathode chamber. Here, hydrogen gas is evolved and is collected and stored. The solution that leaves the cell is about 30% caustic which is concentrated to final 50% through evaporation. This process is carried out continuously and evolving chlorine and hydrogen in a gaseous state and caustic in solution form. A schematic of the membrane cell process is shown in Figure 3.4.

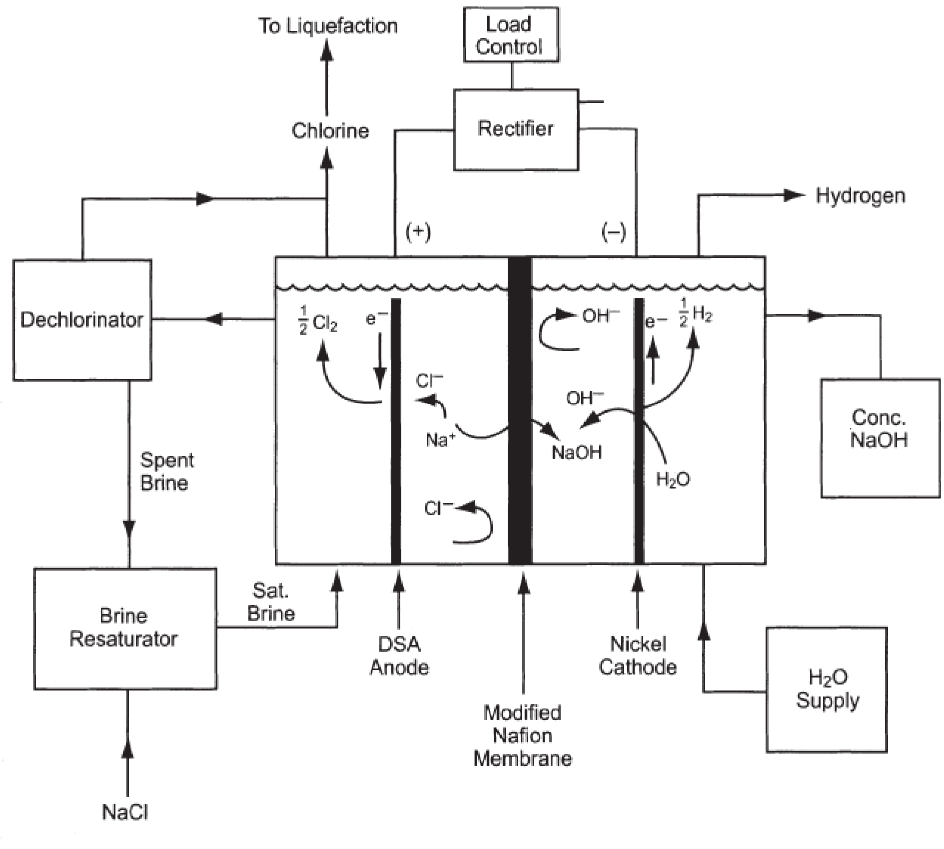

Figure 3.4: A schematic of the membrane cell process (O'Brien, Bommaraju, & Hine, 2007)

It is to be noted that the type of process used for chlor-alkali production is not a limiting factor for customers. Although there are minor quality differences between the different processes, this does not affect the choice of the customer in the majority of cases for both caustic as well as chlorine. In other words, the type of process has a negligible effect on the supply chain.

3.3.2 Product applications

Both chlorine and caustic are produced and used in large quantities downstream. Chlorine is used downstream in the production of PVC (Poly Vinyl Chloride), phosgene, polyurethane, titanium dioxide, hydrochloric acid, hydrazine, ferric chloride and many other chemicals. These chemicals are used for a variety of applications like water treatment, automobile parts, pesticides to name a few.

Similarly, caustic also finds itself in many applications. It is used in the manufacture of sodium-based chemicals like sodium formate, sodium sulphite, sodium lauryl sulfate, bleach and other chemicals like hydrazine, vanillin, epoxy resin to name a few. It is also used in the extraction of aluminium ore. Numerous other industries like paper, water treatment, pharmaceuticals, petroleum, flavours and fragrances are dependent on caustic.

Hydrogen is relatively produced in lesser quantity compared to chlorine and caustic. It is used in the production of hydrochloric acid, ammonia, or in hydrogenation processes. It can also be used as an energy source for chlor-alkali production.

3.3.3 Supply chain characterisation

Data for the following section was collected through direct interview with a professional from the chlor-alkali industry. The supply chain for the products of the chlor-alkali industry is geographically localised. Some of the product properties are shown in Table 3.1 below.

The transport modes for the chlor-alkali products are given in the table. It should be noted that chlorine is in a gaseous state at room temperature and it is stored under pressure as a liquid. It is very reactive and corrosive and causes adverse health impact for humans and other biodiversity upon contact. Thus, for safety, a very less quantity of chlorine is stored (approximately a few hours of production) and it is directly transported to the downstream user via pipeline. In Europe, most of the chlorine is transported like this through pipelines and only about 4% of the total is transported via rail. The users of chlorine are in close geographic proximity to the chlor-alkali plant. Even hydrogen is maintained at low storage volumes. If the hydrogen cannot be sold, it is partly vented.

Table 3.1: Storage and transport criterion of chlor-alkali products

Product	Room temperature condition	Storage condition	Transport condition	Transport mode
Chlorine	Gaseous	Gas/ Liquid	Gas/ Liquid	Gas-via direct pipeline Liquid-via rail
Caustic	Aqueous solution/ Solid	Solid/ Liquid	Solid/ Liquid	Via road/rail/waterway
Hydrogen	Gaseous	Gas/ Liquid	Gas/ Liquid	Gas-via direct pipeline Liquid-via rail/road

There are no restrictions regarding caustic storage and usage. It is usually stored as a 50% (wt.) solution in water and is transported to consumers via road tankers. Customers are geographically more distributed than for chlorine and a customer can have more than one caustic supplier. This is not possible in the case of chlorine.

Thus, the supply chain has a bottleneck with chlorine production and consumption. If the chlorine production rate is affected, the downstream plant also is affected directly with minimum notice. The downstream chlorine consumer plant sets the pace for this chain. Chlorine is produced as per their demand requirements. Similarly, if the downstream plant runs at a lower capacity, the chlorine production rate is also lowered. Consequently, this affects caustic and hydrogen production rates as well. Caustic is stored sufficiently, and this does not affect the downstream immediately, but hydrogen users are affected sooner due to limited storage.

3.4 Conclusion

Due to the large scale of the chlor-alkali industry, automation tools have always been used to a large extent to control the process. Industry 4.0 implementations are underway in the chlor-alkali industry. It is located at the start of many supply chains in the chemical industry. It is like the petroleum and petrochemical industry which also produces products that are used in many applications. The resilience of this industry must be maintained for the smooth functioning of many other industries. Thus, it is aimed to study the effect of Industry 4.0 on the supply chain resilience of the chlor-alkali supply chain. The scope of the supply chain is restricted to one level downstream of the focal organisation. There is the salt industry upstream and the caustic and chlorine consumers downstream.

Chapter 4 <u>INDUSTRY 4.0</u>

This chapter consists of a literature review of Industry 4.0 technologies. This chapter aims to answer the first sub-research question: How is Industry 4.0 implemented in manufacturing organisations?

This chapter consists of five sections. The first section discusses and introduces the concept of Industry 4.0 and chooses a definition that is most applicable to this thesis. It also discusses some of the constituent technologies that comprise Industry 4.0. The second section discusses some of the implementation pattern of Industry 4.0 in manufacturing industries that are derived from literature. The third section discusses the enabling factors for Industry 4.0 from the literature. The fourth section discusses the risks of implementing Industry 4.0 and the final section summarises the literature review and discusses a theoretical framework of Industry 4.0 that is further used in this research.

The procedure used to obtain the articles for review is discussed in detail in Appendix A.

4.1 Introduction

The term Industry 4.0 (Industrie 4.0 in German) was coined around 2011 in Germany and launched subsequently in 2013. The government wanted to boost the industrial sector by automating the production processes and thereby improving productivity by leaps and bounds (Kagermann, Helbig, & Wahlster, 2013). Across other countries in the world, similar programs to improve industrial productivity were launched under different names. In the United States, the same was called by the term *Industrial Internet* and was launched in 2013. In China, *Made in China 2025* was launched in 2015. Although this was called by different terms in various places, they all carry similar connotation (Zhong, Xu, Klotz, & Newman, 2017). For the remainder of this document, the term Industry 4.0 will be used. Some definitions for the term from various highly cited papers are presented below.

> *"… Industrie 4.0 will involve the technical integration of Cyber-Physical Systems (CPS) into manufacturing and logistics and the use of the Internet of Things and Services in industrial processes. This will have implications for value creation, business models, downstream services and work organization (Kagermann et al., 2013, p. 14)."*

> *"The term Industry 4.0 collectively refers to a wide range of current concepts, whose clear classification concerning a discipline as well as their precise distinction is not possible in individual cases. In the following fundamental concepts are listed: smart factory, cyber-physical systems, self-organization, new systems in distribution and procurement, new systems in development of products and services, adaptation to human needs and corporate social responsibility (Lasi et al., 2014, p. 240)."*

> *"Industry 4.0 is the sum of all disruptive innovations derived and implemented in a value chain to address the trends of digitalization, autonomization, transparency, mobility, modularization, network-collaboration and socializing of products and processes (Pfohl, Yahsi, & Kurnaz, 2015, p. 37)."*

From the above definitions, it can be noted that Industry 4.0 cannot be treated as a standalone concept but rather as the manifestation of a group of advanced technologies in the manufacturing sector. These underlying technologies have no much commonalities between them (Lasi et al., 2014). For this thesis, the first definition stated above by Kagermann et al. (2013) is taken as a direction. In this definition, the authors simply state the application of Cyber-Physical System (CPS) into a factory production system as one implementation and the use of IoT and IoS technologies in the value chain as another application. The unit that is being analysed in this thesis is the chlor-alkali supply chain which also has a production system which utilises these technologies. The effect of usage of these technologies on the organisation and the supply chain is being investigated in this thesis which makes this definition suitable.

As the definitions indicate above, Industry 4.0 is not a single technology but a group of technologies and its application for the industrial sector, as shown in Figure 4.1. Some of the key technologies are described below.

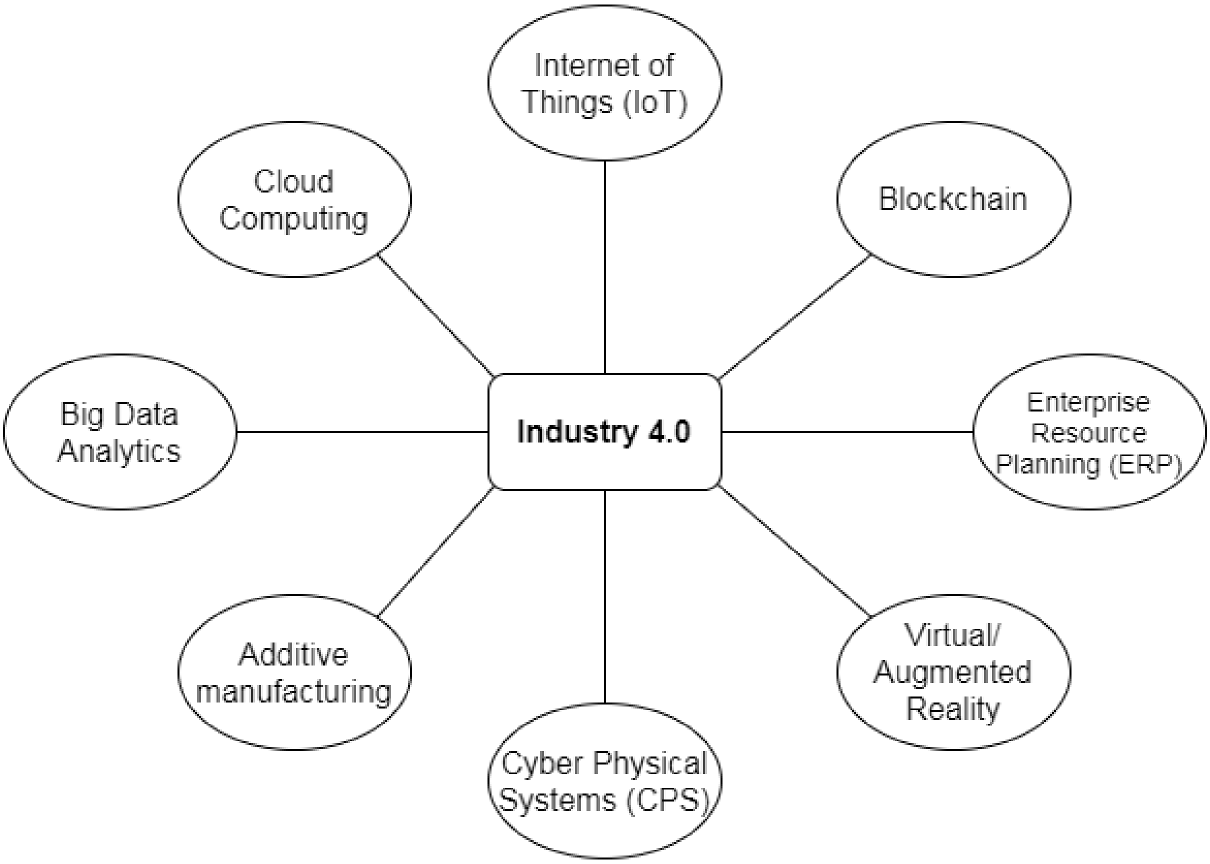

Figure 4.1: Technologies comprising Industry 4.0

1. **Internet of Things (IoT):** IoT consists of a ubiquitous network that connects various machines/objects through wireless/wired connections and assists them in interacting with each other through protocols. It consists of three types of interactions: people to people, people to machine, and machine to machine (Patel & Patel, 2016).
2. **Cyber-Physical System (CPS):** CPS creates a digital replica of the physical equipment on the shop floor. These replicas of various equipment communicate with each other and with humans virtually with the presence of IoT (Yu, Dillon, Mostafa, Rahayu, & Liu, 2019). Due to this reason, this is also called as the digital twin.
3. **Enterprise Resource Planning (ERP):** An ERP system is used for consolidating and processing the customer orders, material and other internal resources planning within a single organization or a group of organizations (Stadtler & Kilger, 2002). From the perspective of Industry 4.0, ERP system can be established with “end-to-end” supply chain connectivity

with suppliers, distributors and end customers to enable real-time data sharing and thereby improving planning (Kagermann et al., 2013).

4. **Big Data Analytics:** “Big Data is a term that describes large volumes of high velocity, complex and variable data that require advanced techniques and technologies to enable the capture, storage, distribution, management, and analysis of the information. (TechAmerica Foundation Federal Big Data Commission, n.d., p. 10).” The three important dimensions of big data are mentioned by Gandomi and Haider (2015). The first is the volume which pertains to the magnitude of data reported. Next is the variety which pertains to the “heterogeneity in a dataset” (p. 138). The next is the velocity that pertains to the frequency at which data is produced and the frequency at which it should be examined, and decisions made thereof.
5. **Blockchain:** “Blockchain is a distributed database solution that maintains a continuously growing list of data records that are confirmed by the nodes participating in it. The data is recorded in a public ledger, including information of every transaction ever completed. Blockchain is a decentralized solution which does not require any third-party organization in the middle. The information about every transaction ever completed in Blockchain is shared and available to all nodes. This attribute makes the system more transparent than centralized transactions involving a third party” (Yli-Huumo, Ko, Choi, Park, & Smolander, 2016, p. 2).
6. **Cloud computing:** “Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction” (Mell & Grance, 2011, p. 2).
7. **Virtual Reality and Augmented Reality:** “Virtual reality is the use of computers and human-computer interfaces to create the effect of a three-dimensional world containing interactive objects with a strong sense of three-dimensional presence” (Bryson, 1996, p. 62). In contrast, augmented reality “supplements the real world with virtual (computer-generated) objects that appear to coexist in the same space as the real world” (Azuma et al., 2001, p. 34). These are used for assisting workers to carry out maintenance activities.
8. **Additive manufacturing:** According to ASTM (n.d.), additive manufacturing is a process of making objects from its 3D model data, usually adding layer upon layer. It is an application of 3D printing technology and a replacement for traditional subtractive manufacturing where objects are removed from a bulk solid to arrive at the final desired shape.

All the above-stated technologies by themselves constitute independent research fields. It is not feasible to study the impact of all technologies on supply chain resilience for this thesis due to time constraint. Also, neither are all technologies adopted to an advanced extent. Thus, in the next section, the adoption trends of these technologies in manufacturing industries are discussed and the technologies considered are narrowed down.

4.2 Adoption and implementation patterns in manufacturing firms

A study conducted by Frank, Dalenogare, and Ayala (2019) shows the current adoption trend of Industry 4.0 technologies across manufacturing companies. The authors use a framework to facilitate this study. This framework consists of two layers: front end technologies and base technologies. The former consists of four main facets of Industry 4.0 that are smart manufacturing, smart products, smart working and smart supply chain. The second layer consists of the core technologies listed above, that form the working skeleton of the front-end technologies. Some examples are IoT, Big data analytics, CPS, and cloud computing. This framework is represented in Figure 4.2.

Amongst the front-end technologies, smart manufacturing plays a central role and other facets are related to this. Smart manufacturing improves the value of the internal processes whereas smart products improve the value of the final product. Regarding external processes, smart supply chain mainly improves the efficiency of the external activities by improving real-time communication whereas smart working provides workers with better conditions and thereby boost their productivity (Kagermann et al., 2013).

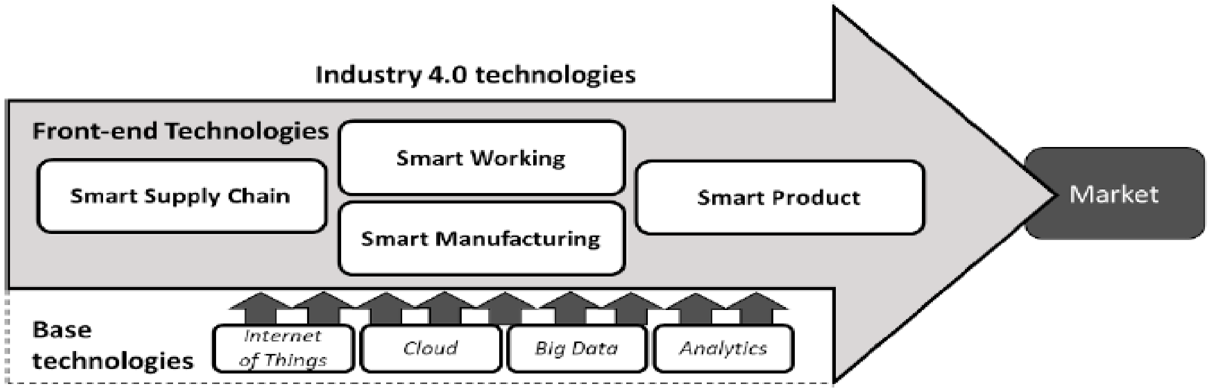

Figure 4.2: Theoretical framework of Industry 4.0 technologies (Frank et al., 2019)

According to the data obtained from a cross-sectional survey of 92 manufacturing organisations, the authors were able to divide them into three broad categories based on their adoption levels viz. low, moderate and advanced adopters. The average level of adoption was found to be statistically different between the three groups. They examine the relationships concerning adoption and obtain the following findings. They also find that the base technologies are complementary and cannot replace each other completely.

Next, regarding the implementation of a smart supply chain, it was found that the adoption of digital platforms with customers, suppliers and distributors was low for all three categories of adopters. The authors assert that cloud computing is adopted by all categories of adopters whereas IoT, big data and analytics are adopted lesser in low and moderate adopters. Moreover, real-time processing and analysing data is done with big data analytics and IoT.

One critique to be stated here is that there is no mention of CPS in the paper. As mentioned in the previous section, establishing CPS enables for all the machines to be connected and readings to be taken which is in turn recorded as data (Yu et al., 2019). This is needed to enable big data analytics in the organisation. It is decided to include this also in the framework.

Another finding reconfirms prior notions regarding the innovation theory was that larger companies were found to be more advanced as they have access to more finance for their new projects.

