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Supply chain resilience: A study of strategies and metrics

Master's thesis in Supply Chain Management

Alexander Andersson
Hanna Klinga

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SERVICE MANAGEMENT AND LOGISTICS

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ALEXANDER ANDERSSON
HANNA KLINGA

Report no. E2023:064
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

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HANNA KLINGA

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Chalmers University of Technology

SUMMARY

In this thesis, we investigate supply chain resilience strategies and metrics. According to our knowledge, simulation-free research on the assessment of supply chain resilience is scarce. There are a few resilience strategies that are frequently mentioned, such as multiple sourcing and localization, but there are also a large number of other strategies available. This report compiles a broad framework of available supply chain resilience strategies developed based on both the literature and interviews with eleven Assa Abloy Entrance Systems respondents. It can be difficult to measure and comprehend the effects of supply chain resilience, to enable this understanding, a list of 34 metrics indicative of resilient supply chains is presented. Additionally, effects of recent disruptions on Assa Abloy Entrance Systems supply chain have been investigated and summarized into a list of symptoms. We believe that the most valuable implications of this research are the comprehensive lists of metrics and strategies that supply chain managers can use to broaden their understanding of available alternatives.

Keywords: Supply Chain Resilience, Robustness, Flexibility, Adaptability, Agility, Collaboration, Visibility, Structure, Strategies, Assessment, Measurement, KPI.

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Finally, we are grateful to docent Gunnar Stefansson, our supervisor and examiner at Chalmers, for assisting us in presenting our content in a structured manner and ensuring that we stay on track.

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KPI	Key Performance Indicator
SCRES	Supply Chain Resilience
SKU	Stock Keeping Unit

1 Introduction

The aim of this section is to introduce the purpose of the thesis and provide the reader with a brief understanding of the subject resilience and how it is relevant to Assa Abloy Entrance Systems. Three research questions will be presented which will reflect what the thesis will be focusing on, along with the scope of the project.

1.1 Background

Normally, supply chains operate behind the scenes, unseen by end consumers. However, in times of disruption, such as the most recent and well-known COVID-19 pandemic, supply chains are brought to light because of breakdowns in efficiency. When the flow of materials and people is severely disrupted, unanticipated vulnerabilities are revealed, leaving organizations impacted for years afterwards. As a result of the enormous effects that various disruptions have on supply chains, interest in the subject of resilience massively increases, as is demonstrated by the number of academic articles released around the time of a disruption. (Sombultawee et al., 2022).

As a result of globalization, global supply chains have grown longer and more complex (Andersson, 2009). To achieve success with economies of scale, companies must inevitably expand internationally. It opens up a number of opportunities, including access to resources and the opportunity to reduce a company's expenses by selecting suppliers in regions with, for instance, lower labor costs. The trade-off, however, is an increased risk of greater impact from disruptions due to longer geographical distances and a higher level of complexity in supply chain network connections. Consequently, attention to supply chain resilience and methods for enhancing it have increased significantly. There are enormous opportunities for businesses to gain market share if they are able to maintain the last viable supply chain and be the most dependable company during a disruption (Andersson, 2009). The optimization of return on investment (ROI) and finding a balance between a cost-effective, sustainable, and reliable supply chain while maintaining a high customer service level is one of the greatest challenges supply chains face today.

Assa Abloy Entrance Systems is one of Assa Abloy's seven divisions and a global manufacturer with facilities and suppliers in every continent. They offer a variety of doors for use in commercial and industrial settings. As part of their business strategy, they put emphasis on their customer service level, and their goal is to have spare parts available within 24 hours (Assa Abloy, 2022). Recent disruptions, the COVID-19 pandemic, and the Russian-Ukrainian conflict have had significant effects on Assa Abloy Entrance Systems supply chain. As a result of the COVID-19 pandemic, there have been shortages of certain components from suppliers. This has prompted the company to examine redundancy in the supply chain and consider alternative methods of placing strategic inventory along the supply chain in order to be better prepared for future material disruptions. In the aftermath of COVID-19, there are also positive insights to be gained from analyzing processes that worked well, which are essential to consider and preserve in the organization. Assa Abloy Entrance Systems was fortunate to have implemented a "supplier involvement" initiative prior to the COVID-19 pandemic, which increased transparency and information sharing between one of its factories and suppliers. Afterward, they realized the importance of timely and accurate information from the suppliers for the factory's ability to plan and respond to potential material shortages or transport delays.

An effect of the Russia-Ukraine conflict is that prior to the conflict, they utilized railways along the Silk Road to transport goods from Chinese suppliers to European factories. Due to geopolitical constraints, it was no longer feasible to use these railway solutions. As a consequence, Assa Abloy Entrance Systems had to switch from rail to sea transport, resulting in a lead time increase of five weeks.

For top and middle management at Assa Abloy Entrance Systems alike, supply chain resilience is now one of the items on top of the agenda. Prior to the recent major events, they had undergone efforts to move their supply base to China. According to present supply chain trends, many companies are looking at increasing inventories, dual sourcing, and moving their whole supply base closer to their factories. This is a costly and lengthy process, which raises the question for Assa Abloy Entrance Systems about whether it is possible to improve their supply chain resilience without continuously changing their supply base or not.

1.2 Purpose and research questions

Traditional supply chain management did not consider supply chain resilience, instead focusing on the influence of supply chain decisions on cost and service level (Ivanov et al., 2019). In light of the current state of the world, which is characterized by a growing number of major disruptions, *the purpose of this thesis is to highlight the effects that disruptions have caused and what organizations can do to improve the supply chain resilience*, the ability to deal with disruptions in the future. Further on, it will serve as an inspiration for Assa Abloy Entrance Systems and suggest how they can improve their upstream supply chain resilience. The thesis will achieve its objective by addressing the three research questions listed below.

The aim of the first research question is to present a framework of available supply chain resilience-improving strategies for organizations. The framework will include strategies found both in the literature, and from empirical data when investigating two previous case projects that have been implemented by Assa Abloy Entrance Systems. In addition, there is no magic formula for calculating the resilience of a company's supply chain; however, relevant Key Performance Indicators (KPIs) that can serve to illustrate resilience will be presented in order to better understand how to assess supply chain resilience. The combination of a literature study and two real case studies will contribute to a broad overview of possible strategies as well as a deeper understanding of what effects that implementations of supply chain resilience strategies can result in.

RQ1: How can organizations improve the resilience of their upstream supply chains?

The second research question is related to recent disruptions and their impacts. COVID-19, the Russia-Ukraine conflict, and other events have harmed the supply chain of Assa Abloy Entrance Systems. It is unclear, however, precisely what effects it had. Therefore, the effects that various disruptions have had on Assa Abloy Entrance Systems supply chain, from the first-tier supplier to the factory assembly, will be summarized in a symptomlist.

RQ2: What impacts have previous disruptions had on Assa Abloy Entrance Systems supply chain?

The third research question will incorporate the resilience strategy and measurement theory, the effects of disruptions, as well as the context of three of Assa Abloy

Entrance Systems segments. The objective is to present recommendations of actions that Assa Abloy Entrance Systems may take to improve their supply chain resilience.