From the above study, it can be concluded that some base technologies like IoT, CPS, ERP, Cloud computing and Big data analytics will be preferentially adopted by manufacturing organisations that are transforming under the Industry 4.0 wave. Thus, the scope of this thesis can be narrowed down *to the above-stated technologies. And concerning the front-end technologies, it is practical to consider smart manufacturing and smart supply chain.*

A study by Mittal, Khan, Romero, and Wuest (2019) similarly shows that IoT, cloud computing, big data analytics and cyber-physical systems are some of the major technologies used by companies to implement smart manufacturing. It also asserts that technologies like blockchain and additive manufacturing are in their early-stage application and are less frequently adopted by companies. This provides additional motivation to consider the narrowed down technologies in this study.

4.2.1 Classification of adopters

In addition to this, the classification of adopters into categories like low, moderate and advanced is quite irregular and a paper by Müller, Buliga, and Voigt (2018) comes up with a better classification system for organisations. Although this is mainly for manufacturing SME's, the classification can also be adapted to all types of manufacturing organisations.

They categorise organisations as craft manufacturers, preliminary stage planners, Industry 4.0 users and full-scale adopters. The characteristics are mentioned in Table 4.1.

Table 4.1: Classification of organisations based on the adoption of Industry 4.0 (Müller et al., 2018)

Category	Characteristics
Craft manufacturers	They are not interested in applying Industry 4.0 technologies and would rather rely on human labour with very little automation in their processes.
Preliminary stage planners	They acknowledge that opportunity exists with Industry 4.0 and they plan implementation in the medium-long range term.
Industry 4.0 users	Companies in this group implement Industry 4.0 technologies due to pressure from their suppliers or customers. They mainly do this to improve their internal efficiency and communication capabilities with suppliers and customers.
Full-scale adopters	The companies are willing to fully implement Industry 4.0 and harness its capabilities. They also want to reap the early adopter benefits.

4.3 Enabling factors of Industry 4.0

The factors that influence the companies to adopt Industry 4.0 technologies can be broadly divided into internal and external factors to the organisation. A study by Ghobakhloo and Ching (2019) explores the same and they categorise the factors into three broad categories: technology, organisation and environment. They conclude the following as per the response received from SME's.

Regarding the technological perspective, three factors are found to be statistically significant which are: perceived value, perceived cost and perceived compatibility of the technology. Next, about the organisational perspective, three factors are found to be statistically significant. These are internal information processing requirements, knowledge competency of the technology and strategic road mapping. Finally, from the environmental perspective, there is only one factor identified which is the pressure for digitalization from government, customers and suppliers. Surprisingly, the researchers did not find any effect of competitive pressure for the adoption of Industry 4.0 technologies.

Similar research by Havle and Üçler (2018) categorises the enablers of Industry 4.0 into three main dimensions as human, organisation and technology. The technology perspective is further sub-divided onto four major branches namely digitalization, communication, hardware and software. This study does not consider the external environment that affects the adoption of Industry 4.0 technologies.

A study by Mittal, Khan, Romero, and Wuest (2017) conducted a detailed literature review of the technologies and enabling factors associated with smart manufacturing. It lists the following enabling factors for smart manufacturing implementation: law and regulation, innovative education and training, and data sharing systems and standards. These are already covered in the previous studies showing a broader classification of the enabling factors.

Combining the first two studies the enablers can be broadly classified into four categories: human, organisation, technology and environment.

4.4 Risks of implementing Industry 4.0

As per a broad classification done by Birkel, Veile, Müller, Hartmann, and Voigt (2019) in their paper, which discusses risks due to Industry 4.0. They gather data by conducting a multiple holistic case study of multiple industries. Data is primarily gathered through interviews of employees from 14 organisations. These are grouped into 13 different industrial sectors. Thus, these results are very broad and valid for many types of organisations.

They broadly classify the risks as financial, technological, IT, organisational, ecological and legal/political. Each of these risks is discussed below.

4.4.1 Financial risk

Returns: Birkel et al. (2019) argue that all organisations investing in Industry 4.0 technologies will face significant financial risk as there is uncertainty accompanied by the performance and usefulness of the investment. Investing too heavily will cause cash flow burden on the organisation. Contrarily, there is also a risk of delaying the investment and losing out on gaining competitive advantage in the industry.

Timing and distribution: Next, the timing of investment is crucial. Companies do not want to invest in outdated or immature technology. Further, it is also important when to invest in Industry 4.0 technologies and how to distribute the investment within different parts of the organisation to achieve the maximum effectiveness from the investment. Also, late investment in this technology can render an organisation to be less competitive in the industry. Thus, organisations must prudently invest in these technologies and in a phase-wise manner to limit financial strain and improve internal competency with technology usage (Frank et al., 2019).

Business model: With the proliferation of Industry 4.0 technologies, organisations can no longer operate in the same traditional way and their business models need to evolve (Müller et al., 2018). A business model is said to be how a company organises its operations to create value and earn revenue. If the alignment between the business models, the technology application and the organisation are not adequate, this can also create risk for the organisation in the form of revenue loss, customer loss etc. Müller et al. (2018) argue find in their research that if the value of the new technology is not captured properly in the business model, companies may lose their customers and market share to rivals.

Competition: The implementation of Industry 4.0 leads to increased competition. Additionally, not all customers will be willing to pay for these new technologies which can also pose a risk. Usually, when implemented in a supply chain, it provides partners with more information about the focal firm, which can be used against them during a negotiation process which causes financial risk.

Dependency: Finally, the installed systems need to be repaired, maintained and updated periodically which also requires dependence on external vendors as this cannot be done independently. This makes a focal company excessively dependent on the maintenance vendor. If the vendors choose to hike the price for maintenance, that can also pose a risk.

4.4.2 Technological risk

The next category of risks stated by Birkel et al. (2019) is technological risks.

Integration: They state that the former pertains to choosing whether to replace existing systems completely with new systems or to integrate new systems into the existing ones. The current equipment can be retrofitted with Industry 4.0 systems making the integration process simpler. But this is not possible in many cases. This makes the shop floor integration a challenging task.

Dependency: Additionally, the authors also state that the dependency on the technology increases greatly and any failure can cause operations stoppage for the whole supply chain.

Standards: Software used in ERP system can come from several providers in the market who provide different standards of the same technology. Problems arise when integrating this software across different companies in the supply chain. Even the equipment on the shop floor needs to be integrated into an interface. There is a need for clear interfaces between various departments in a company also in the supply chain. Only by adhering to standards, seamless communication can be ensured.

4.4.3 IT/Cybersecurity risks

Cyber-attacks: Elkhawas and Azer (2018) broadly classify several types of attacks that can happen. They are espionage, denial of service, replay attacks, and deception attacks. These types of attacks are described briefly in Table 4.2.

Table 4.2: Types of cyber-security attacks (Elkhawas & Azer, 2018)

Attack type	Brief description
Espionage	It is an attack that pertains to obtaining trade secrets of a company without the knowledge of the company that owns this information
Denial of service	In this type of attack, a server is flooded with many illegitimate requests that block it from responding to legitimate requests
Replay attacks	This is found in instances in which attackers capture the data packets between two points and replay them
Deception attacks	In this attack, the integrity of the transferred data is damaged

Another classification by Pandey, Singh, Gunasekaran, and Kaushik (2020) identifies the types of cyber-attacks on supply chain management systems. It is listed in the below in Table 4.3.

They further argue that the digital supply chain is only as strong as its weakest link and find it necessary to classify cyber-security risks mentioned above, from the perspective of the supply chain (Pandey et al., 2020). Thus, they classify the cyber-security risks as demand (downstream), supply (upstream), and operational (focal company) depending on where it originates.

Table 4.3: Types of cyber-security attacks (Pandey et al., 2020)

Attack type	Brief description
Password sniffing/cracking software	This is one of the most common types of attacks in which the attacker gets hold of the password either by using password cracking software or guessing the password using combinations.
Spoofing attacks	This happens when a message originated from a random place rather than the actual place but is still accepted by the server and processed.
Denial of service attacks	This happens when a network is flooded with requests and results in a server crash and consequently the resources become inaccessible.
Direct attack	In this attack, the computer server is directly hacked, and information is either stolen or rewritten.
Malicious tampering	This occurs when equipment comes preinstalled with software that helps in the network being compromised at a later stage.
Insider threat	When an attack is initiated by an employee working in the organisation, it is called an insider threat.

Data possession: All companies have intellectual property that is a critical component for their success. Implementing Industry 4.0 and sharing data across companies will give data access to other organisations in the supply chain. It should be protected such that it does not fall in the hands of a direct competitor.

Data handling: Enabling Industry 4.0 across the supply chain will result in recording a lot of data. The distribution and access to this data need to be controlled. There also needs to be a consistency of data across the supply chain.

Cloud computing: There are some risks mentioned about operating Industry 4.0 systems on cloud systems. Having low connection speeds, cloud server failure, location of the server in other countries are a few risks that need to be evaluated. Also, it is tough to achieve real-time capabilities by using cloud computing.

4.4.4 Organisational risk

Job losses: Researchers have claimed that the implementation of Industry 4.0 will likely result in job losses. It also requires employees to be able to adapt quickly to the requirements of the new system. Only then can they operate the system properly and ensure smooth operation. This changes the nature of jobs in the labour market.

Resistance: In most cases, there is resistance from employees and mid-level management. This feeling from employees should be acknowledged and they must be included in the transformation process. Employees must be encouraged to attend training sessions regarding new technologies. Bringing an open culture can also help with abating resistance among employees.

Employee training and qualification: As discussed in financial risks, there is also a need for employees who are trained and qualified to operate the Industry 4.0 systems. This personnel come at a higher cost. Moreover, they are also very hard to find in the labour market. There is a requirement for personnel who are knowledgeable with IT-related processes and the internal processes within the organisation and are capable enough to mediate between both.

Employee stress: Employees also come under duress under such changing environments as they are faced with more challenges compared to their routine work. This excess of stress and tension can also fuel the resistance culture that was discussed earlier. When more equipment is installed, it can also cause isolation from other employees as many jobs are now being performed by machines.

Distrust over the technology: The management of many companies may not trust the Industry 4.0 technologies when there may be incidents of wrong decision making that have had adverse effects on the organisation. There is also the problem of accountability with this. When the equipment makes a mistake, is it held accountable by the equipment itself or the person who programmed it?

Manufacturing relocation: When management is faced with excessive pressure from employees about implementation, there is a possibility that factories can be closed, and the manufacturing relocated to other countries where conditions are more favourable.

Capability loss: Capability loss can be defined as knowledge and skill loss related to a particular process, that occurs in employees after it is made automatic (Handley, 2012). During a disruption, when the said automated system is down, employees can't revive it or operate it manually, thus causing the event to cascade and worsen further. As per the argument by Ralston and Blackhurst (2020), due to capability loss associated with Industry 4.0 implementation, the functionality of the system may be compromised if the system fails as employees cannot function those tasks. This leads to a loss of resilience.

4.4.5 Ecological risk

Birkel et al. (2019) state that the implementation of Industry 4.0 might bring environmental benefits or even risk.

Consumption and Pollution: They quote the example of increased energy consumption of newly installed electronic systems. If the benefits of efficiency gains cannot offset this increased energy consumption, then there will be a net higher consumption of energy. Other ecological risks can also include waste generation and emissions. This can happen when old equipment cannot be used anymore and is disposed of, that can cause excess waste to be generated.

4.4.6 Legal and Political risks

Lastly, Birkel et al. (2019) argue that the implementation of Industry 4.0 technologies can also create legal and political risks.

Infrastructure: The support of laws and legislations is necessary for smooth diffusion of technologies and can be said to be one of the most important initial necessities. Further, it is also the responsibility of politicians to provide the necessary infrastructure also. These constitute political risks. Although the authors use the term 'risk' in describing this, in other research, it is described as an enabling factor (Mittal et al., 2017). Hence, I feel that this would be more appropriate to be described as an enabling factor as this can be a prerequisite to smoothly enable Industry 4.0 technologies. In the absence of facilitation by laws, private organisations can still implement these technologies within their organisations, and it does not pose any risk to the supply chain.

Legal aspects: Birkel et al. (2019) also highlight the presence of legal risks concerning data handling. Companies that undergo digital transformation under Industry 4.0 must chalk out the agreements in well-defined contracts that specify the control of each organisation. Usually, this is an intensive process.

The types of risk explored through literature are categorised in Figure 4.3.

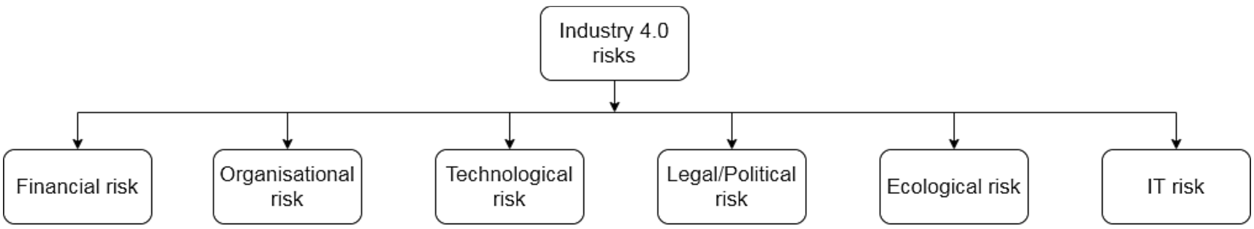

Figure 4.3: Types of risk due to Industry 4.0 implementation (Birkel et al., 2019)

4.5 Conclusion

This chapter discussed the literature findings of Industry 4.0 technologies. The sub-research question for this chapter is - How is Industry 4.0 implemented in manufacturing industries? There are many factors involved in answering this. As many underlying technologies make up Industry 4.0, it was first necessary to narrow down the key technologies that are being prioritised and adopted. In section 1.2, a study by Frank et al. (2019) is discussed which states that manufacturing companies will preferentially adopt this technologies-IoT, ERP, CPS, Big data analytics, and cloud computing. The objective to consider these technologies is to make the organisational processes more automated and less dependent on human controls. It is also used to improve real-time communication between supply chain partners. Although there are deemed benefits in implementing this, there are also challenges which are discussed in risks of implementing Industry 4.0.

The framework for Industry 4.0 based on the above discussion and the narrowing down of technologies is shown in Figure 4.4.

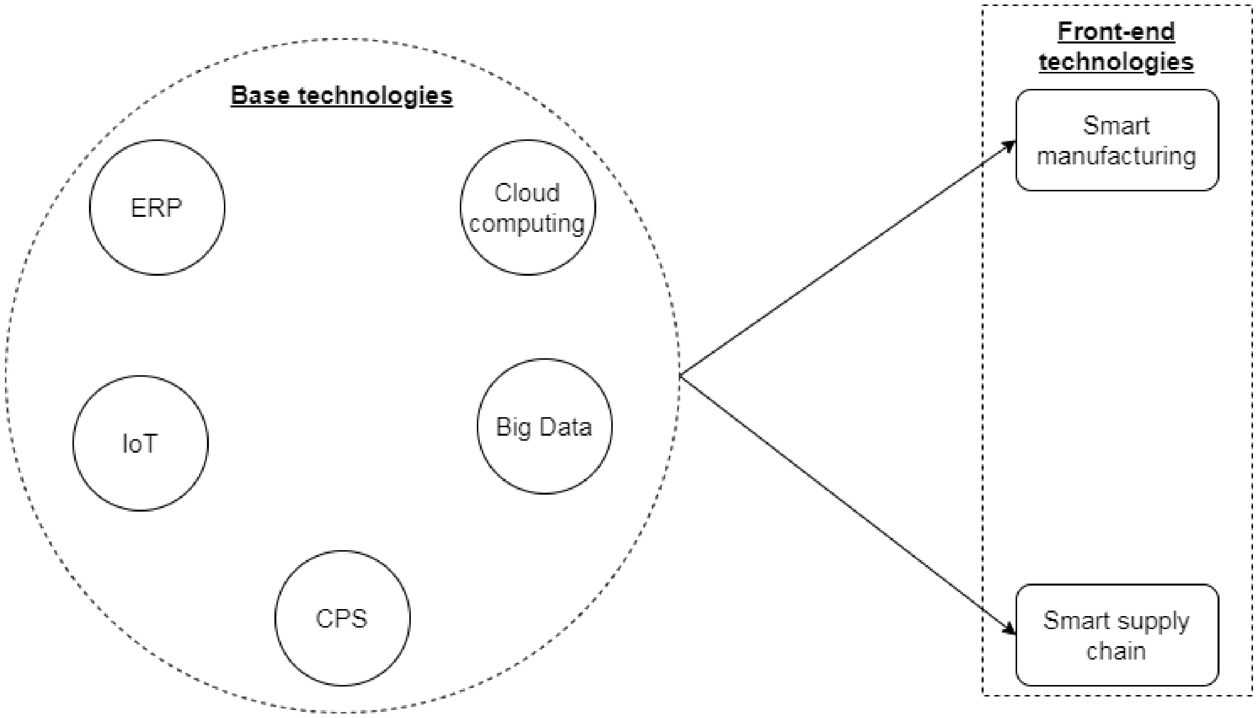

Figure 4.4: Framework of Industry 4.0 (Adapted from Frank et al. (2019))

Chapter 5 SUPPLY CHAIN RESILIENCE

This chapter is a literature review on supply chain resilience. The methodology used to obtain articles for the review is described in the appendix. The second sub-research question about supply chain resilience is answered in this chapter i.e. What capabilities are required to build a resilient supply chain?

The content in this chapter is organised as follows. First, the term 'resilience' is discussed in many fields. This is followed by a discussion of the work by Christopher and Peck (2004) which describes how to establish a resilient supply chain. Next, the definition of the term supply chain resilience is discussed followed by the literature review on the topic. This is followed by the operationalisation of supply chain resilience for this thesis.

The search methods used to obtain articles for the literature review is discussed in Appendix A.

5.1 Introduction

The concept of resilience is present in many disciplines. According to the Oxford Dictionary (2012), the word resilient is described as "able to recover quickly from difficult conditions". The concept of resilience is extended to infrastructure, human (psychological and emotional), organisational, and ecological to name a few branches.

In a recent report published by the World Bank, the economic losses due to poor infrastructure in underdeveloped nations have been highlighted (Hallegatte, Rentschler, & Rozenberg, 2019). Infrastructure breakdowns cost \$391-\$647 billion on the households and firms in these economies. Thus, it is an urgent necessity to invest in more resilient infrastructure (bridges, buildings, transport, water etc) that can withstand adverse climatic effects.

For human productivity, it is necessary to have a resilient mindset as well. This has been recognised in psychology literature. It helps people who are facing low productivity in difficult times to bounce back to a routine productivity level and proceed towards their goal.

Not surprisingly, the concept of resilience was applied to the supply chain also. The term supply chain resilience was first coined by Rice and Caniato (2003) and Christopher and Peck (2004), where they emphasise the need to build resilient supply chains. The authors argue that the nature of the supply chain is becoming longer and more complex by the day and it becomes important to build resilience for continuing the business even at times of disruption. Rice and Caniato (2003) further argue that a supply chain can face disruptions from unforeseen environmental disruptions. They quote the example of the terrorist attack on the World Trade Centre in 2001 which brought many supply chain operations to a halt. This was an important realisation for many companies to build secure and resilient supply chains.

During the recent disruption of Coronavirus pandemic, many companies have struggled due to uncertainties in the business environment and many companies have also gone bust. Thus, there is a need now more than ever to build resilient supply chains. Christopher and Peck (2004) define supply chain resilience as its ability to revert to the original state or a new desirable state in case of a disruption occurrence.

The four general strategies to become resilient (Christopher & Peck, 2004) are listed as follows:

1. Supply chain reengineering
2. Supply chain collaboration
3. Agility
4. Supply chain risk management culture

Each of these strategies is discussed briefly.

5.1.1 Supply chain reengineering

As per the study by Christopher and Peck (2004), usually, supply chains are designed with cost reduction and efficiency in mind. Very rarely risk reduction is also considered. They suggest looking at supply chain considerations from the risk management perspective. The authors suggest undertaking the following steps as a part of reengineering.

5.1.1.1 Supply chain understanding

It is first necessary to map and understand the supply chain in which the focal organisation operates. This enables the identification of critical paths in the supply chain and taking actions to improve resilience. These critical paths may have one or more of the following attributes-long lead times, single source of supply with no other suppliers, poor visibility and/or high-risk level. This analysis is used to create a risk register for the supply chain where these criticalities and vulnerabilities are monitored.

5.1.1.2 Supply base strategy

The authors stress the importance of choosing suppliers for the organisation. They discourage using a single supplier for a material or service. Although this may have cost advantages, this reduces the resilience of the supply chain. Also, the suppliers should be chosen based on their risk awareness and how they deal with their risks. In other words, the risk management cultures of both the focal organisation and supplier should be congruent.

5.1.1.3 Design principles

The authors further suggest two main principles to use for designing resilient supply chains. The first involves keeping several options open. This may not help with keeping the costs low but will help deal with disruption.

The second option is to choose carefully between the two strategies of efficiency vs. redundancy. Traditionally, to save costs in supply chain operations, inventory is seen as an unnecessary expenditure and their levels are reduced to a minimum. The authors propose using some strategic inventory especially in the critical points that were discussed earlier. This will ensure operational continuity in case of a disruption event. The challenge lies in selecting the optimum quantity of inventory to be held at the critical points in the supply chain.

5.1.2 Supply chain collaboration

Next, collaboration across the supply chain is required to help in the mitigation of risks. The main objective of the collaboration is to exchange information on a timely basis so that action can be planned and executed to reduce the impact of disruptions. Sharing information also reduces the uncertainty attached to the operations. Knowledge is created amongst supply chain partners that are valuable to all members of the supply chain.

5.1.3 Agility

Supply chain agility is defined as the "ability to respond rapidly to unpredictable changes in demand or supply" (Christopher & Peck, 2004, p. 18). This is the next dimension required for building a resilient supply chain. Sometimes, during the occurrence of a disruption, the supply chain may not be able to perform at the required level. But with an agile supply chain, it responds quickly to the disruption and gains back the performance levels.

There are two components to agility as outlined by Christopher and Peck (2004). They are supply chain visibility and supply chain velocity. The former is defined as the capability to see and know what is happening at the ends of the supply chain. The latter is defined as the time it takes to move products from one point in the supply chain to another.

5.1.4 Risk management culture

The last requirement to build resilient supply chains is the adoption of a risk management culture. Many companies are adopting techniques like lean, six sigma, total quality management into their internal processes as a part of continuous improvement. Similarly, risk awareness and management should also be encouraged in the organisation. Having a culture requires commitment and drive from the top management in the firm. Also, this should be included in the decision-making process at all levels in the organisation. Further, this should be extended to the entire supply chain as well. The risks in the supply chain should be reviewed periodically and must include inputs from all levels in the organisation.

It should be noted that the four strategies are not exclusive but rather are interrelated and boost each other to achieve resilience. Perhaps, having a risk management culture is very imperative. This leads to building collaborative relations within the supply chain members which leads to improved agility that can be used to respond to disruptions.

5.2 Definition

For this thesis, it is necessary to define supply chain resilience which is done in this section. Ponomarov and Holcomb (2009) conducted a detailed study of the concept of resilience from many scientific perspectives and arrived at a definition and conceptualisation of supply chain resilience. Borrowing from the concept of resilience from other disciplines, they formulate a definition for supply chain resilience which is used as a standard by researchers to date. The definition follows.

> *"The adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function" (Ponomarov & Holcomb, 2009, p. 131)*

Numerous studies that have been reviewed as a part of this thesis, have considered the definition as given by Ponomarov and Holcomb (2009). Thus, for this thesis as well, this definition is considered for the rest of the study.

5.3 Literary findings

5.3.1 Distinguishing resilience from robustness

According to Wieland and Wallenburg (2013), the concept of supply chain resilience can be visualised into two types. It can be understood to be a combination of proactive and reactive strategies to deal with disruptions. The proactive strategy refers to the preparedness of the supply chain in advance of the occurrence of any risk event. This has been linked to building the robustness of the supply chain. Whereas, the reactive strategy entails garnering a swift reaction after the occurrence of a risk event. This majorly deals with building an agile supply chain. Each strategy has its costs on the supply chain and mostly many organisations adopt a mix of both robustness as well as agile strategies in their supply chain operation (Wieland & Wallenburg, 2012).

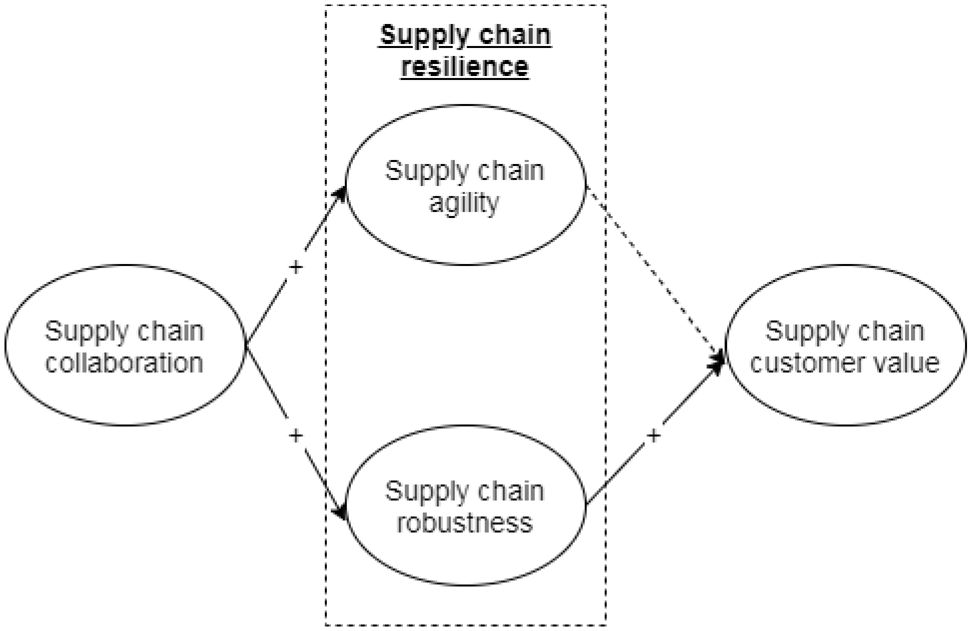

Figure 5.1: Effect of supply chain collaboration on supply chain resilience (Wieland & Wallenburg, 2013)

Wieland and Wallenburg (2012) surveyed to study if both agility and robustness affect the performance of the organisation. They conclude that agility does not significantly affect the performance, but it does affect the customer value. This is understandable as one major requirement from the customer would be prompt communication which can be established by agile working. The relationship proposed by them is shown in Figure 5.1.

But later research showed resilience to be a different entity from robustness. Brandon-Jones, Squire, Autry, and Petersen (2014) conducted a study about how organisations create resilience and robustness. They surveyed 264 organisations from various industries. When testing the data for its "goodness", they found that resilience and robustness, both have different factor loadings while doing factor analysis. Thus, previously it was believed that robustness and agility are both parts of resilience, but now in this new study, resilience is completely differentiated from robustness.

Brandon-Jones et al. (2014) argue that resilience and robustness are two very different concepts. They define resilience the same as stated in the introduction by Christopher and Peck (2004) - the ability of the supply chain to return to an acceptable state of performance after being disrupted for some time. Additionally, they define robustness as the ability of the supply chain to continue performing at the same level, despite a disruption (Kitano (2004) cited from Brandon-Jones et al., 2014).

For this thesis, the concepts proposed by Brandon-Jones et al. (2014) will be considered as it is more logical. Although their finding is from a statistical perspective, it also has sound theoretical backing. Resilience is said to be the ability in which, the supply chain performance drops at the occurrence of a disruption event and it is restored by the capabilities that have been built beforehand. Correspondingly, robustness is said to be the ability in which, when a disruption occurs the supply chain performance is not affected, and it maintains at a constant level. In other words, the notion of a drop in performance is implicit in the concept of resilience and it focuses on reviving the supply chain operations after a disruption. The relationship proposed by Brandon-Jones et al. (2014) is shown in Figure 5.2.

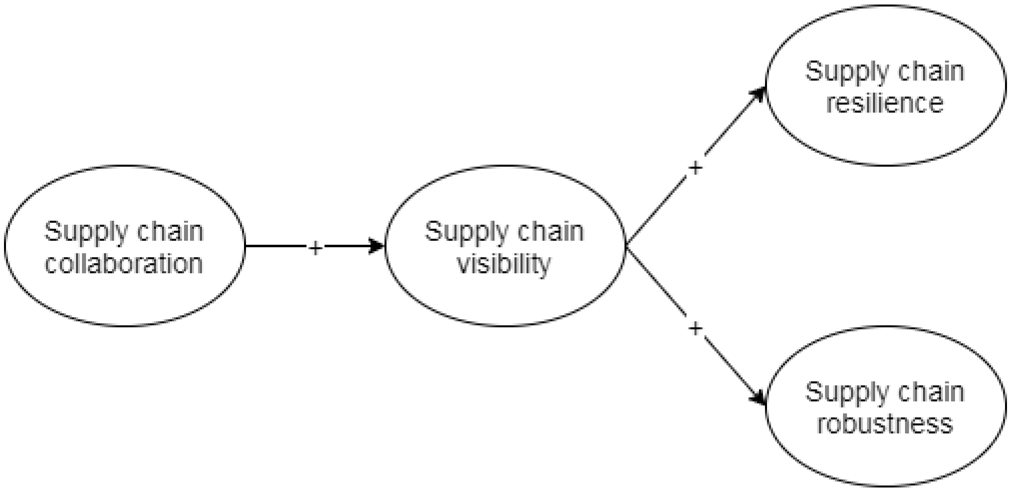

Figure 5.2: Effect of supply chain collaboration on supply chain resilience and robustness (Brandon-Jones et al., 2014)

5.4 Resilience enablers

There is a considerable amount of research when it comes to identifying the enablers of supply chain resilience. This section identifies and discusses some of these enablers that were identified as a part of the literature review.

5.4.1 The power of collaboration

As previously discussed, collaboration is a key element in establishing resilient supply chains. Jüttner and Maklan (2011) investigate the relationship between Supply Chain Risk Management (SCRM), supply chain resilience and supply chain vulnerability. They break down supply chain resilience as flexibility, velocity, visibility and collaboration in the supply chain. They conduct a qualitative case study of three companies where they try to examine if undertaking SCRM activities in the supply chain leads to better collaboration, flexibility, velocity, and visibility which in turn leads to improved resilience in the supply chain. They gather primary data through interviews with various employees at the companies. They interview employees working in different functions within the same organisation. This helps them to study the phenomenon from various perspectives. Also, they gather secondary data from suppliers and customers by collecting internal documents and reports for data triangulation.

From the data collected by interviewing professionals, they conclude that carrying out SCRM activities has a positive effect on flexibility, velocity, visibility, and collaboration which leads to improved resilience. This improvement in resilience in turn leads to lowering the vulnerabilities in the supply chain. This relationship is shown in Figure 5.3

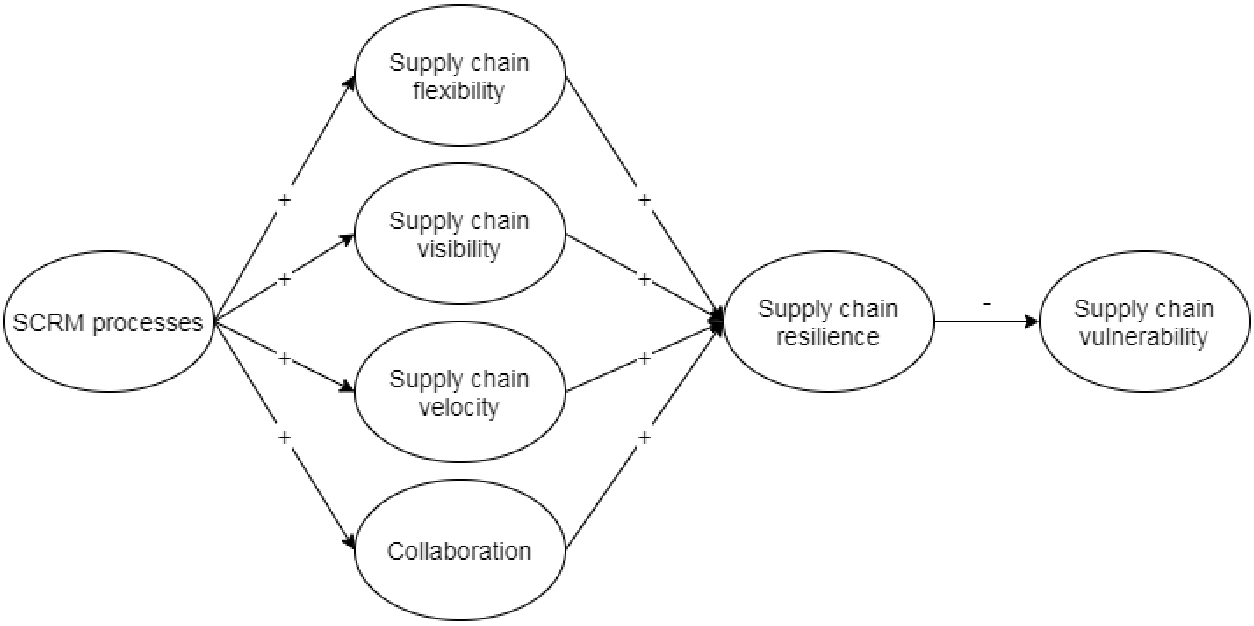

Figure 5.3: Effect of SCRM processes on supply chain resilience (Jüttner & Maklan, 2011)

The above research is investigated further in a paper by Scholten and Schilder (2015). The authors try to seek how collaboration in the supply chain influences its resilience capabilities. The collaborative activities in the supply chain are categorised as information sharing, goal congruence, decision synchronisation, incentive alignment, resource sharing, collaborative communication, and joint knowledge creation (Cao, Vonderembse, Zhang, & Ragu-Nathan, 2009). These aspects are explained further in Table 5.1.

Table 5.1: Types of collaboration in a supply chain (Cao et al., 2009)

Collaborative activity	Definition
Information sharing	The level in which a firm discloses appropriate, true, and private plans and procedures with supply chain members at the right time
Goal congruence	The degree to which a firm perceives its objectives fulfilled by accomplishing the objectives of the supply chain
Decision synchronisation	Supply chain partners plan and take decisions together to optimise supply chain benefits
Incentive alignment	Sharing of costs, risks, and benefits amongst supply chain members
Resource sharing	Exploiting capabilities and assets and creating new ones together with supply chain partners
Collaborative communication	The connection and message relaying process among supply chain partners in terms of frequency, direction, mode, and influence strategy
Joint knowledge creation	The degree to which supply chain partners work together to understand the market forces and respond to it

Scholten and Schilder (2015) conduct a case study of two companies and for each of the two companies, they also consider four major suppliers, thus they study eight different cases of buyer-supplier relationships. Primary data is collected through 16 semi-structured interviews and secondary data is collected from internal reports, Enterprise Resource Planning (ERP) data, and company websites.

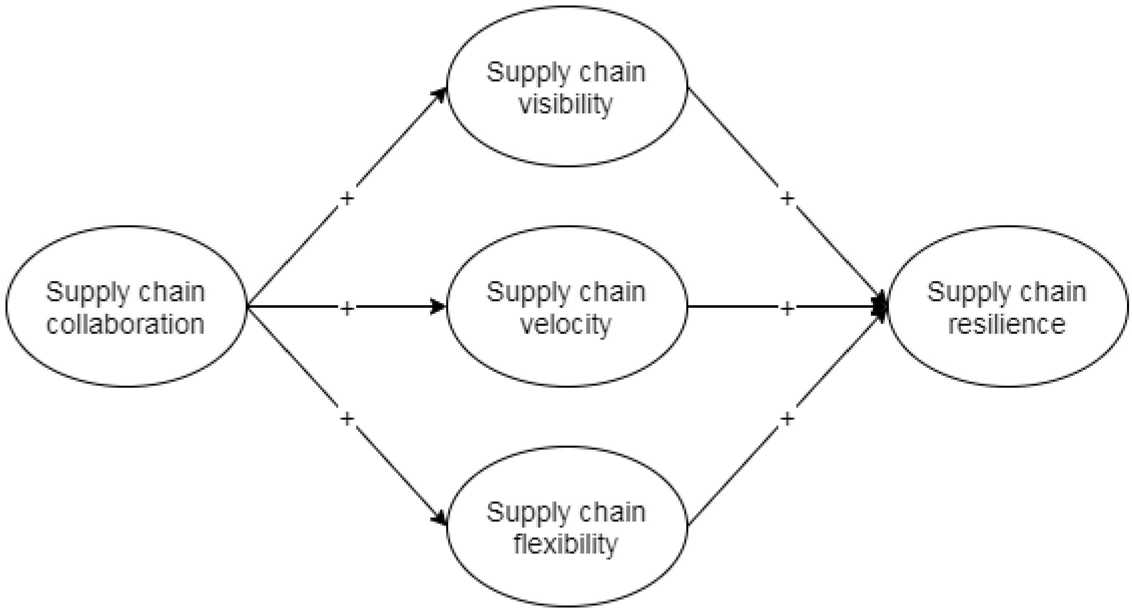

Figure 5.4: Effect of supply chain collaboration on supply chain resilience (Scholten & Schilder, 2015)

The findings from the qualitative data indicate that collaborative activities listed in the above table lead to an improvement in visibility, velocity and flexibility in the supply chain which in turn improves supply chain resilience. Thus, the authors were able to argue that collaboration does not directly impact resilience but rather improves visibility, velocity, and flexibility which in turn improves resilience. This relationship is shown in Figure 5.4.

Another important aspect that imparts supply chain resilience is the social capital of the organisations in the supply chain. A paper by Gölgeci and Kuivalainen (2020) explores this phenomenon by surveying 265 firms. The chemical and pharmaceutical industries together constitute 21 firms of the total. Social capital is defined as the total resources available to a firm from its resources and also through relationships with other firms (Nahapiet & Ghoshal (1998) cited from Gölgeci & Kuivalainen, 2020). As already discussed previously, any firm having adequate social capital by collaboration with other firms stands to gain better resilience (Jüttner & Maklan, 2011; Scholten & Schilder, 2015). But the methodology of the previous studies was mainly through case studies whereas this paper gathers data through a survey and tests it by statistical methods.

Gölgeci and Kuivalainen (2020, citing Zahra & George (2002)) also use another concept called the firm's absorptive capacity which refers to the methods with which firms obtain, integrate, modify, and use information outside the firm and thereby produce competitive capabilities. They propose that absorptive capacity mediates the relationship between social capital and supply chain resilience.

The authors propose that social capital allows a focal firm to identify and gain information from its network. Thus, having adequate social capital positively influences the absorptive capacity of the firm. Similarly, social capital also helps firms mitigate risk events by collaborating with its partners and try to act on the situation together. Thus, having adequate social capital is also positively beneficial for supply chain resilience.

Also, with social capital, a focal firm can gain critical information from its network, it can use it for gaining an advantage or even avert risk event occurrence. Thus, absorptive capacity also positively influences supply chain resilience.

Gölgeci and Kuivalainen (2020) propose a partially mediated relationship between social capital, absorptive capacity, and supply chain resilience. They conduct a statistical survey from manufacturing organisations and find support for all the theoretical claims made above. A conceptual diagram representing their theory is shown in Figure 5.5.

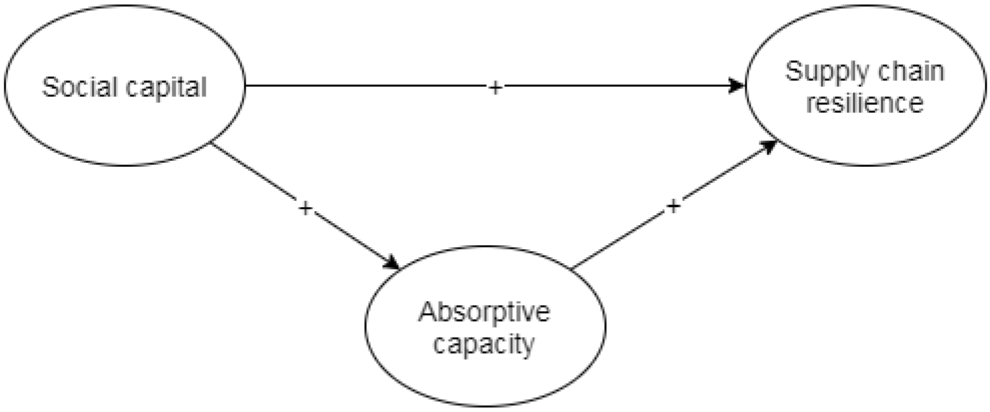

Figure 5.5: Effect of social capital and absorptive capacity on supply chain resilience (Gölgeci & Kuivalainen, 2020)

5.4.2 The power of advanced preparedness

There is also a necessity for planning proactively in anticipation of risk occurrence. Scholten et al. (2014) investigate the relationship between theoretical supply chain resilience and practical disaster management processes. Their objective is to improve the understanding of supply chain resilience practically and thereby guide organisations in building it.