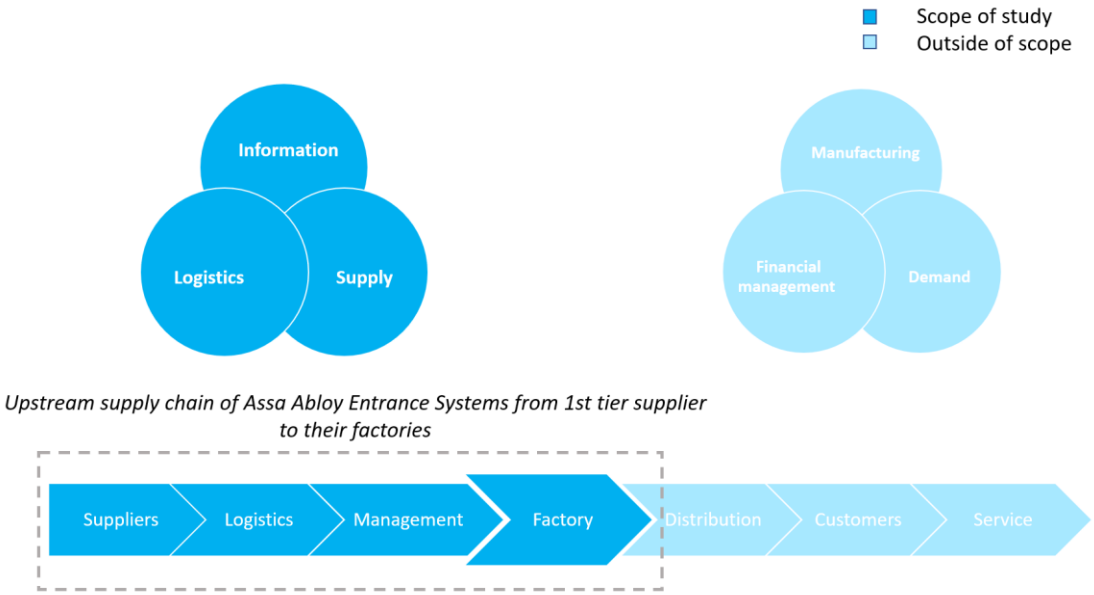
RQ3: What are the main areas and actions Assa Abloy Entrance Systems may focus on to prepare for future supply chain disruptions?

1.3 Scope

Micro-level strategies are divided into six subcategories by Rahman et al. (2022): supply, demand, manufacturing, information, transportation, and financial management. These areas served as inspiration for the thesis, which was then modified and restricted to include only literature from the fields of information, logistics, and supply. The areas were selected based on what appeared to be most relevant for an external stakeholder to analyze. The scope encompasses Assa Abloy Entrance Systems upstream supply chain from their first-tier supplier to their factories and delimits their downstream supply chain from their factories to their customers. Figure 1 illustrates the project's scope.