They carry out a single case study of the organisation Voluntary Organisation Active in Disaster (VOAD). They assess the activities carried out by VOAD across the four phases of disaster management – preparedness, response, recovery, and mitigation. Supply chain resilience is visualised as per the article by Christopher and Peck (2004) that was discussed previously. In addition to the four parameters that were mentioned, this paper also considered knowledge management as a fifth formative resilience element.

Primary data was gathered from nine interviews and an hour observation of a meeting attended by 15 members. Secondary data was gathered from documents like internal reports. The interviews were conducted with members working in different functions and hierarchies to gather data from various perspectives as well.

The findings are discussed as described next. Each formative element of resilience was considered individually, and it was analysed from the qualitative data whether they were required in the various stages of disaster management. The importance of supply chain collaboration (both horizontal and vertical) was found to be critical in all stages of disaster management. Similarly, knowledge management was also found to be important for all four phases of disaster management. Agility was critical in the preparedness and response phases. Supply chain reengineering was critical for mitigation, preparedness and response phases. Lastly, risk awareness was critical in the mitigation phase and to an extent useful during the recovery phase. This relationship is shown in Figure 5.6.

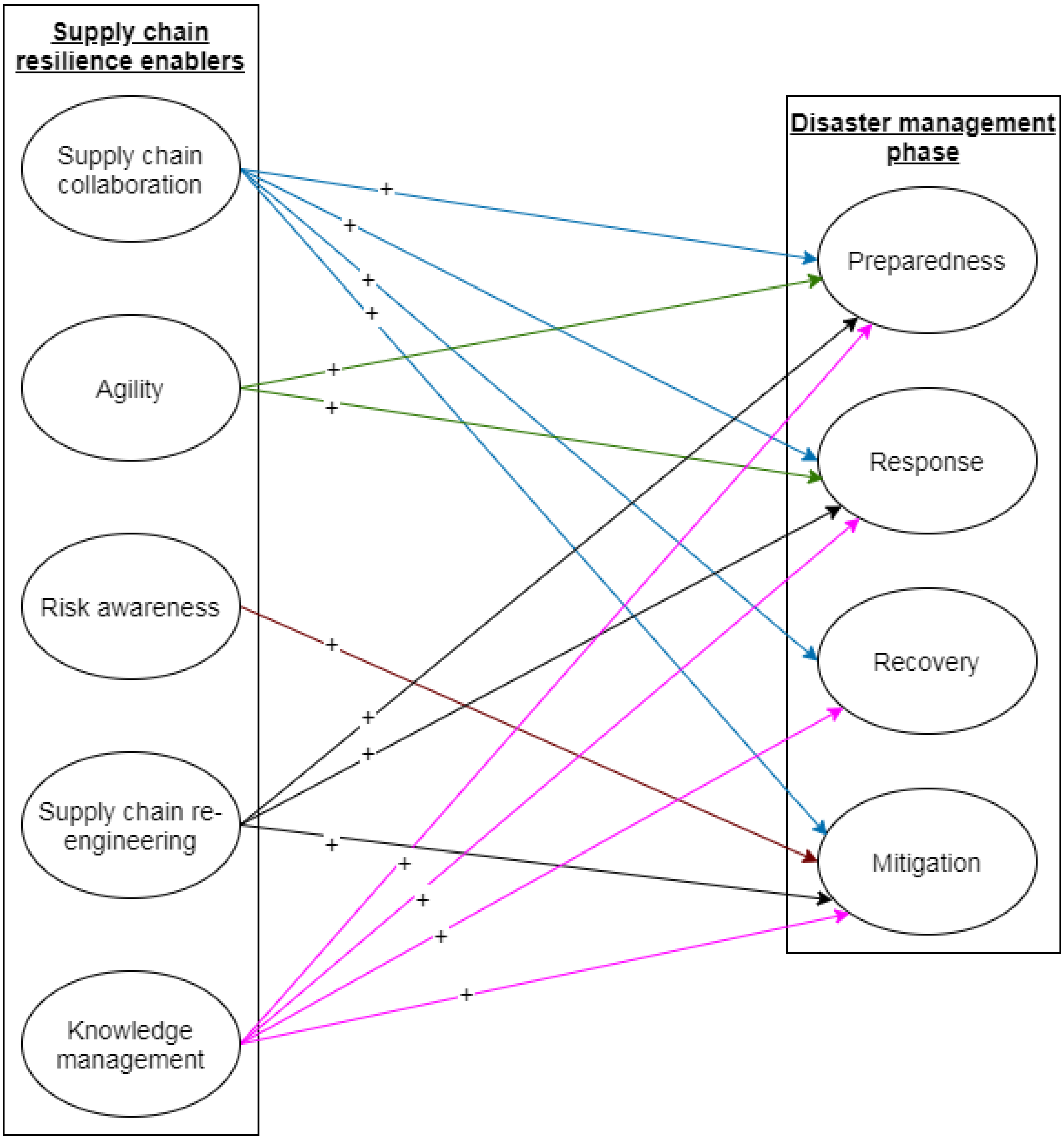

Figure 5.6: Significance of supply chain resilience enablers in different phases of disaster management (Scholten et al., 2014)

Thus, from this study, organisations can learn about which resilience elements are important in which stages during the mitigation of a disruption. Although this was investigated from the perspective of disaster management, this is also applicable to routine organisations.

5.4.3 The learning capability

Learning mechanisms within an organisation help in building supply chain resilience. An article by Scholten et al. (2019) investigates this relationship between learning mechanisms and supply chain resilience. Learning can be defined as the implanting of practical knowledge gained from real-events into organisational routines (Levitt and March (1988) cited from Scholten et al., 2019). Scholten et al. (2019) propose that learning can be achieved in two ways – by 'critical internal analysis' and knowledge transfer within the organisation/supply chain.

The case study is the method used by Scholten et al. (2019) to answer this research question. They use multiple case study of five organisations that have had a disruption in their supply chain. Data were collected by conducting 28 semi-structured interviews from employees across these organisations. Secondary data was also collected by accessing relevant documents from companies.

The main objective of the authors was to categorise the types of learning activities that took place in different stages of a disruption – preparedness, response and recovery. The results of the types of learning that take place are summarised in Table 5.2.

Table 5.2: Types of learning in different phases of disruption (Scholten et al., 2019)

Disruption Phase	Type of learning	Definition
Preparedness (Pre-disruption)	Processual	When there are changes in organisational strategy and growth, it results in the proactive unintentional creation of knowledge to help enable the change.
	Anticipative	The organisation anticipates possible disruptions and transfers knowledge within the supply chain to establish new routines or improve existing ones.
Response (During disruption)	Situational	If there is a disruption in the material flow, an immediate solution is necessary to resume operations. Knowledge transfer that occurs here depends on the situation and type of disruption and is unintentional
	Collaborative	When an immediate solution is not available to respond to a disruption, a plan is created in collaboration with supply chain partners to mitigate the situation. This type of learning is unintentional.
Recovery (Post-disruption)	Experiential	While recovering from a disruption, intentional learning occurs through knowledge creation about the disruption.
	Vicarious	While recovering from a disruption, intentional learning occurs through knowledge transfer about the disruption.

In conclusion, learning positively affects the formative elements of resilience (flexibility, visibility, velocity, collaboration) thereby improving resilience as such. This relationship is shown in Figure 5.7.

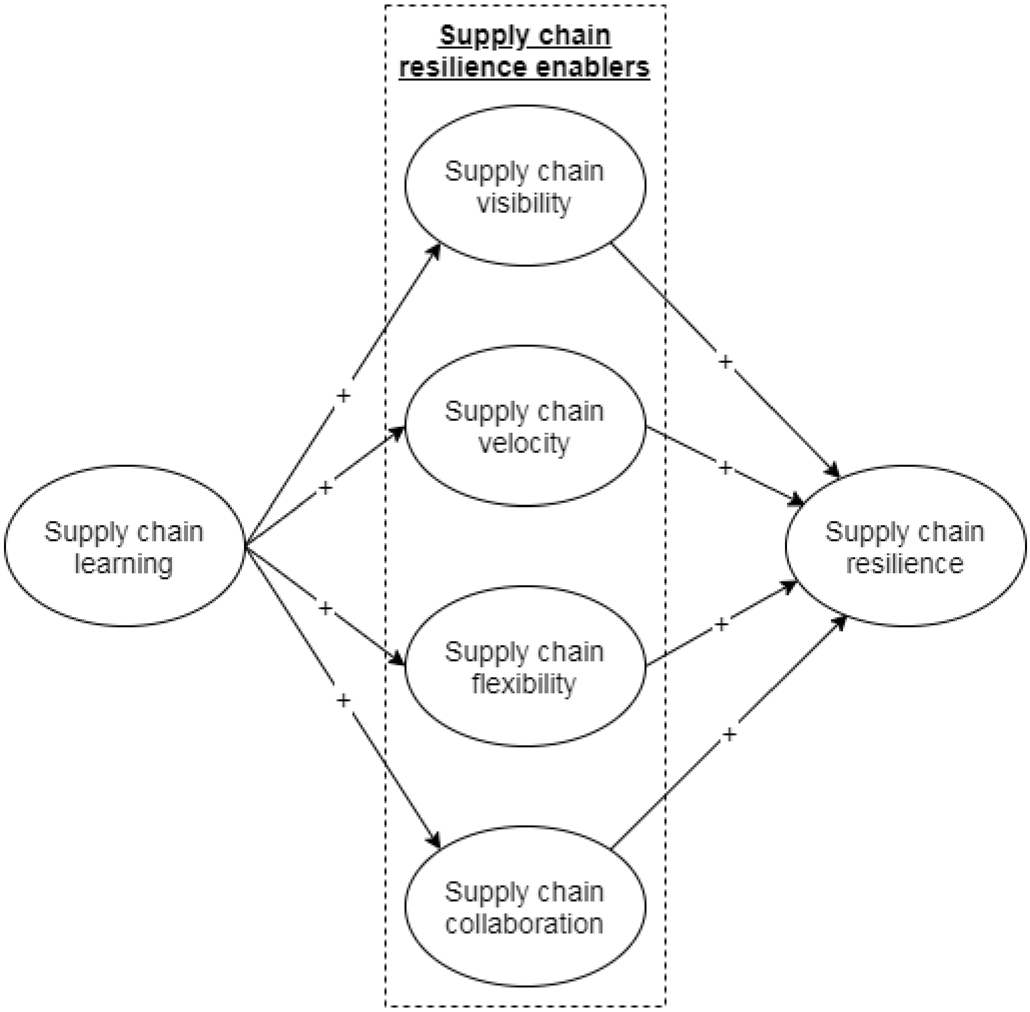

Figure 5.7: Effect of the learning process on supply chain resilience (Scholten et al., 2019)

5.5 Conceptual model

From the data collected through the literature review, a conceptual model of supply chain resilience can be constructed which is shown in Figure 5.8.

It consists of a diagram that depicts the relationships between organisational resources and how they lead to improved supply chain resilience. Culture of innovation and risk management is identified as the preliminary requirement. By improving the organisational culture, it establishes better collaboration and learning. Both these resources when used properly can lead to better flexibility, velocity, and visibility in the supply chain that leads to improved resilience.

The social capital is improved by both risk management culture and collaboration in the supply chain. This leads to the better absorptive capacity of the supply chain which will also improve resilience.

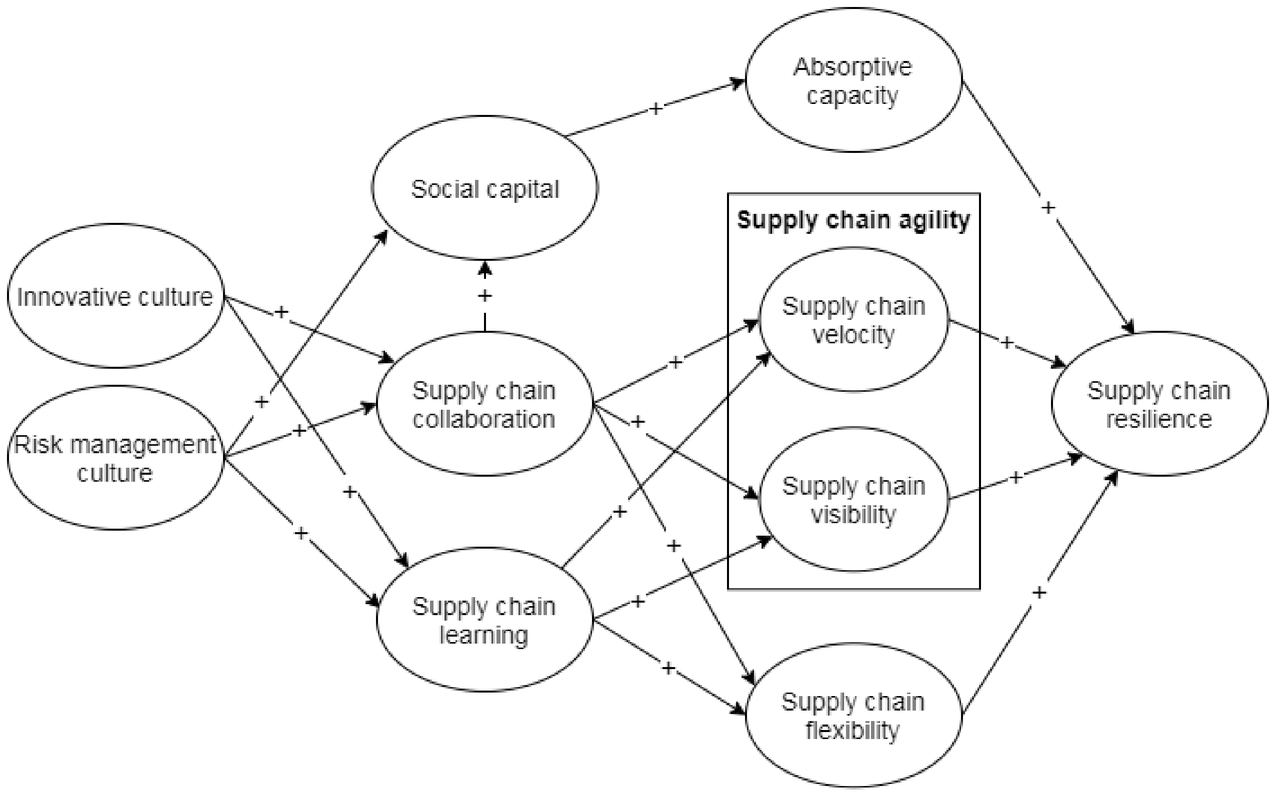

Figure 5.8: Conceptual model of Supply chain resilience capabilities (Own representation)

5.6 Conclusion

The research question posed at the beginning of this chapter is – What capabilities are required to build a resilient supply chain? After the literature review, it can be concluded that supply chain resilience is a multidimensional capability that is developed with the help of many other capabilities. Supply chain collaboration is one of the foremost of these capabilities that foster relationship and helps develop better visibility, velocity, and flexibility. Collaboration helps build resilience directly and indirectly through the mediating variables mentioned previously. Visibility and velocity are components of agility which also positively contributes to resilience.

Next, it is important to be prepared for some known and predictable risks that can occur in the supply chain. Making strategies to mitigate the effects of some risk events is also an important contributor to build supply chain resilience.

The organisational culture plays an important role in building capabilities. The encouragement of a risk management culture from the top management will encourage employees to think from this perspective as well and contribute to building better resilience capabilities. Similarly, an innovative culture is also found to be useful. An innovative culture gives more freedom to employees and the organisation experiments with radical and new methods to solve problems. An out-of-the-box approach is encouraged at all levels in the organisation. These factors can also contribute to better resilience capability.

Collaboration in the supply chain builds its social capital which can also lead to improved resilience. And lastly, an organisation can only improve its competencies if it learns from unexpected events that happen either within the organisation or outside it. Learning capability is also argued to be an antecedent of resilience capability.

A list of all the different types of enablers of supply chain resilience is given in Table 5.3. It is to be noted that these were uncovered as a result of the literature review and effort has been made to uncover everything possible.

Table 5.3: Summary of supply chain resilience enablers

Antecedent	Author
Supply chain collaboration	Christopher and Peck (2004), Wieland and Wallenburg (2013), Scholten and Schilder (2015)
Visibility	Christopher and Peck (2004), Scholten and Schilder (2015)
Velocity	Christopher and Peck (2004), Scholten and Schilder (2015)
Flexibility	Christopher and Peck (2004), Scholten and Schilder (2015)
Agility	Brandon-Jones et al. (2014)
Risk management culture	Christopher and Peck (2004)
Innovativeness	Gölgeci and Ponomarov (2015)
Mitigation processes	Scholten et al. (2014)
Learning	Scholten et al. (2019)
Social capital	Gölgeci and Kuivalainen (2020)

Chapter 6 <u>DATA COLLECTION AND ANALYSIS PROTOCOLS</u>

So far, the work that has been carried out in this thesis has been theoretical. From this point onwards, the data gathering process starts which helps us to answer the remaining research questions posed in this thesis. As this is a qualitative case study, there is a need to gather data from different sources. This research is classified as a case study in Chapter 2. According to Yin (2018), a case study can perform data collection by utilising any combination of the six sources: documents, archival records, interviews, direct observation, participant-observation and artefacts.

In this thesis, data is gathered through interviews and documents of organisations that are published online. Other forms of data collection are not suitable for this study. Archival records and artefacts are more useful in historical event analysis. Observation of organisational activities could have provided useful insights, but it was not possible to have appointments with the companies and being in the middle of the COVID-19 pandemic made this unfeasible.

The primary source through which data is gathered for this thesis is through personal interviews with professionals working in the chlor-alkali industry. Interviews provide rich qualitative data. Moreover, data was also gathered from secondary sources like company reports, consultancy reports, and other publications from the internet. This data is analysed, and conclusions are drawn for further review.

This chapter discusses the procedure used for collecting and analysing the data. The first section of this chapter deals with conducting interviews for data gathering. The next section deals with collecting secondary data and then the procedure for data analysis is discussed. Then the data gathered is analytically summarised and some themes are drawn. By analysing the collected data, the answer to sub-research question 3 is attained - How does Industry 4.0 implementation influence supply chain resilience, in the context of the chlor-alkali supply chain?

6.1 Interview

Data can be gathered primarily by many methods-questionnaire, interview, observation, and experiment to name a few popular methods. Sometimes, more than one method can also be employed in a single study which makes it a mixed-method study and lends more robustness to the results.

Due to the qualitative nature of this thesis, the interview was best suited to interact with professionals who could understand the objectives of this study and provide the required data. Through interviews, it is possible to have detailed discussions and explanations with interviewees. There are some weaknesses in the interview method as well.

The respondents may withhold information or not reveal the full extent of information. There is a chance to display bias by the interviewer due to poorly framed questions. Then, non-verbal cues cannot be interpreted if the interview is over an audio call. The interviewee does not participate due to identity anonymity. Some measures were taken to overcome these weaknesses that together with the method and procedure followed for obtaining the primary data is explained in the following sections.

Due to the ongoing COVID-19 pandemic, it is not encouraged to visit companies directly and remote working procedures are encouraged. Hence, the interviews were planned through online video calling platforms like Skype, Teams etc. This method offers convenience and assures safety during the time of a pandemic. Other than this, an interview can also be conducted over a phone call. But it does not offer the advantages of having a face-to-face conversation with the interviewee. So, whenever possible, interview through online video call will be insisted with interviewees.