Figure 1

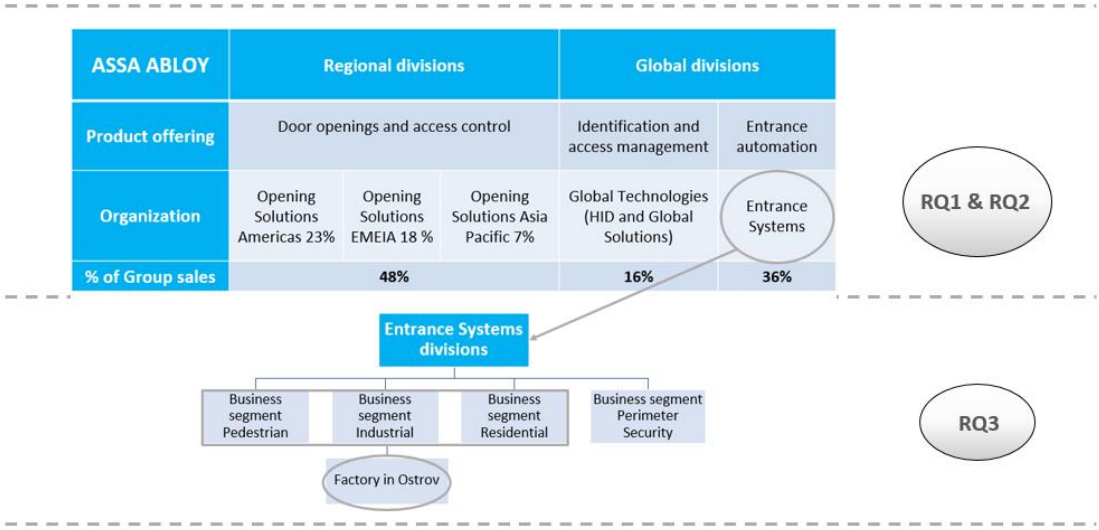
Project scope



The work is constrained to the Assa Abloy Entrance System division and not the entire Assa Abloy organization. In order to increase the sample size, data collection for supply chain resilience initiatives is conducted across segments within the Assa Abloy Entrance Systems division. In contrast, the empirical scope for the third research question is limited to the industrial, pedestrian and residential segments within the Entrance Systems division. Within the industrial segment, an operator factory in Ostrov, Czech Republic, that operates the controllers for the industrial segment will be analyzed in further detail. The Ostrov factory was chosen as it was the site where we had access to most information. The limitations within Assa Abloy Entrance Systems are depicted in Figure 2.

Figure 2

Empirical scope



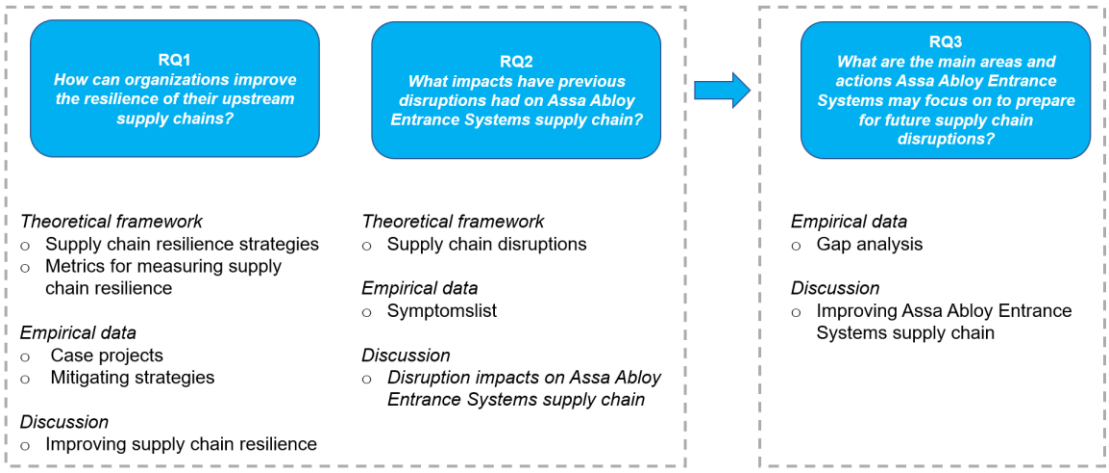
Through interviews, the impacts of recent disruptions on Assa Abloy Entrance Systems' supply chain will be analyzed. However, because the scope ends at Assa Abloy Entrance Systems' facilities, customer-side effects will not be considered. In addition, the work will be restricted to events and disruptions that have occurred within the last four years, limiting the range from 2019 to 2023.

2 Method

This thesis is divided into three sections, mandating the use of distinct data collection techniques to address the three research questions. To answer research question one, the information has been gathered from literature regarding strategies and metrics, and empirical data including data from case projects and mitigating strategies performed by Assa Abloy Entrance Systems that show positive effects on supply chain resilience. For the purpose of addressing research question two, theoretical data was first gathered to be able to guide the interviews. Secondly, empirical data regarding how Assa Abloy have been affected by previous disruptions have been collected to get an overview of the situation and whether there are areas especially critical to look at in the future. Finally, the third research question analyzes the strategies covered in literature and empirical data to derive suggestions of future supply chain resilience improvements for Assa Abloy Entrance Systems.