6.1.1 Structure and format

There are three types of interviews: structured, semi-structured, and unstructured. The main difference between the three types of approach is the level to which the interviewer is prepared with the order and questions to be asked to the respondent. In a structured interview, all the questions are known beforehand and there is no deviation from the interview protocol. In contrast, with an unstructured interview, the interviewer asks very broad questions to address a problem area and tries to listen very keenly to the respondent and try to analyse and probe with further questions. Once the interviewer has formed a general idea on the problem, then a structured interview format can be developed to explore the problem with more interviews.

There is a third type of interview that is much used by many researchers conducting case studies and it is the semi-structured format. I observed that it is used in many studies in the literature of supply chain resilience (Scholten et al., 2014; Scholten & Schilder, 2015; Scholten et al., 2019; Ralston & Blackhurst, 2020). It has characteristics of both structured and unstructured interviews. Researchers typically use it to loosely bound the interview protocol with questions but when the interviewee responds with a new dimension or reveals new factors, that can also be explored with further probes by the interviewer. Thus, a semi-structured interview was designed for data collection in this thesis mainly due to the flexibility that it offered.

The interview was conducted in two rounds to build trust with the respondent and to put them at ease. This will help them to give accurate information and try to reveal the maximum possible that will be useful for this thesis. The general flow chart for conducting the interview is given in Figure 6.1. The steps involved in data collection are explained below.

Contacting respondent: The eligible respondents from the chlor-alkali industry are contacted and their permission is sought for collecting data. It is decided to contact operations professionals who have a broad interpretation of the operations in the whole supply chain. The details of the interviewees are discussed in the next section.

Sharing study details: A short document is shared with them via email to brief them about the objective of the study. An additional document regarding 'Informed consent' is also shared with them to get prior consent for audio recording the interview. The document containing thesis details is in Appendix B and the informed consent form is in Appendix C. Getting the consent of the interviewee was very important to proceed with further data collection.

Introductory call: A one on one introductory call with the respondent was first held where there was a discussion on how to proceed and what to expect with this study. There was a chance to have an informal conversation about each other's background which helped establish a good rapport with the respondents. At the end of this introductory call, a brief discussion took place regarding the supply chain. The questioning protocol of the introductory interview is in Appendix D.

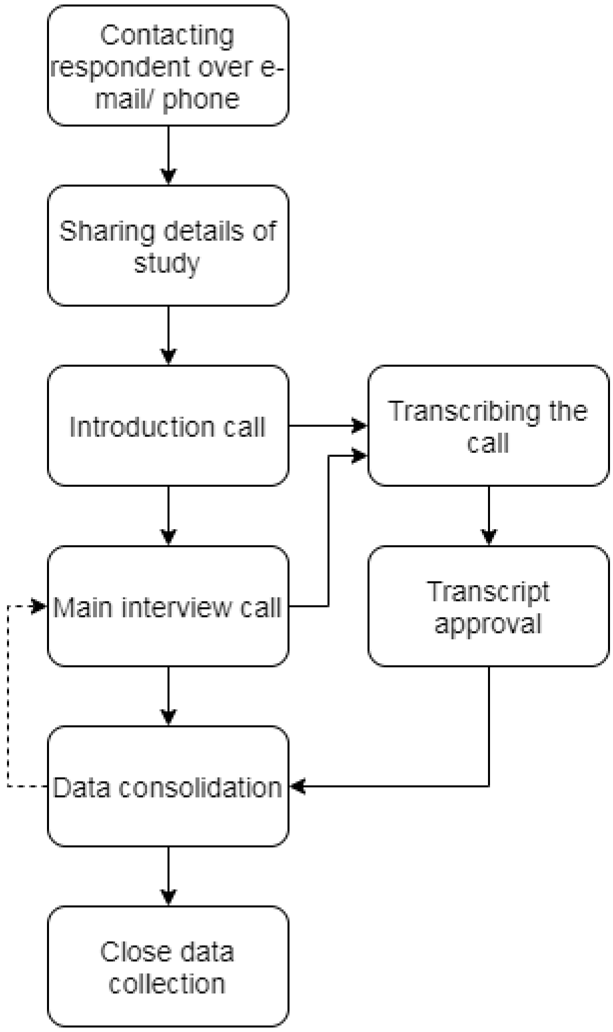

Figure 6.1: The interview protocol

Interview call: This is the main step where the data for the thesis is collected. The interview took place online at a time fixed beforehand. A protocol was developed regarding the line of questioning to be followed during the interview. This protocol is available in Appendix E. Before the interview, a detailed information sheet was shared with the respondent that is shown in Appendix F.

At the beginning of the discussion, the respondent was briefed about the organisation of the data collection. The interview was broadly divided into three parts. The respondents were informed when the discussion moved from one part to the next. The first part of the interview discussed the influence of using Industry 4.0 on the organisation and how it affected supply chain resilience. The second part of the interview discussed the risks generated due to the usage of Industry 4.0 and what steps were taken to mitigate them. The last part discussed the operationalisation of supply chain resilience.

Transcription: Immediately after conducting the interview, the contents were converted into a transcript that would be used for data analysis and further interpretations. The recorded conversation was used in constructing the transcript. In case the permission to record was not granted by the interviewee, then notes were taken during the call they were converted into a transcript.

Once the transcripts were ready, they were sent to the respondent for checking the contents and making the necessary revision, if needed. After the approval of the respondent, the transcripts were anonymised and the names and details that could reveal the identity of the respondent were removed from the document.

Data consolidation: While analysing the data for this thesis, there was a need for additional data requirement as some gaps were found and these were discussed with the respondents through email and correspondingly, the transcripts were also updated. Once all the data consolidation was completed, then the data collection was stopped.

These anonymised transcripts are uploaded in a separate file into the repository for further reference. Planning and conducting the interview was one of the most challenging areas that I worked on during this thesis. More details about the difficulties are discussed in the final chapter in the Reflection section.

6.1.2 Details of interviewees

To preserve the anonymity of the respondents, their names are not revealed anywhere in this document. Instead, their names are replaced with alphabets. The interviewees were selected based on their knowledge about the chlor-alkali production process and their experience of the entire supply chain operations involved. The interviewees thus had a very sizeable experience in the chlor-alkali industry.

It was very important to search for possible interviewees and try to convince them to participate in this research work to provide data. Although I knew the companies to contact for making it to the right persons, I found it very difficult to convince professionals to participate in my thesis. One main reason for this is the language gap with companies outside the Netherlands. It was tough to speak with professionals in English. Next, due to the COVID-19 pandemic, many offices were closed, and employees were working from home. Despite this, I was able to gather two respondents who were willing to participate in my study. Their details are given below.

It is to be noted that both the respondents are not currently working in the chlor-alkali industry. Both respondents previously worked at Nouryon (previously known as AkzoNobel Speciality Chemicals). Respondent A is still acquainted with the chlor-alkali industry in a representative organisation whereas Respondent B is currently working at another chemical organisation.

Table 6.1: Details of interviewees

Interviewee name	Mode of discussion	Data capture	Interview type	Interview date	Interview duration (min)
Respondent A	Online voice call with audio recording	Audio recording	Introduction	18.06.2020	35
			Main	16.09.2020	40
Respondent B	Online video call without recording	Note making	Introduction	14.08.2020	40
			Main-1	08.09.2020	50
			Main-2	20.10.2020	45

Throughout the thesis, I have been trying to contact prospective respondents. I have spent at least a day in a week trying to contact companies. But due to the reasons cited above, I was unable to convince and include many respondents in my study.

6.1.3 Measures taken for improving the validity

As discussed in the previous section, using interviews as a method to collect data also has its weakness. Some measures were taken to improve their validity and to try to harness their potential to the best possible level. They are discussed below.

Conducting interviews in parts: The time needed to conduct interviews can run up to a total of 90 minutes if conducted in one sitting. Conducting an intensive activity for a long duration can be draining for both the interviewer as well as interviewee. There are high chances of obtaining data that is not accurate and deviating from the main line of inquiry.

Thus, it was conducted in parts. Both respondents gave interviews in two sittings each. The first sitting was only a very general introductory call to get to know each other and a broad discussion about the organisation and supply chain in which they worked. This also has the added advantage of gaining trust with the interviewee through open communication and interaction on a general topic.

Interviewer preparation: A lot of training and preparation is required to conduct interviews (Yin, 2018). Only then, the interviews can proceed smoothly, and the required data can be collected. Before conducting the interviews, I prepared the outline, topics and questions to be discussed beforehand. Advanced preparation allowed me to stay calm before and during the interview call. I prepared opening statements, briefings, and talking points as well so that I do not lose precious time and try to explain the interviewee in the best manner possible. I jotted down a rough order to guide the discussion in my notepad and tried to steer the call in that direction. Most importantly, I had to listen very intently to what the interviewer was saying and try to process that to ask further probes. In conclusion, having high levels of advanced preparedness helped me gain confidence that was needed to conduct interviews and manage the data gathering activity in a short period.

Interviewer bias: This is a major point that I had to address during my preparation phase. As I have a background in chemical engineering and have worked in engineering roles in plants, I am acquainted with the core processes that are carried out. I am aware of the difficult areas to deal with. In other words, I have some preconceived notion about the implementation of Industry 4.0 technologies in a chemical plant. The challenge was to use my knowledge to improve my questioning techniques, sense gaps in the respondent reply but not introduce a bias in my questioning technique as this will hamper the validity of the results.

This was a challenging avenue that I faced while preparing for the interview. The simple and straightforward strategy that I followed was to concentrate on the dependent variable of this study i.e. supply chain resilience. I found that focussing too much on Industry 4.0 technologies has the potential to introduce bias into my questioning. In hindsight, I also found this to be true. Another strategy that I followed is to exhibit patience while formulating the question to the respondent. It helps to have unbiased questions readily formulated on the screen so that it can be readout. With all this justification, preparation is an important requirement to carry out interviews.

Confidentiality: The interviewees are working in organisations and may sometimes feel reluctant to voice personal opinions in interviews which may be against the organisational rules. So, their identities are not revealed in this document and their contributions are anonymised. This will encourage the interviewees to share more information freely.

6.2 Secondary data

As a secondary source of data, documents and reports about the usage of Industry 4.0, smart manufacturing system and their usage in the Chlor-alkali industry were retrieved and analysed. According to Yin (2018), documents can provide a rich source of data providing very accurate information. But their main weakness is that they are difficult to find from the internet. There may be some useful internal documents, but their access is restricted due to their confidentiality. The interviewees discussed in the previous section were requested for some internal documents, but nothing was shared by them as they were no longer affiliated with the chlor-alkali industry anymore.

It is advised by Yin (2018) to use data from the documents carefully for a case study. It is better to use the data to corroborate the findings from the interview rather than an independent source. So, in this thesis, it is tried to rather corroborate the data from the documents along with the data from the interview findings.

The search procedure used to obtain these documents is as follows. The list of chlor-alkali organisations was known from Eurochlor. The websites of these companies were visited and searched for terms like Industry 4.0, smart manufacturing, and smart supply chain. The search results were checked for relevant documents and they were collected for further use.

6.2.1 List of data gathered

In this section, the documents that have been gathered as a part of secondary data collection are listed below in Table 6.2.

Table 6.2: List of Secondary data

S.No.	Data type	Title	Author/Creator
1.	Webpage	Building the chemical factories of the future	Marco Waas
2.	Video	Creating the factories of the future: Industry 4.0 at Nouryon	Nouryon
3.	Webpage	Chemistry 4.0 – sustainable and digital	BASF
4.	Webpage	Nouryon to use digital technology from Semiotic Labs to boost plant reliability	Nouryon
5.	Webpage	Smart manufacturing	BASF
6.	Video	Smart Manufacturing at BASF	BASF

6.3 Data analysis

In this section, the methodology used to analyse the data obtained so far is discussed. This is a critical step in this research and the result of this analysis is discussed in the findings section subsequently.

For conducting a qualitative case study, as per the guidelines stated by Yin (2018), it is necessary to have an analytical strategy to examine the data and use it to find the answer to the study's research questions. Yin (2018) suggests using qualitative analysis software to assist in looking through the data. However, in this thesis, I have not used any software to assist with the analysis. The main reason for this is the limited amount of qualitative data dealt with in this study. As discussed previously, the bulk of qualitative data comes from interviewing two respondents and there are some additional supporting secondary documents. It is more efficient to handle this data manually without using the software.

The strategy used to examine the data is one suggested by Yin (2018) which is trying to build up the theory from "ground up". This is an inductive strategy in which researchers try to look at the data as it is and build theory from it without having any prior ideas or propositions.

A generic procedure used for analysing data in this thesis is given in Figure 6.2.

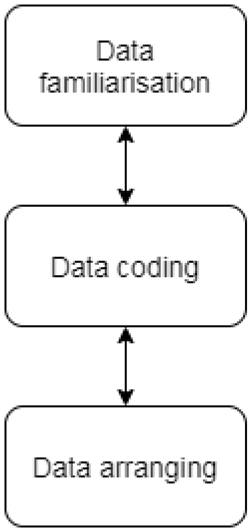

Figure 6.2: Procedure used for data analysis

Familiarising: It is important to read through the data first and get to know the full contents of the interviews and secondary data as well. This is useful in knowing the total breadth of the data and the 'spread' of the various items discussed within.

Coding: Once the data is familiarised, it is examined again trying to translate the existing data into terms relating to the concepts in this thesis (like automation, Industry 4.0, supply chain resilience etc.). The explanation of the respondent is examined and the method in which they relate the concepts is noted separately in another document. In qualitative research, this is essentially referred to as data coding.

Arranging: After obtaining the codes, they are examined, and it is tried to match these codes into a pattern that explains the research problem at hand. They are further categorised into appropriate categories. In this case, they have been categorised by the manner with which they affect supply chain resilience capabilities.

These three processes are not done just once in a sequential manner, but it is done multiple times cyclically to reveal and highlight new themes. In my observation, the more the iterations with which the data was analysed from various perspectives, the clearer the interpretations became. Some of these perspectives are looking at the data as is, trying to find explanations for the research questions, and trying to check for good practices that can be recommended to the industry.

Some examples of data coding from the transcript are given in Table 6.3.

Table 6.3: Examples of data coding from transcripts

Transcript	**Code**
"Our chlorine consumers dictate our production rate. So, if they go down, we go down and if they go up, we go up" (Respondent A, 2020a)	Close link with chlorine consumer plant
"Yeah, so chlor-alkali is at the start of a huge amount of chemical products, you cannot imagine where chlorine, caustic or hydrogen is involved. So, when you look through, where all the major outlets of chlorine and caustic are. And then you see it's really, on, on the, on the start of everything" (Respondent A, 2020a)	Huge downstream supply chain to chlor-alkali
"the whole problem is that we produce three products in one step. So, if there is a problem is one of the chlorine customers we also produce caustic, less caustic and less hydrogen, so also those consumers are affected. So, it's always a chain effect" (Respondent A, 2020a)	Chlorine production bottleneck
"Electricity is our main raw material. So, when there is lack of electricity, we have to tune down our chlorine production as well" (Respondent A, 2020a)	Fast response to electricity grid
"Looking to caustic over the last years, we are connected with the biggest customers and their storage tanks in order to keep a certain level in their storage tanks. So, our logistic chain… is steered based on the consumption, and the desired levels of storage at our customers" (Respondent A, 2020a)	Direct connectivity with caustic consumer
"When you look at Industry 4.0, it goes to more than just logistics and production, sometimes, for very critical equipment in our installation, we are connected to maintenance service organisation" (Respondent A, 2020a)	Using Industry 4.0 for equipment maintenance and monitoring
"In my opinion, resilience is not an independent phenomenon, but rather it should be related to sustainability. This sustainability is not the one related to environment (people, planet and profit) but rather the longevity of the business" (Respondent B, 2020b)	Resilience required for business longevity
"On a more general note, these (Industry 4.0) technologies were implemented with a purpose to reduce some manpower requirement and essential safety functions – the process is too fast for humans to control it well and needs a high level of automation to stay safe" (Respondent B, 2020b)	Priority for safety, Critical processes automation

Transcript	Code
"Well, in the occurrence of a risk event, there is a drastic drop in demand, as I said earlier. The forecasting mechanism totally fails in this context. It cannot recognise the drop in demand and the system still predicts a normal range of demand" (Respondent B, 2020b) "… most of the prediction systems built today are predicting at a monthly or quarterly frequency. They cannot pick up events that have happened recently. By the time this is picked up, it is already too late, and we might be well into the recovery phase" (Respondent B, 2020b)	Failure of prediction
"During occurrence of a risk event, humans are the component that can adapt faster than programmed machines" (Respondent B, 2020b)	Employee adaptability
"If due to some reason, the automation system fails, then there is a practiced plan B in place that helps with the process continuity" (Respondent B, 2020b) "You must train the people about what the automation system is doing and what they are still able to do when certain things fail. So, to help in this, we try to fake an incident of system failure and train them how to bring back the system to life" (Respondent A, 2020b)	Employee training, Failsafe requirement, Continuity planning, Recovery capability

6.4 Dynamic Capabilities Theory

Throughout this analysis, the phenomena and relations encountered have been analysed from the lens of dynamic capabilities theory (Teece, Pisano, & Shuen, 1997). This is one amongst the many theories about strategic management in an organisation to attain competitive advantage. This section discusses the theory briefly and motivates its usage.

This theory is found to be well suited to the analyses undertaken in this thesis. The Dynamic Capabilities theory tries to explain how organisation attain competitive advantage in times of turbulent technological changes in the environment. The latter point mentioned about technological change is to be noted here. In this thesis, the adoption of Industry 4.0 technologies is considered.

The theory postulates that the competitive advantage of a firm depends on their assets, the path they have endured and the unique way their internal processes are arranged. Additionally, it is postulated that organisations possess dynamic capabilities to gain competitive advantage. The term dynamic signifies that competencies are renewed with fluctuating business environment and the term capabilities signify the role of strategic management to adapt resources, competences, and skills to match the changing environment.

In this thesis, Industry 4.0 machinery is a resource that is at the disposal of the focal organisation. Supply chain resilience is the dynamic capability that is to be studied due to the adoption of the resource. Organisational routines and competencies are developed with the usage of Industry 4.0 and uncovering how these ultimately affect the dynamic capability is the essence of this study. This relationship is represented in Figure 6.3.

Supply chain resilience is considered as a dynamic capability of an organisation in other studies exploring its antecedents (Sabahi & Parast, 2019; Scholten et al., 2019). This gives additional motivation to use this theory. It is not be noted that this theory and its mechanisms are not mentioned explicitly in the main text of this thesis but the terms like resources, capabilities will be used often.

Figure 6.3: Dynamic Capability theory (Teece et al., 1997)

6.5 Conclusion

In this chapter, the protocols used for data collection were discussed. A general game plan was devised for conducting interviews. The importance of preparation for conducting interviews has been explained in this chapter. The interview was scheduled over two appointments with the respondents. The first appointment is a general introductory call and the second call consisted of the main interview. This was done to establish rapport with the respondents which will make them share data more willingly. Initially, data was to be gathered from about five respondents but due to the COVID-19 pandemic, it was tough to contact companies and convince employees to participate in the interview. So, only two respondents were interviewed.

After primary data collection, secondary data was collected that could be used to support and corroborate the primary data collected. These documents and pieces of evidence were mainly collected from company websites.

After the collection of data, it was to be analysed to get meaningful results and answer the remaining research questions. An analytical procedure was devised as suggested by Yin (2018) to examine the data and try to uncover themes. A simple procedure was devised consisting of three steps-data familiarisations, data coding, and data arranging. These steps were done cyclically, and it was necessary to move back and forth rather than a linear fashion. The data is analysed from the lens of the dynamic capabilities' theory.

The results of the data collection are discussed in the next chapter.

Chapter 7 LEARNING POINTS AND STRATEGIES

This chapter aims to answer sub-research question 3 and the main research question posed in this study. They are reiterated in the orders mentioned.

> *How does Industry 4.0 implementation influence supply chain resilience, in the context of the chlor-alkali supply chain?*
>
> *How can Industry 4.0 be used to improve supply chain resilience, in the context of the chlor-alkali supply chain?*

The questions will be dealt with in the order that they are mentioned here. The findings of the data collection and analysis are summarised first, and they are examined from the perspective of sub-research question 3. Next, some overarching themes are derived from the data and their importance is discussed from the context of the main research question. Some recommendations are drawn from these themes and they are meant to be incorporated into the discussions leading to the implementation of Industry 4.0 within chemical organisations.

7.1 Findings of data collection

The chlor-alkali industries are very large-scale production industries that undertake chemical processes at high throughput rates. The scale of operations was discussed in Chapter 3. At such fast speeds, it is important to respond to process changes very quickly. It is not always possible for humans to have such a fast response speed; thus, the use of sensors and automation have been prevalent in the chlor-alkali industry for the last few decades. Even with Industry 4.0, chlor-alkali organisations have been at the forefront of adopting these technologies to make their manufacturing and supply chain processes more efficient and safer. Some applications of these technologies are discussed in this section and insights are drawn from them.

The findings from the data collection can be categorised into two broad categories. The first type involves disruptions to the material flows within the supply chain and operations. The second involves unexpected and unforeseen high impact disruptions (like an economic depression or COVID-19). Each of these categories is discussed hereafter.

7.1.1 Disruptions within the supply chain

7.1.1.1 Production process

The chlor-alkali supply production runs continuously and is a very large-scale production unit. Such an entity requires continuous monitoring of several key parameters by operators and action needs to be taken for any changes in the parameters (like temperature, pressure, flow, tank levels etc.).

If any parameter change is not noticed and left unattended, there is a chance that this can lead to a breakdown of the whole production unit and the worst case is it can cause chemical disasters that affect not only the plant but also immediate surroundings and cause damage to biodiversity.

Thus, the importance of process control is very high, and many automated controls are installed in place that gathers readings continuously and monitors the status of the process. The chlor-alkali industry has achieved a high level of sophistication in the automatic operation of the plant with the application of Industry 4.0 technologies. The usage of equipment interconnectivity to achieve a self-standing CPS is very evident (Respondent A, 2020b; Respondent B, 2020c).

The most challenging processes in a plant are the start-up and stoppage. Many processes can go haywire and cause disruption or accident during the start-up and stoppage procedures. Having a smart manufacturing system helps in controlling these processes and not cascading the disruption further. BASF uses a digital checklist to verify the statuses of equipment and maintenance in the plant. This way, all data is centralised and none of the important things is left unchecked. This verification is carried out by employees taking field rounds and entering the status of the equipment in their handheld tablets (BASF, 2017).

It should be noted here that the main objective to install sophisticated control systems is to improve process safety and prevent chemical accidents. But, efficiency improvements, data analytics, and decision making are added benefits of having a CPS based production system. Establishing this system has a positive impact on resilience. When using this system, the changes in plant parameters are monitored and controlled more effectively and they are not allowed to go out of control. This supports the plant to run continuously with improved reliability levels and lesser chances of operational disruption.

7.1.1.2 Raw material availability

The system is also designed to be responsive to disruptions in raw material availability. The production of chlorine and caustic is done through electrolytic cell process and electricity is a main raw material to carry out this electricity process. It singlehandedly contributes to about 50% of production costs. The production is dependent on the electricity available in the grid. In the case of electricity shortage, the production process also has to be slowed down accordingly (Respondent A, 2020b). Sudden failure of the grid and total power outage can disrupt the production process which needs to be halted immediately. With the availability of Industry 4.0 based control system, the electricity usage is streamlined.

The availability of grid power is continuously monitored and the production process is tuned accordingly so that the process requirements are met (Respondent A, 2020b). The manufacturing system also helps when there is a total loss of power from the grid by bringing the production process to a safe halt (Respondent A, 2020b). The production process is sensitive concerning electricity because it cannot be stored in huge quantities and it is to be used as and when available. Recently, Nouryon has implemented an inhouse technology called 'e-flex' that not only helps optimise the grid power but also exploits any chances when there is excess power availability in the grid which saves money for the company (Nouryon, 2019; Waas, n.d.).

Like Nouryon, even BASF has implemented a similar process to manage energy requirements. At the Ludwigshafen site in Germany, BASF has a large chemical manufacturing complex that makes many chemicals including chlor-alkali. There are three power plants on-site to provide the required steam and electricity. In addition to this, they also purchase electricity from the grid. So, whenever there is a shortage, they purchase electricity and in times of excess production, they sell it back to the grid. Trading in the electricity market is critical as prices change every fifteen minutes and decisions need to be made quickly. To facilitate this, they built a big data analytics-based tool that forecasts steam and power requirement, checks previous data sets, checks current market conditions, and decides about selling or buying energy (Hellmann, 2019; BASF, n.d.). The accuracy improved by up to 60% for predicting steam requirements when using the big data-based system.

Other raw materials are used in the chlor-alkali production process. They are water and salt. Unlike electricity, these can be stocked up, and their levels can be monitored. In case of disruption of the supply of these raw materials, it does not translate into an immediate disruption for the production process. It can continue till the stock in hand is depleted and then the stoppage can be planned.

7.1.1.3 Products storage and distribution

Next, the discussion continues about the downstream requirements. There are two products- chlorine and caustic. As discussed in Chapter 3 describing the chlor-alkali industry, for safety reasons, chlorine is delivered to the customer directly through a pipeline. There is no large intermediate storage of chlorine. Whereas, caustic is stored after production and delivered to customers based on their order requirements.

In other words, the chlorine stream is critical to the whole chlor-alkali production. Any disruption to the chlorine stream will spread throughout the supply chain like a ‘snowball effect’ (Respondent A, 2020b). It is necessary to coordinate between both the chlorine producing and consuming plants. The production systems of these two plants are indeed highly connected and coordinated. The status of the chlorine plant can be monitored downstream and vice-versa. If there is a disruption at either of these plants, it is communicated at the other plant and processing speed is adjusted automatically. These activities take place with minimal human interaction. Sometimes, these plants may be from different organisations but still, they are connected.

Similarly, even for caustic users, there are automatic provisions available. Caustic is delivered to customers by road, rail or even waterways. For example, the caustic tank level at the customer site is shared with the chlor-alkali producer. Contracts are worked out with two parties which state that the tank is to be maintained at certain fixed levels. But the rate of consumption of the customer can vary and it is tough to predict the tanker requirements. Thus, the two parties at the different organisations communicate their plans with each other so that they can deliver the required tankers which aid the tanks to be maintained at pre-agreed levels.

In the case of chlorine distribution, the system is designed to be more flexible and responsive to the downstream requirement. Both plants also have better visibility to each other. So, it affects supply chain resilience positively. In the case of caustic, there is only visibility of the customer inventory. This also improves resilience but lesser than that of the chlorine stream.

7.1.1.4 Equipment maintenance and monitoring

In the production, the performance condition of critical equipment is important to perform at a consistent level. The failure of this equipment sometimes means halting the process and replacing the equipment to continue with production. This equipment can vary from pumps, motors, membranes etc. The health of this equipment can be monitored by measuring the performance by fitting them with sensors provided by the vendors.

In the chlor-alkali production, membranes are critical in the production process and damage to them results in operations stoppage and losses as well. According to Respondent A (2020b), these can be monitored remotely by the vendor by connecting with them and transmitting the data to them on a real-time basis. This enables the equipment health to be monitored continuously and the vendor can notify the focal firm in case it detects any anomalies from the readings. Technologies like IoT help in transmitting the data and Big data analytics helps decipher the data. Thus, having this information in advance helps to undertake a planned maintenance activity rather than an unexpected breakdown. This is used to monitor much critical equipment in the chlor-alkali plant.

This system has also been implemented recently at the Ibbenbüren chlor-alkali plant of Nouryon in Germany. This monitors the status of the equipment continuously and predicts the upcoming maintenance needs for equipment like pumps, compressors, and conveyors. This prevents unexpected interruptions and improves the reliability of the plant (Nouryon, 2020).

This ability has a positive influence on resilience as it improves the preparedness and visibility of the organisation towards possible disruptions.

7.1.1.5 Connectivity in the supply chain

The chlor-alkali industry is connected to the salt industry upstream and to immediate consumers of chlorine and caustic in the downstream. There was no evidence for further connectivity in the supply chain wherein the activities and stocks of companies further downstream can be known. The downstream customers' customer does not have a significant effect on the chlor-alkali production process.

The chlorine customer is geographically close to the chlor-alkali industry and there are only a limited number of consumers for a single producer whereas there are many customers for caustic consumption. Switching suppliers for caustic is very simple whereas switching suppliers for chlorine is not possible in most cases (Respondent A, 2020b).

As discussed previously, the chlor-alkali plant and the downstream chlorine consumer are closely connected such that any disruption in one plant that causes a slowdown is communicated to the other plant instantaneously and a slowdown is initiated there as well.

With the data gathered from Respondent A (2020b) and Respondent B (2020c), it can be inferred that a disruption in second-level customer does not have a significant effect on the production of chlorine and caustic. Moreover, the supply chain downstream expands so broadly that it is not possible to connect with every customer and their customer as well. So, it is more feasible to stay connected only with large customers. From this, it is inferred that the usage of smart supply chain technologies is limited to large customers of the supply chain.

Thus, the improvement in resilience is only observable in the limited context of immediate upstream and downstream partners. A further level of supply chain connectivity is not observed formally due to the sheer magnitude of customers downstream.

7.1.2 Disruptions outside the supply chain

This section discusses the disruptions that originate outside the supply chain. These can include events like a terrorist attack, cyber-security compromise, getting hacked, and even unique events like COVID-19.

In scenarios like these, the applicability of Industry 4.0 to mitigate the risks is quite limited. Industry 4.0 can lead things astray. In a discussion with Respondent B (2020a), it was uncovered that in a situation like COVID-19 pandemic, there is a quick change in consumption patterns of customers which brings about changes in product requirements. But in this situation, the sales prediction system cannot recognise this and will make inaccurate demand predictions. Following these predictions will only lead to losses. Some of these systems have not been programmed to consider conditions like these. Respondent B (2020b) further points out that in the case of an external disruption, human adaptability is faster than machine adaptability. In the instance of COVID-19 disruption, the company starts to majorly conserve cash by delaying payments to suppliers, reducing stock levels, stopping all improvement projects and similar activities. In such cases, employee resilience and adaptability play a bigger role than Industry 4.0 systems.

As per the discussion with Respondent A (2020a), hacking was highlighted to be a significant risk of implementing Industry 4.0 across the supply chain and with other key partners. The data transmission takes place through the internet. The usage of the internet makes the systems more vulnerable to cyber-attacks that can cause the system to crash and bring major disruption to the organisation. Companies prefer to make the system standalone instead of connecting to the internet.

From the data gathered in this thesis, it cannot be said clearly whether the usage of Industry 4.0 technologies improves the supply chain resilience against unknown and random external events like COVID-19, terrorist attack or even hacks. On examining the data, no useful themes could be envisaged that help in answering the research question concerned. Hence, for this thesis, it is concluded that, concerning external risks, Industry 4.0 does not have a clear-cut impact. In the cases examined, the impact is either found to be nil or even negative. Therefore, due to limited evidence, this must be explored further and will not be discussed in this thesis.

7.2 Emergent themes

7.2.1 Critical area mapping

Resilience is not a single strategy used to mitigate risks in the supply chain. It is often used with redundancy as well. Supply chain redundancy can mean holding additional stocks, have many suppliers, have additional capacity etc. Examples of redundancy can be seen in this case study of the chlor-alkali supply chain.

In the case of raw material requirement, some redundant stocks are available on-site to ensure operational continuity. The same applies to the distribution of caustic to customers. It is stocked at the producer and at the customer end to ensure operational continuity.

In instances where the material cannot be stocked up, like electricity and chlorine due to practical and safety reasons, the system is designed to be more responsive and flexible to any minor deviations in availability and demand.

In other words, when the stream in the supply chain is critical, then it can be automated with Industry 4.0 to have better responsiveness, flexibility, visibility or velocity, which are the enablers of resilience. In circumstances where this criticality is not present, redundancy can be used as a major business continuity strategy. The conditions for criticality are already discussed in the literature review of supply chain resilience (Section 5.1.1.1).

7.2.2 Design and programming of the system

The system design and programming were found to be a critical factor that determined the impact of Industry 4.0 on supply chain resilience. At any time, a chemical plant needs to monitor many parameters simultaneously. A change in one parameter can lead to change in other parameters. As discussed in the previous section, these changes need to be monitored very closely and need to be kept in control. Before Industry 4.0, these were the major responsibilities of a process operator who does this manually with minimal assistance from automation.

But now, these are sophisticated systems that are capable to handle all controls on their own with very minimal human involvement. These systems consist of multiple sub-systems that are integrated. Designing this is not a straightforward task and is accomplished with the experience of the organisation with the process, identifying the limits and boundaries of each process and aligning them to attain synchronisation. It also requires dry runs and simulations with various scenarios to attain reliability.

In other words, efficiencies are gained not just with the usage of Industry 4.0 technologies but by designing a robust operating environment that uses these systems effectively and requires minimal human intervention. This is majorly achieved with the knowledge the organisation has accumulated over time by operating the plant.

Another observation regarding the design of the plant was that it is involved with reducing risks with disruptions to the material flow and the parameter control. It is not sensitive to the influence of the environment. As discussed previously, the Industry 4.0 systems are partly disabled during the occurrence of an environmental risk that affects the demand for the product. For instance, in the context of COVID-19, demand dropped quite rapidly for many firms, but their sales predictions generated from data patterns did not recognise this. So, the predictions needed to be reworked manually and the plant had to be run at a much lower capacity.

7.2.3 Enhancement of visibility and preparedness

In many of the applications of Industry 4.0 within the chlor-alkali supply chain, the improvement of visibility is seen as a major area through which resilience is improved. It can be seen in many instances in the data collected. The interconnection between the chlor-alkali plant and downstream chlorine consumer plant has been discussed previously. Both the plants can access the status of the other plant in real-time basis and whenever there is any disruption at one of the plants, it is communicated to the other plant instantaneously and it is faster than human communication.

Regarding equipment monitoring, the suppliers of key equipment can monitor the performance remotely on a real-time basis. When anomalies are detected in the data, it can be informed to the focal company immediately. Even in this instance, the supplier has real-time visibility of the focal company. And this is followed for multiple pieces of equipment with their vendors. Having these high levels of visibility gives the supply chain partners ample time to detect anomalous events and prepare against the disruption.

The effect through other resilience enablers like velocity and flexibility is observed to a limited extent.

7.3 Risks of implementing Industry 4.0

As discussed in the literature review of Industry 4.0 (Chapter 4), there are some risks with its implementation. These risks can be broadly categorised into six categories-financial, organisational, ecological, technological, IT, and legal risks. Data gathered regarding some of these risks are discussed in this section.

Organisational risk: An important reason for automating plant activities is to create lesser jobs and in turn reduce employee costs. The findings from this study are contrary to this argument. As per the argument stated by both Respondent A (2020b) and Respondent B (2020b), the implementation of Industry 4.0 does not cause job loss in the chemical industry.

The main reason for its implementation is to help employees to operate a difficult and complex process in a much simpler way and thereby improving process safety. Sometimes, due to unforeseen circumstances, even with a high level of automation, processes can go out of control and cause problems. To assure safety in such cases, a minimum number of employees are needed on-site to control the process. Thus, there is always a need for skilled employees even though processes may be automated. Moreover, it was also stated that there is no resistance from employees regarding the automation of processes.

It was also discussed regarding employee skill requirement and training regarding automated systems. Both Respondent A (2020b) and Respondent B (2020b) identified this as one of the most challenging areas when implementing Industry 4.0. Employees are continuously trained regarding these technologies-especially what it can and cannot perform. This is especially useful when there is a total failure of the automated production system. Employees are educated on how they can still control the system and try to bring the process to a safe halt.

Cyber-security risks: Although Industry 4.0 can be used to connects with many partners across the supply chain, these connections outside the organisations require internet usage which makes the risk of hacking higher. While interviewing both the respondents, this risk was pointed to be very high. Due to this, many companies prefer to design these systems as a stand-alone equipment. Planning against the cyber-security threat is an important precursor to Industry 4.0 usage.

Regarding other risk categories, no significant information was uncovered.

7.4 Conclusion

At the outset of this chapter, two research questions were posed that were dealt with in this chapter. Regarding sub research question 3, this thesis states that the implementation of Industry 4.0 has a limited positive effect on supply chain resilience. This positive influence is seen with context to operational risks. Operational risks are divided into five scenarios- production process control, raw material availability, product storage and distribution, equipment maintenance, and supply chain connectivity.

The conditions by which this affect resilience is summarised in Table 7.1 below. The tick symbol represents a positive influence whereas the hyphen represents no significant relationship.

Table 7.1: Influence of Industry 4.0 system on resilience enablers

Disruption area/ Resilience enabler	Visibility	Velocity	Flexibility	Responsiveness
Production control	✓	✓	-	✓
Raw material availability	✓	-	✓	✓
Product storage and distribution	✓	✓	✓	✓
Equipment maintenance	✓	-	-	-
Supply chain connectivity	✓	-	-	-

By having a production system equipped with Industry 4.0 technologies, if there is any disruption in the plant parameters, it is known immediately and acted upon before human detection. It leads to better visibility, velocity, and responsiveness. Regarding raw material availability, electricity is the most crucial raw material, and any fluctuation is immediately detected, and acted upon, thus providing with better visibility, flexibility and responsiveness.

Regarding disruptions that originate from outside the supply chain, it is not exactly clear whether Industry 4.0 is useful in mitigating their effects. From the limited findings of this thesis, it is concluded that Industry 4.0 does not influence supply chain resilience against risks external risks of the supply chain and sometimes they also have a negative impact. In these circumstances, it is up to the employees of the organisation to come up with coping strategies to mitigate the risk.

Next, regarding the main research question on how to use Industry 4.0 to improve resilience, a 3-way framework is proposed that is shown in Figure 7.1.

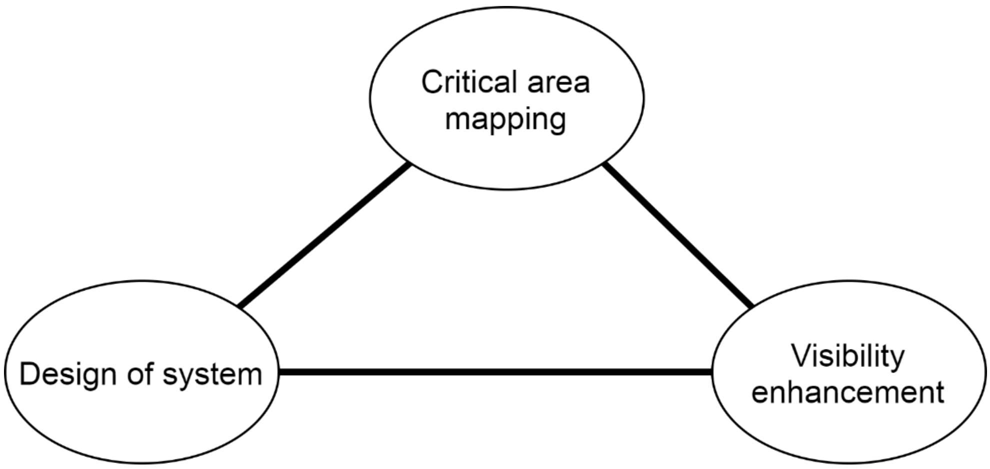

Figure 7.1: The proposed three-way framework

From the above findings, now it is possible to arrive at strategies to improve resilience when implementing Industry 4.0. Some of the criteria that are investigated when evaluating Industry 4.0 are as follows.

Firstly, it is always necessary to find a balance between using resilience and redundancy strategies in the supply chain. Both have their own merits and demerits. A general guideline that can be suggested is the usage of resilient systems in critical areas where safety and fast responsiveness is required and redundancy in non-critical areas where safety is not a key issue and response need not be as fast.

Secondly, the design of the system is very critical and when it is badly designed without taking all parameters into account, it does not impact resilience positively. The design needs to be made so that it is flexible to future capacity requirements and can be modified for other reasons at a later stage. It also depends on the knowledge accumulated by the focal organisation.

Lastly, Industry 4.0 technologies can be used for mainly improving the visibility in the supply chain by improving the real-time communication capability. This makes the supply chain detect supply chain disruptions and take necessary action for mitigation.