Figure 3

A summary of the parts that belong to each research question



2.1 Literature review

The procedure was organized as follows: As search criteria, particular keywords were selected. The terms supply chain, supply chain resilience, and management were used to locate books covering the fundamentals of supply chain resilience. At the outset of the literature evaluation, selection criteria for the literature were established. The complete list of selection criteria is presented in Table 1. The books helped us expand the list of keywords used for supply chain resilience strategies and discover additional definitions for the same topic, such as proactive, 'Readiness', 'Concurrent', 'Reactive', and 'Growth'. Following this, literature reviews, such as those by Rahman et al. (2022) and Han et al. (2020), were used to gain an overview of the available publications on the topic. Multiple sources were discovered through a cascading effect initiated by the literature evaluations. The literature reviews and snowballing process generated keywords for supply chain resilience strategies, such as 'Preparedness,' 'Response,' and 'Recovery,' and keywords for relevant resilience capabilities, such as 'Flexibility,' 'Robustness,' 'Adaptability,' 'Density,' and 'Visibility'. These were used for a more structured process to increase our comprehension of

the literature and fill in the gaps that the snowballing method did not address. The complete list of keywords is presented in Table 2, and the search structure is summarized in Table 3. Various academic databases, such as Chalmers Library and Google Scholar, were used to locate relevant articles, and the material was published by a number of different publishers, such as Emerald, Elsevier, Springer, IEEE, and Harvard Business Review. Finally, several news forums were searched for up-to-date information on the topic of resilience.

Table 1

Selection criteria

Selection criterion	Motivation
Literature written in English	English is the main language when discussing supply chains. As an example, Swedish literature could lead to confusion of terms and misunderstanding.
Literature that discusses components included in the concept of supply chain resilience.	The thesis aims to answer what supply chain resilience is
Literature that discusses how supply chain resilience can be measured.	The thesis aims to answer what supply chain resilience is and arguably measurements is a good method to make supply chain resilience tangible.
Literature that discusses resilience strategies for supply chain resilience as a whole or a single capability.	The thesis aims to discuss strategies and their tradeoffs in the context of Assa Abloy Entrance Systems.
Literature that discusses resilience on the upstream side of the supply chain including the areas of supply, information, and logistics.	The thesis is limited to these three areas and the downstream side of the supply chain is filtered out.

Table 2

Keywords used in literature review

Review stage	Keywords used
Find Books	‘Supply chain’, ‘Resilience’’, ‘management’
Find literature reviews	‘Supply chain’, ‘Resilience’, ‘strategies’, ‘Review’
Rest of the literature	‘Supply chain’, ‘Resilience’, ‘Strategies’, ‘information’, ‘logistics’, ‘supply’, ‘Flexibility’, ‘Redundancy’, ‘Agility’, ‘Robustness’, ‘Adaptability’,‘Collaboration’, ‘Visibility’, ‘Control’, ‘Design’, ‘Density’, ‘Complexity’, ‘Node criticality’, ‘Assessment’, ‘Measure’, ‘Metrics’ ‘Index, ‘Disruption’, ‘Risk’, ‘COVID-19’, ‘Russia-Ukraine’

Table 3

Structured literature search for supply chain resilience strategies and measures

Keyword	Delimitation	Hits	Used	Snowballed
Supply chain resilience	Chalmers lib Print books	5	3	
Supply chain management	Chalmers lib Print books	20	2	
“Supply chain resilience strategies” AND “Literature review”	Chalmers lib	20 (13)	1	7
“Supply chain resilience strategies” AND (information OR logistics OR supply), including snowballing from these articles.	Chalmers lib	94(17)	4	6
"Supply chain resilience" AND (KPI OR "Key performance indicator" OR ASSESSMENT OR MEASURE OR INDEX OR Metrics) AND (Flexibility OR Redundancy OR Agility OR Robustness OR Adaptability OR Collaboration OR Visibility OR Control OR "Supply chain design" OR "Supply chain density" OR "Supply chain complexity" OR "Node criticality")	Chalmers lib abstracts	305 (38)	5	25

Note: () = Browsed through

The review of relevant literature focuses primarily on the supply chain characteristics associated with resilience, as well as the three dimensions of supply chain resilience strategies: preparedness, response, and recovery, and similar definitions. On the

upstream side of a supply chain, the strategies will concentrate on how to approach resilience in three distinct areas: information, logistics, and supply. Measuring the effects of supply chain resilience can be challenging, but creating a measurement of an abstract area may be an effective way to concretize it. Consequently, literature on measuring and evaluating supply chain resilience has been included. In addition, the literature on recent disruptions is reviewed in order to explain the global effects and to understand the problems confronting supply chains. This provided support for the semi-structured interviews regarding the disruptions and effects at Assa Abloy Entrance Systems.