Usage of Industry 4.0 systems have many advantages, but *contingency planning* must be done for the total failure of the system. For this, employees need to be trained continuously on how to operate even when there is a failure. It is most important to envisage different scenarios and train employees by simulating different failure situations. Moreover, employees need to be trained regularly about the system. Actions also need to be taken for cyber-security threats.

Chapter 8 RESEARCH CONCLUSION

In this thesis, the influence of Industry 4.0 implementation on supply chain resilience was studied. Due to the explanatory nature of questions, a case study protocol was chosen to undertake this thesis. The 'case' being studied here is the usage of Industry 4.0 technologies in the chlor-alkali supply chain.

The literature of the concepts was reviewed, and a conceptual model of Industry 4.0 and supply chain resilience was drawn. To help answer the main research question, data was primarily gathered through conducting interviews with two professionals from the chlor-alkali industry. Supporting data was also gathered through websites and reports of chlor-alkali companies.

The research questions framed at the outset of this thesis are reiterated and their brief answers are also mentioned.

How is Industry 4.0 implemented in manufacturing industries?

From the manufacturing perspective, Industry 4.0 consists of a group of technologies that are applied in the organisational processes and make it more safe, autonomous, and efficient. The technologies that are preferentially adopted by companies are – Cloud computing, IoT, ERP, Big data analytics, and CPS. By using a combination of these technologies, organisations establish smart manufacturing and smart supply chain protocols which enable the operations to become more autonomous.

Organisations and their supply chains also face risks and challenges to implement these technologies. The risks due to the implementation of Industry 4.0 are categorised into financial, organisational, technological, IT, ecological and legal risks.

What capabilities are required to build a resilient supply chain?

Supply chain resilience is a multidisciplinary and multidimensional concept. Building supply chain resilience ensures that even unknown and unforeseen risks can be mitigated effectively and efficiently. Of all the necessary drivers, supply chain flexibility, visibility, and velocity are found to be the key constituents. These are in turn driven by collaboration, learning, and social capital within the supply chain. These are fostered with a risk management culture and innovative culture within the supply chain.

How does Industry 4.0 implementation influence supply chain resilience, in the context of the chlor-alkali supply chain?

From the proceedings of this study, it can be concluded that the implementation and usage of Industry 4.0 positively influence resilience. The relationship is not direct but rather indirect. The influence is mediated through resilience enablers like visibility, velocity, responsiveness etc. Moreover, this positive relationship is only observed for some instances of operational risks within the supply chain. When risk events originate from outside the boundaries of the supply chain, Industry 4.0 technologies does not help in mitigating their effects.

It is important to note that in chemical industries, performance is not the only incentive for implementing Industry 4.0. Safety of processes forms a major requirement for automation of processes and usage of Industry 4.0 technology. Having a smart manufacturing system allows the organisation to be more resilient to its internal operational risks. These risks include the breakdown of equipment, risk of misoperation etc. But when it comes to affecting the whole supply chain, the effect is very limited.

How can Industry 4.0 be used to improve supply chain resilience, in the context of the chlor-alkali supply chain?

Regarding the main question that is of significance to managers, a three-way framework has been proposed in the previous that captures three patterns in the implementation of Industry 4.0 within the chlor-alkali industry. These can be used by other chemical industries for the implementation of Industry 4.0.

The first strategy involves the resilience vs redundancy approach. The need for resilient and fast responding systems are required only in critical conditions where the speed of response is utmost important. Recollect electricity management and chlorine flow management in the chlor-alkali industry. These are critical entities as they cannot be stocked up. They determine the throughput of the entire supply chain. In such critical cases, it is better to invest in expensive Industry 4.0 based systems that can monitor these parameters and react accordingly. Evidence has shown that they can improve the reliability and accuracy of response to any disruptions.

The second strategy involves the design of the system. This designing process is also dependent on the knowledge the firm has gained through its learning processes. This is a critical step and it requires many trials and simulations to arrive at a suitable design that can also boost resilience. It is also important to make designs that can be flexible to any new changes in the process.

The third strategy involves the usage of Industry 4.0 to promote connectivity between supply chain members that can enhance visibility. In the chlor-alkali industry, this is the main strategy. The chlor-alkali production unit is connected to the chlorine and caustic customers. The chlorine production and consumption are very coordinated to avoid excess intermediate storage of chlorine. This is possible only because each plant shares data and has visibility of the status of the other plant. This communication can boost the resilience a great deal. Having visibility of the supply chain can send advance signals of any upcoming disruption and mitigation can be planned.

One recurrent theme that emerged during the discussion with respondents is that the connectivity between organisations needs to use the internet. Many companies would like to use these technologies to share information with other companies but are hesitant to do so because of the risk of cyber-attacks. This leaves the technology to be heavily underutilised. A recommendation that can be suggested here is the implementation of a private communication network between companies that can enable them to share information seamlessly and securely. This falls outside the scope of the company and as a responsibility of the government authorities. This can be considered for chemical industries as they are usually present in geographic hubs. It is possible to enable standalone communication system between organisations that are at proximity to each other. The profitability/feasibility analysis of this suggestion is not in the scope of this report. Thus, this can be taken as a course for future research.

The three-way framework is only a guide to implementing Industry 4.0. There may be other such relevant strategies and insights that can be obtained by studying other companies that operate in different sectors. These findings are based on the data analysed for this thesis alone.

8.1 Implications

The findings of this study have managerial implications which are explained in this section. This study looks at Industry 4.0 from a resilience perspective. It suggests ways to implement Industry 4.0 technology such that not only efficiency and process improvements are achieved, but also the resilience of the organisation towards risk events is also improved.

One of the important questions that managers need guidance is where to invest in Industry 4.0 technologies? Which part should be given priority first and which can be dealt with later? The first strategy of critical area mapping helps in establishing this priority. The critical areas are defined as those that are high risk, single source of supply, long lead times and/or poor visibility. Managers can use these factors to identify the critical areas and evaluate if risks are managed well in these areas. Further estimation can be made whether usage of any Industry 4.0 technologies to automate the process, to remotely monitor it or make it autonomous can help with better risk management. If yes, then this can be used for mitigating the risk better.

The next important criteria come in with the design of the system. Managers are presented with many choices and ways the system can be implemented. At this juncture, the learning of the organisation and the supply chain from past events is to be used to come up with an optimum design of the system. The design proposed by the vendor should not be considered outright and modifications should be considered to make the design more compatible with the process at hand. The system needs to be designed by considering the previous incidents that took place with it. Also, it is important to design open and flexible systems so that they can be modified and connected with other systems later.

The last strategy suggested in the framework helps managers to focus on some areas and applications. In many instances observed in this thesis, it is observed that Industry 4.0 is found to have a positive influence on supply chain visibility. Here, visibility can be defined as the extent to which the focal organisation knows about the operations of its supply chain partners. It is also the ability to predict with more accuracy about the occurrence of an event so that mitigation action can be planned better. Managers can take up the initiative to improve the visibility in the supply chain by planning for these with their supply chain partners.

8.2 Limitations

The first limitation that I would like to discuss is regarding the data collection. Due to several constraints, it was possible to obtain data from only two respondents. And both used to work for the same organisation previously (Nouryon). This effectively made it a single case study as opposed to conducting a multiple case study as was the initial plan. Thus, the results are not very robust as that of multiple case study. And arriving at conclusions from the data provided by only two respondents leads to a lower validity of results. But still, the patterns revealed are also very convincing and logical.

Next, data were collected from only one organisation in the chlor-alkali supply chain. In the short project duration, it was not possible to consider the larger extent of the supply chain. In similar case studies, researchers have investigated buyer supplier relations by interviewing professionals from both companies. This lends more robustness to the results and investigates the phenomenon more thoroughly.

Then, the data has been collected only about a very particular section of the chemical industry (chlor-alkali industry), so, the results cannot be generalised to any manufacturing environment. It can be generalised to the chemical industry to a large extent. Future research must have a sample of different types of industries to draw more broad and generalised results.

One of the main requirements for a case study is the exploration of possible rival explanations (Yin, 2018). In this study, this activity has been done to a very limited extent and this is also another weakness that can be identified.

The skill required to conduct the interview and gather required data can be attained only with preparation and practice. During this thesis, I carried out a few interviews and with each interview, I could observe a visible improvement in my skill and clarity. With the availability of more respondents, it would have been more beneficial as I could have collected data more efficiently. The limited number of interviews I have done was only enough to get me acquainted with the method but not enough where I could explore more and use it to my advantage.

8.3 Recommendations for future research

The implementation of Industry 4.0 also brings about changes in organisational processes that can pose new risks to the supply chain. These risks have not been explored in this thesis due to time constraint and unavailability of more respondents. This will also affect resilience capabilities and can be explored in further studies in the future. An example is a study by Ralston and Blackhurst (2020) that discuss the impact of Industry 4.0 on the capability loss of an organisation that may ultimately affect resilience. Other than capability loss, other dimensions like ecological, financial etc. can also be explored.

The focus on individual technologies that comprise Industry 4.0 was not done in this thesis. The technologies like IoT, CPS, ERP can be considered separately and studied so that the contribution made by each technology can be ascertained. A mapping can be obtained for the type of technologies and in what ways they affect the supply chain. This framework will also be useful for managers.

Resilience is formed not only in the supply chain but also within the organisation and from the employees (Adobor, 2019). The resilience at these three levels is related to each other. In this thesis, the resilience of the organisation and the supply chain is focussed, and resilience of personnel is scoped out. The impact of Industry 4.0 for the resilience at the employee level can be dealt with in future research. For instance, data can be gathered about Industry 4.0 from the personnel that deal with these systems daily. In this thesis, data was gathered from professionals from higher management.

This study can also be repeated for other industries to ascertain what are the capabilities that they value more in their supply chain and what constraints they face in their processes. The methodologies and literature used in this study are fully documented in this report and it will help in the replication.

8.4 Reflection

As a novice researcher, I feel it is important to reflect on my research process and the findings. First, the reflection regarding the research process is discussed followed by the reflection on research methodology and findings.

8.4.1 Self-reflection

Conducting a case study with limited resources was indeed a very challenging task and has tested my capabilities to the core. To summarise the feeling in a few words, I was mostly lost dealing with lots of variables during the initial half of the thesis. I narrowed down on these only after conducting one round of interviews and primary data collection. This gave a much-needed directionality to the study.

Firstly, I would like to discuss the COVID-19 pandemic and the effect it had on my thesis progress. The whole world is going through a very tough, grim, and challenging time right now by battling a pandemic. But at the same time, it is not possible to stop all essential processes and work conditions have been modified so that all the necessary processes can proceed smoothly. In March 2020, the COVID cases were rapidly increasing in the Netherlands and measures were taken across many organisations to curb the spread of the infection. All universities across the world had closed their campuses and educational activities were moved online. Universities in the Netherlands were no exception to this and had also closed access to their buildings.

Due to the sudden unavailability of the faculty, I had to align my routines to work from home. These thoughts needed to be adapted to the current situation in which home was to be used for both study and leisure. This process itself took me a few weeks to get used to and regain my productivity levels. Moreover, I felt that throughout conducting this research, due to the pandemic and the changes that were brought with it, my productivity levels were also fluctuating cyclically. There were times when my productivity was very good and there were some poor times as well.

In such uncertain times, the meetings with graduation committee members helped boost my morale and bring me back on track. All committee members gave insightful feedback to help with the progress of my thesis. I was in frequent contact with my first supervisor whose timely feedback helped me set a good pace.

Primary data collection through interviews was another challenge that I faced. I underestimated the amount of effort needed to design, structure, and conduct an interview. It took a few actual interviews to develop a design that could provide insights for this study. The first challenge that I encountered is asking ‘good’ questions to the interviewees. This meant a lot of mental preparation ahead of the interview to be calm and attentive. The questions framed need to be clear, unbiased, and not loaded. Only then the response given by the interviewee would not be influenced by my bias. I found this especially difficult as I was also from the chemical field and was interviewing professionals about something that I was already acquainted with.

The next challenge I faced was keeping track of where the interview was going and to bring it back on track whenever it went astray. Sometimes, the respondents can get carried away and after responding to a question, can get diverted by talking about some related phenomena which were not contributing to the thesis. Also, it was important to listen to the responses very keenly and try to interpret it and to ask for follow up explanation wherever necessary. This along with keeping track of the time limit of the interview and track of how much is still to be covered was very challenging. After conducting a few interviews, I can say that my skills have improved but there is still a lot to be learnt.

While conducting research work, it is necessary to have an outline of the whole document and try to update the contents regularly (Yin, 2018). In the latter half of my thesis, I fell behind on the documentation process and it was very hard to pick it back up and try to update all the relevant documents. This is also a very intensive process concerning time and effort. It would have been better to spend a day in a week to update the documents. That way, it is easy to visualise the progress and make decisions on how to proceed further.

Another important facet to the research that every researcher must face is the aspect of planning and time management. As per my self-observation, I feel that there were two distinct roles that I undertook while doing this research. They are the roles of planner and researcher. The planner in me looked at the macroscopic progress and made plans as to which tasks need to be undertaken at what time. Whereas, the researcher in me was responsible to perform critical thinking, analysis and design, and in writing a thesis. Juggling between these two roles is a skill that can be developed only with experience and it is desirable to recognise and develop this early on when starting the thesis.

8.4.2 Research methodology and findings

As discussed in the limitation section, one of the biggest weakness of this thesis is the smaller number of respondents from whom information was gathered. The availability of more respondents would have led to the identification of more themes and lent more robustness to the results. Nevertheless, with the data obtained from two respondents, I was able to identify some similarities and build explanations with good grounding.

I felt that case study is a very rigorous methodology that requires high level of dedication and perseverance. As Yin (2018) points out, after a day's work on the research, tiredness and mental exhaustion can be experienced. I also experienced similar fatigue. Designing a case study for good data validity and reliability is a challenging work. I have tried to be as transparent as possible regarding the design, data collection, and analytical procedures used in this study. I found the textbook by Yin (2018) very useful as it provides very detailed guidelines about how to conduct case studies. I would recommend this book to my acquaintances who are carrying out case studies.

The next point that I would highlight is my prior acquaintance with the chemical industry and how I tried not to let those notions affect the research activity. This required a very conscious effort from my side, especially when interacting with the respondents. I had to frame the questions by choosing the wording very carefully. In hindsight, after examining the transcripts of the interviews, I feel that I have not let my priors adversely affect the process.

Regarding the topic explored in this thesis, the influence of Industry 4.0 on the supply chain resilience, there was an interesting notion that I wanted to explore but could not do so due to time constraint. This is the angle that considers the risks a company faces due to the implementation of Industry 4.0. These risks are discussed briefly in the literature review. These risks can also cause a loss in the resilience of the organisation/ supply chain. This was only explored to a limited extent in this thesis and I have also stated this in recommendations for future research to consider researching from this angle.

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APPENDICES

Appendix A: Search procedure for literature review

The data for writing Chapter 4 and 5 have been obtained through literature reviews. To improve the reliability of the thesis, the procedures followed for obtaining articles are described in detail in this appendix.

The first activity needed to perform a search for finding literature online is to find suitable keywords that can fetch relevant articles. Once the keywords were developed, then a search procedure is carried out that generated various articles as search results. The titles and abstracts of these articles were read, and they were downloaded if they were found to be relevant.

A general procedure was used for obtaining articles from several different sources. The search engines used were Web of Science, Elsevier, Sage, and Taylor and Francis. The first option is a search engine facility specially meant for looking up scientific articles and the rest are websites of publishers. These options were chosen as their search protocols are very similar and the search procedure defined for one can be replicated for other services.

For Industry 4.0, two searches were performed. The first was to study the implementation patterns and the second was to study the risks of implementing it.

Industry 4.0: Literature search 1

For the first search, the first sub-research question was referred to and keywords were taken from there. The research question is – "How is *Industry 4.0 implemented* in *manufacturing industries*?"

Three sets of keywords were taken, and their synonyms were also considered as shown in Table A.1.

Table A.1: Keywords for Industry 4.0 literature search

Keyword 1	Keyword 2	Keyword 3
Industry 4.0	Manufacturing organisation	Implementation
Smart manufacturing	Manufacturing industry	Adoption
Smart system		Classification
Cyber physical system (CPS)		

Next, these keywords were combined using search operators (AND, OR) and they were entered into the search query. The search engine used, exact keyword entered, and articles downloaded are shown below in Table A.2.

After reading the title and abstract of the article, a reflection was made if the article is closely related to the question outlined above i.e. the implementation pattern and usage of Industry 4.0 technologies, what factors drive them and any classification systems. Then, a judgement is made to see if the article is relevant or not. If it is found to be relevant, then it is downloaded for reading further.

Table A.2: Summary of search results for Industry 4.0

Search engine/ website	Keywords	Search results	(New) articles downloaded
Web of Science	((industry 4.0 OR digitalization OR smart system OR smart manufacturing OR cyber physical system) AND ((manufacturing organisation) OR (industry))) AND (implementation OR clas sification OR adoption))	2739[1]	4
Web of Science	(("smart system" OR "smart manufacturing" OR "cyber physical system") AND ((manufacturing ((organisation) OR (industry)))) AND (implement* OR classi f* OR adopt*))	278	15
Taylor and Francis	(("smart system" OR "smart manufacturing" OR "cyber physical system") AND ((manufacturing ((organisation) OR (industry)))) AND (implement* OR classi f* OR adopt*))	461 (81)[2]	6
Science Direct	(("smart system" OR "smart manufacturing" OR "cyber physical system") AND ((manufacturing ((organisation) OR (industry)))) AND (implement OR classif y OR adopt))	140	3
Sage	(("smart system" OR "smart manufacturing" OR "cyber physical system") AND ((manufacturing ((organisation) OR (industry)))) AND (implement* OR classi f* OR adopt*))	144	3
Total number of articles downloaded			**31**
Additional articles downloaded			**5**

A total of five searches were performed in the first instance. The first two searches were done on the Web of Science platform and then the remaining searches were done on Taylor and Francis, Science direct, and Sage publication platforms respectively. The keywords used on each platform is shown in the second column of Table A.2. The total search results are shown in the third column.

The article titles and abstracts were scanned and judged for relevance. If found relevant, the article was downloaded. The total number of downloads are reported in the final column. While downloading these articles, if it was noticed that the same article was already downloaded from other publications, it was deleted to avoid accounting it twice.

By combining all these searches, a total of 31 articles were downloaded which is reported in the penultimate row. While skimming these articles, other useful and relevant articles were spotted in their bibliography. A total of five articles were downloaded from the bibliography of various articles and were also analyzed as a part of the literature review. This is reported in the final row of Table A.2. The contents of Table A.4 and Table A.5 are also to be interpreted similarly.

Using the term Industry 4.0 yielded search results in high numbers and it was not possible to review all articles, highly cited articles were checked, and four articles were downloaded from them. After

[1] Due to very high number of search results, the articles were sorted by number of citations and four highly cited articles were downloaded for refining the keywords.

[2] Only 81 articles were accessible.

reviewing these four articles, the search keywords were modified. The term Industry 4.0 was dropped from the search query as it was yielding a very large number of articles.

Industry 4.0 risks: Literature search 2

Next, articles related to the risks due to the implementation of Industry 4.0 need to be searched. The keyword sets considered were like the previous one. The keywords chosen are shown in Table A.3.

Table A.3: Keywords for Industry 4.0 risks literature search

Keyword 1	Keyword 2	Keyword 3
Industry 4.0	Implementation	Risk
Smart manufacturing	Adoption	liability
Smart system	Classification	
Cyber physical system (CPS)		

Like the previous case, the keywords were combined and used in search queries to get articles. They are discussed in Table A.4.

Table A.4: Summary of search results for Industry 4.0 risks

Search engine/ website	**Keywords**	**Search results**	**(New) articles downloaded**
Web of Science	("smart manufacturing" OR "smart system" OR "cyber physical system" OR cps) AND (risk OR liability) AND (implement* OR adopt*)	185	2
Web of Science	industry 4.0 AND risk management	155	7
Taylor and Francis	("industry 4.0" OR "smart manufacturing" OR "smart supply chain") AND (risk OR challenge OR liability) AND (manufacturing organisation)	655	9
Science Direct	("industry 4.0" OR "smart manufacturing" OR "smart supply chain") AND (risk OR challenge OR liability) AND (manufacturing organisation)	40	1
Sage	"industry 4.0" AND risk	3	0
Sage	"industry 4.0" AND risk management	3	0
Total number of articles downloaded			**19**
Additional articles downloaded			**4**

The criteria used to download articles in this search is to check if the articles contained details regarding the risks and challenges of implementing Industry 4.0 and whether it contains any frameworks or classification systems for the same. If it is found to be relevant in these perspectives, it is downloaded for further reading.

Supply chain resilience: Literature search 3

Next, to review the topic of supply chain resilience, the keywords are derived from sub-research question 2- What *capabilities* are required to build a *resilient supply chain*?

Only two sets of keywords were used. The first is supply chain resilience and the second is antecedent/strategy. The keywords were used in different search engines to obtain articles. The search summary is shown in Table A.5.

Table A.5: Summary of search results for supply chain resilience

Search engine/ website	**Keywords**	**Search results**	**(New) articles downloaded**
Web of Science	("supply chain resilience" AND (antecedents OR strateg*))	146	17
Taylor and Francis	("supply chain resilience" AND (antecedents OR strategy))	41	7
Science Direct	("supply chain resilience" AND (antecedents OR strategy))	24	4
Sage	("supply chain resilience" AND (antecedents OR strategy))	20	2
Total number of articles downloaded			**30**
Additional articles downloaded			**10**

The criteria used to download the articles in this search is to check for relevant frameworks to understand the concept of supply chain resilience in a better way. This also includes the strategies and antecedents that are required to build resilience in the supply chain. Some articles with quantitative models to measure resilience also came up in the results, but these were not selected. Only articles with qualitative descriptions were selected and downloaded.

Appendix B: Case study introduction sheet

This appendix contains the document shared initially with the respondents that give a brief idea about my thesis.

Investigating the influence of Industry 4.0 on supply chain resilience

In the last few decades, due to globalisation, the supply chains have become more complex in nature and longer in length. There has been an increasing interest to manage supply chain risks for companies with global supply chains. This has been reflected in scientific research as well. The field of supply chain risk management (SCRM) has gained widespread attention recently and is now an established research area with several publications in the last two decades (Fan & Stevenson, 2018).

Building supply chain resilience is a way to mitigate supply chain risks (Christopher & Peck, 2004). **Resilience in the context of the supply chain can be defined as its ability to withstand the impact of risks and also to return to an acceptable performance level at the earliest** (Christopher & Peck, 2004). The four pillars of building a resilient supply chain are supply chain reengineering, supply chain collaboration, supply chain agility, and improving the risk management culture in the organisation (Christopher & Peck, 2004). Nowadays, many organisations are investing to improve the resilience levels of their supply chain.

Industry 4.0[3] is a recent phenomenon that has a huge impact on manufacturing industries through the application of digital technologies (Lasi et al., 2014). This has an impact not only for production management but also for wider entities in the value chain (Haoud & Hasnaoui, 2019). Some of these technologies include big data analytics, Internet of Things (IoT), advanced manufacturing with sensors, advanced robotics, augmented reality and additive manufacturing.

The introduction of these technologies will not only affect supply chain operations and performance but also create new risks (Ivanov et al., 2018). This prompts the need to study the impact of these technologies so that adequate action can be taken to safeguard the supply chain and re-engineer it wherever required. There have been a few studies that focus on the impact of Industry 4.0 on supply chain (risk) management (Ivanov et al., 2018; Müller & Voigt, 2018; Haoud & Hasnaoui, 2019) but very few studies that focus on supply chain resilience.

Many manufacturing-based organisations are adapting Industry 4.0 technologies to modify their internal processes and thereby improve supply chain performance. These technologies are still in their infancy and managers do not completely understand the ramifications of this technology and how it affects supply chain resilience. With the proliferation of Industry

[3] Industry 4.0 is a term coined in Germany around 2011 to promote the use of advanced technologies in manufacturing and thereby improve productivity. It can be used synonymously with similar terms like smart manufacturing system, autonomous system, cyber-physical system to name a few.

4.0 technologies, it is important to explore how these technologies affect supply chain resilience and the interaction between supply chain partners.

For this thesis, I have narrowed down the technologies considered from the perspective of the supply chain. If the technology satisfies any of the criteria listed below, it can be considered for this study:

1. Fully automates a process and eliminated the need for human intervention. This process should affect the whole supply chain performance
2. Improves the communication between supply chain partners without human intervention (e.g. real-time communication of raw material inventory to suppliers)

Since this is a relatively unexplored field, I would like to begin by interviewing supply chain professionals who can shed light on the practical aspects of implementing Industry 4.0 technologies and how it affects supply chain resilience on a case basis. Organisations that have not implemented these technologies can also participate. Organisations that are planning to implement them soon are also eligible. Their responses combined with existing literature will be used to build a framework which will be later tested using questionnaires.

Scope

As I am a chemical engineer, I am interested to explore this relation for the chemical industry in Europe. Narrowing down the scope of this important industry makes the project practical and feasible. Hence, there is a necessity to interview supply chain professionals from the chemical industry.

Interview requirements

The interview is planned for 30 minutes and will be done using a phone call, skype or zoom. A video call would be preferred for better communication. The call will be audio-recorded and transcribed to obtain qualitative data. The personal information of the respondents will be removed from the transcripts and they will be anonymised. The original recordings and transcripts will be deleted after thesis completion. At no point in the thesis, will the personal information and identity of the participants be revealed. It will remain confidential with me.

Deliverable

A digital copy of the thesis report and an executive summary will be shared with all respondents after the completion of the thesis. This will also contain a framework that managers can use to assess Industry 4.0 technologies and implement them in their organisations.

Appendix C: Informed consent form

This section contains the informed consent form used to obtain consent from the respondents.

Consent Form for studying the influence of Industry 4.0 on supply chain resilience

Taking part in the study

I have read and understood the study information, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.

I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.

I understand that taking part in the study involves taking part in an interview by Subbaraman Chittur Ramasubramaniam to obtain data for studying the influence of Industry 4.0 on supply chain resilience.

The data will be stored in the form of audio recordings of the interview session. The same will be transcribed and anonymised. Any information that can reveal my identity will be removed from the transcript. All the original recordings and transcripts will be deleted after the study is completed.

Use of the information in the study

I understand that information I provide will be used after anonymising, for thesis report publication and presentation

I understand that personal information collected about me that can identify me, such as my name, my job description, my organisation and this signed consent form will be accessible only to Subbaraman and will be deleted after completion of the study.

Future use and reuse of the information by others

I give permission for the data that I provide to be archived in storage facility of Subbaraman and TU Delft and in the 4TU data repository so it can be used for future research and learning; except for personal information. The archived data will be fully anonymous.

Consent

I have read and understood this consent form completely. Any questions I have had are clarified by the researcher. I hereby agree and provide my consent to all the points mentioned above.

Signatures

______________________ ______________________ ________

Name of participant

Signature Date

Researcher contact details for further information:

Subbaraman Chittur Ramasubramaniam

Appendix D: Interview structure for an introductory interview

General questions:

1. What is your name? Briefly describe your job responsibility and about Eurochlor.
2. Who are eligible to become Eurochlor members and how many members are there currently?
3. What is the nature of the relationship between Eurochlor and Chlor-alkali industries in Europe?
4. Can you briefly describe the Chlor-alkali industry process?
    a. What are the raw materials and products?
    b. What are their main applications of the products?
    c. What are the physical properties of the products?
    d. What is the storage criterion?
    e. What are the major differences between the three different processes of Chlor-alkali production (mercury cell, diaphragm cell and membrane cell)?
5. How can you describe a typical Chlor-alkali supply chain?
    a. What is upstream and downstream of the chlor-alkali industry?
    b. Can you describe the quantum of the supply chain, i.e. in what quantity are the products produced?
    c. What is the impact of operations stoppage of Chlor-alkali industry on the downstream industries?
    d. Is there competitive pressure from Asian, American or other markets?
6. Is there any important criterion about the European chlor-alkali supply chain that have not been covered by the previous questions? If yes, please elaborate.

Supply chain resilience:

7. How will you define supply chain resilience and what steps have been taken to improve them in the chlor-alkali industry?
8. What fraction of organisations manage their supply chain risks by systematically identifying and responding to risks?

Industry 4.0:

9. Were you familiar with the term of Industry 4.0 technologies prior to this interview? If yes, how will you define Industry 4.0 in your own words?
10. What is the perception of the *chemical industries* towards Industry 4.0? At what stage of adoption/implementation are the *chemical industries* presently?
11. What is the perception of the *chlor-alkali industries* towards Industry 4.0? At what stage of adoption/implementation are the *chlor-alkali industries* presently?
    a. Can you provide one or two examples of implementation of such technologies within the chlor-alkali industry?
12. What are the benefits of the implementation of Industry 4.0 systems with respect to performance metrics?
13. Are there any unplanned outages in such systems?

    a. Can you recount an example of when this happened?
    b. What business continuity plans are in place in case of Industry 4.0 system breakdown?
    c. How is the disruption identified and communicated to employees?
    d. Can you think of any other risks that are caused due to the implementation of Industry 4.0?
14. How does the implementation of Industry 4.0 impact supply chain resilience i.e. ability to respond to disruptions in the supply chain?
    a. What are the positive impacts?
    b. What are the negative impacts?
15. Is there any aspect you feel is relevant and have not been covered by the previous questions? If yes, please elaborate.

Appendix E: Interview structure for main interview

This section contains the general protocol that was used for questioning the interviewees.

1. What is supply chain resilience? What are the capabilities that make up supply chain resilience? For instance, preparedness, responsiveness, and adaptability to name a few.
2. Discussion about influence of smart manufacturing on preparedness, adaptiveness, and responsiveness.
    a. How is smart manufacturing implemented within the production plant?
    b. How is smart manufacturing implemented to connect with supply chain partners?
    c. How is smart manufacturing implemented to help with plant maintenance?
3. Are Industry 4.0 systems responsive to environmental risks (that originate outside the supply chain)? How?
4. How can risks caused by Industry 4.0 be mitigated?
    a. Financial risk
    b. Organisational risk
    c. Ecological risk
    d. Technological risk
    e. IT risk
    f. Legal/ political risk
5. Any lessons for companies that are establishing Industry 4.0.

Appendix F: Pre-interview information sheet

This section contains the detailed document shared with respondents before conducting the interview.

This document has been prepared by the researcher to update the respondent regarding the concepts and definitions required for the interview. Using the terminology given in this document will enable the communication between the researcher and interviewee to take place smoothly. For any queries on the information in this document, kindly contact the email listed below.

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There are three sections in this document. The first discusses the types of risk to the supply chain and which risks are considered in the scope of this research. The second discusses the risks due to the implementation of Industry 4.0 technologies within companies. The third section discusses the conceptualisation of the term supply chain resilience.

Types of risk

For the purpose of analysis in this thesis, the types of risk to the supply chain are classified into two broad types: operational risk and environmental risk (Kleindorfer & Saad, 2005; Shekarian & Parast, 2020). The former concerns the risks that may occur within the focal organisation or any organisation within the supply chain that causes an impact on the supply chain performance. This can be further divided into known and unknown risks. Known operational risk includes issues like equipment breakdown, logistics breakdown which occur time and again, and their mitigation strategy is already planned. Unknown operational risk includes motivation of employees, new competition from industry, and supplier/customer bankruptcy which are events that do not occur often and cannot be foreseen.

Whereas, the latter environmental risk concerns events that take place outside the scope of the supply chain but still manage to affect the supply chain performance. These include events like natural disasters (flood, earthquake, cyclone), war, economic depression, and terrorist attacks to name a few. Environmental risk is also divided into two types: known and unknown risks. Known environmental risk includes those events that can be predicted before its occurrence like floods and cyclones. Unknown environmental risks are those events that are either radically new and/or unpredictable and it includes events like earthquake, terrorist attack, and the COVID-19 pandemic. For the purpose of this thesis, it is decided to exclude these unknown environmental events as they are difficult to be predicted and their nature differs greatly with respect to other types of risk.

Industry 4.0 related risks

Industry 4.0 implementation can bring forth a lot of challenges and risks within an organisation. It can be broadly divided into six different types like financial, organisational, technical, IT, ecological and legal risks. Each of these types of risk is discussed in detail below. It is to be noted that these risks are not independent of each other but rather relate to each other. This framework has been adapted from the paper by Birkel, Veile, Müller, Hartmann, and Voigt (2019).

Financial risk

Returns: Investment into Industry 4.0 is quite heavy and needs to be planned accordingly. It is one of the barriers to its implementation. It is possible that profits in the short-medium term may be negative and that the profitability prediction will be uncertain. This makes the situation even more challenging for SME's. There is also a necessity for hiring highly skilled workers that comes at a higher price to the organisation.

Timing and distribution: Next, the timing of investment is crucial. Companies do not want to invest in outdated or immature technology. Further, it is also important when to invest in Industry 4.0 technologies and how to distribute the investment within different parts in the organisation to achieve the maximum effectiveness from the investment. Also, late investment in the technology can take out the important place of an organisation in the industry.

Business model: The strategy with which a company makes money in the market is essentially its business model. The implementation of Industry 4.0 brings in changes to the existing business models that are radically different. Coping with these changes can be very demanding in an organisation. Next, there is the inexperience in the usage of data driven business model. The expertise required to analyse these data driven business models is not possessed by the companies. Organisations tend to stick to 'product driven' rather than 'data driven' models.

Competition: The implementation of Industry 4.0 will lead to increased competition. The entry barriers for an industry are lowered and IT related industries can enter the traditional industries. It also leads to pressure in performance and price of the products. As stakeholders in the supply chain are connected, they also get access to information about the company and this may lead to pressure from them to negotiate prices and terms of the contract.

Dependency: Implementation of Industry 4.0 also creates dependencies on a few key technology suppliers. Some companies fear losing control over their process and the high level of dependency it creates. It is not easy to switch between these suppliers and this can create a monopoly like situation for the technology provider. They can charge higher prices for their products and services which makes the focal organisation vulnerable.

Ecological risk

Consumption and Pollution: Application of Industry 4.0 in a business increases the demand for new equipment both physical and digital that are compatible with each other. This increase in consumption can lead to generation of waste to the environment. The additional equipment also accounts for higher energy consumption and it is not clear if this is offset with the gain in efficiency of the organisation. Mostly, it is not possible to use the existing equipment to connect with new Industry 4.0 systems. Thus, there is a requirement for new equipment which is compatible with Industry 4.0. If the parts from the old equipment cannot be recycled, it leads to generation of waste.

Organisational risk

The below discussed risks are from the organisational perspective. It is to be noted that these can also be analysed from the perspective of social risk as these phenomena also affect society.

Job losses: A major claim by many researchers and practitioners is that the implementation of Industry 4.0 will reduce the manpower requirement and will lead to loss of jobs. This is also accompanied with a shift in requirements needed for employees. A need is created for employees to develop new competencies. This will also change the nature of jobs in the labour market.

Organisational structure: The organisational structure is an important parameter when implementing Industry 4.0, it needs to be compatible so that the implementation process can be smooth. An ‘entrepreneurial spirit’ is required for enabling these organisational transformations. This is said to be difficult for traditional manufacturing companies that adapt to a functional organisational structure. Also, open and transparent communication needs to be established between top management and the employees in an organisation.

Resistance: In most cases, there is resistance from employees and mid-level management. This feeling from employees should be acknowledged and they must be included in the transformation process. Employees must be encouraged to attend training sessions regarding the new technologies. Bringing an open culture can also help with abating resistance among employees.

Employee training and qualification: As discussed in financial risks, there is also a need for employees who are trained and qualified to operate the Industry 4.0 systems. These personnel come at a higher cost. Moreover, these personnel are also very hard to find in the labour market. There is a requirement for personnel who are knowledgeable with IT related processes and the internal processes within the organisation and are capable enough to mediate between both.

Employee stress: Employees also come under duress under such changing environments as they are faced with more challenges compared to their routine work. This excess of stress and tension can also fuel the resistance culture that was discussed earlier. When more equipment is installed, it can also cause isolation from other employees as many jobs are now being performed by machines.

Distrust over the technology: The management of many companies may not trust the Industry 4.0 technologies when there may be incidents of wrong decision making that have had adverse effects on the organisation. There is also the problem of accountability with this. When the equipment makes a mistake, is it held accountable by the equipment itself or the person who programmed it?

Manufacturing relocation: When management is faced with excessive pressure from employees about implementation, there is a possibility that factories can be closed, and the manufacturing relocated to other countries where conditions are more favourable.

Capability Loss: According to a paper by Ralston and Blackhurst (2020), automating a process with Industry 4.0 can lead to employees slowly losing the knowledge and skills to perform that job. This loss of skills can lead to a loss of responsiveness during a risk event which creates loss for the supply chain.

Technological risk

Integration: With the implementation of Industry 4.0, there is a need to integrate current equipment with IT based systems which makes the whole system more complicated. The current equipment can be retrofitted with Industry 4.0 systems making the integration process simpler, but this might not be possible in many cases. Thus, integrating the technology on the shop floor is a challenging task.

Dependency: When the processes are automated with Industry 4.0 technologies, it results in a high level of dependency on the technology that if there is any breakdown of the system, it can affect the whole supply chain.

Standards: Software used in ERP system can come from several providers in the market who provide different standards of the same technology. Problems arise when integrating this software across different companies in the supply chain. Even the equipment on the shop floor needs to be integrated into an interface. There is a need for clear interfaces between various departments in a company also in the supply chain. Only by adhering to standards seamless communication can be ensured.

IT risks

Cyber-attacks: A major vulnerability of using IT-based technology to enable connectivity and implement Industry 4.0 is that the system can be attacked from outside the network. The vulnerability is more when there are more interfaces connected in the supply chain. Such attacks can create downtime in the equipment costing the company losses.

Data possession: All companies have intellectual property that is a critical component for their success. Implementing Industry 4.0 and sharing data across companies will give data access to other organisations in the supply chain. It should be protected such that it does not fall in the hands of a direct competitor.

Data handling: Enabling Industry 4.0 across the supply chain will result in recording lot of data. The distribution and access to this data needs to be controlled. There also needs to be a consistency of data across the supply chain.

Cloud computing: There are some risks mentioned with reference to operating Industry 4.0 systems on cloud systems. Having low connection speeds, cloud server failure, location of server in other countries are a few risks that need to be evaluated. Also, it is tough to achieve real-time capabilities by using cloud computing.

Legal risks

Infrastructure: Politicians must provide adequate infrastructure facilities that are compatible with Industry 4.0 technologies. This includes network and power infrastructures. Sometimes, companies are located outside urbanised areas where adequate infrastructure may not be always present.

Legal aspects: Companies that undergo digital transformation under Industry 4.0 must chalk out the agreements in well-defined contracts that specify the control of each organisation. Usually this is an intensive process.

It is also necessary to comply with the legislations of the local region regarding Occupational Health and Safety. Operating under the framework of Industry 4.0 also has data protection and data security issues. The legislations to handle these disputes are not very clear in many countries.

Supply chain resilience

In this section, the concept of supply chain resilience is defined and conceptualised for the understanding of the respondent.

It can be defined as “the adaptive capability of the supply chain to prepare for unexpected events, respond to disruptions, and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function” (Ponomarov & Holcomb, 2009, p. 131).

From the definition, resilience is the ability of the supply chain to be prepared, adaptive, and responsive to recover from disruptive events. Thus, it is essential to build these capabilities into the supply chain by reengineering it whenever possible. These capabilities are built gradually with time and there is no pre-existing solution for organisations that can be implemented straight away.

Preparedness is the proactive nature of an organisation wherein the risks to supply chain are reviewed periodically and actions are taken to reduce the risks faced. This includes maintaining a risk register and reviewing it periodically to update it in line with new development.

Next, the adaptability of the supply chain comes in, which is important to set the standards for the recovery. The requirements for the supply chain may be different after the occurrence of a risk event. The supply chain must be capable to recognise this and to deliver to this expected performance levels. Supply chain adaptability is also synonymous with supply chain flexibility.

Next, the responsiveness of the supply chain is important. Once a risk event occurs, it is important to identify the event occurrence at the earliest and craft and execute an adequate response to the event. Continuous monitoring of the event is required to check whether the supply chain has recovered or not.

Moreover, the concept of supply chain resilience has been mostly qualitative, and the nature of this study is also qualitative. Data is built from verbal discussions, company reports, and journal discussions as recommended for qualitative case study.