2.2 Data collection

The different methods and structures used to obtain relevant data for the thesis are explained further in this section.

2.2.1 Sampling

Early on in the research process, interviews were conducted to understand the events that disrupted Assa Abloy Entrance Systems operations and the problems they caused. Multiple sampling techniques were utilized to compile the list of events that disrupted Assa Abloy Entrance Systems supply chain. A snowball approach, as described by Bell et al. (2019), was used to generate the initial list of Assa Abloy Entrance Systems interviewees, which included two top-level managers. We added the additional criterion that the employee must have worked on supply chain issues at Assa Abloy Entrance Systems for at least four years to ensure that the interviewee has primary knowledge of recent events. According to Bell et al. (2019), the primary determinant for the number of interviews conducted is data saturation; thus, the sampling was conducted sequentially, with new interviews added as new events and problems arose. Compared to the median sample size in business research, the symptom list sample size is relatively small (Bell et al., 2019). As a result, when data saturation became apparent because no new problems were discussed, we conducted an interview with our supervisor at Assa Abloy Entrance Systems, who has a comprehensive understanding of supply chain issues, to confirm that the data had been exhausted. There is a summary of the interviews in Table 4.

In order to collect data for the case projects, snowball sampling was also employed. First, the Material Management Director and the Vice President of Operations were consulted regarding which projects were appropriate, followed by interviews with the resilience project managers.

Table 4

List of interviewed employees to create a symptomlist and to understand previous case projects initiated by Assa Abloy Entrance Systems

Nr Interview	Role	Subject	Business Unit
1	Category Manager AAES Electronics	Symptomlist	ESD Göteborg
2	Sourcing director	Symptomlist	ESD Landskrona
3	Plant Manager	Symptomlist	IDS Ostrov
4	Senior Sourcing Specialist	Symptomlist	IDS Ostrov
5	Material Management Director	Symptomlist	ESD Landskrona
6	Supply Chain Controller	Symptomlist	PDS Landskrona
7	Logistics manager	Symptomlist	Landskrona
8	Logistic Manager	Project B	ESD Production Romania
9	Master Planner Manager Silkroad Pilot Project	Project A & symptomlist	PDS Landskrona
10	Sourcing Director	Symptomlist	IDS
11	Global Sourcing Manager PDS	Project A & symptomlist	PDS

2.2.2 Interview structure

As it is a flexible interview structure, all sessions of interviews were conducted in a semi-structured manner (Bryman & Bell, 2011). A flexible structure may be appropriate for answering our research questions, given that management may not be aware of all problems that have arisen as a result of disruptions. To allow the interviewee to relate the story from their perspective and to ensure that no issues were overlooked, a primarily inductive approach was used. Although the scope was limited, the interviewee was requested in advance to discuss information, logistics, and supply; thus, there are hints that a deductive method was used to structure the interview and the answers and prevent scope creep. The categories of information, logistics, and supply were selected because the topics related to previous pilot

projects at Assa Abloy Entrance Systems and were covered in the literature on supply chain resilience. Before conducting interviews, research was done on the general supply chain effects of COVID-19 and the Russia-Ukraine conflict. This allowed us to inquire about the general effects of the events if the interviewee did not address the specific topic in their narrative. As a result, none of the interviewees were discouraged from discussing a topic that did not precisely align with the interview guide, as doing so could yield new insights. An interview guide was also provided to interviewees prior to the scheduled meeting in order to increase the credibility of the interviews. The interviews were documented and summarized before being sent to the interviewee for validation and any additions that the interviewee deemed significant but that had not been addressed. The qualitative data from the interviews were coded into the categories of supply, information, and logistics; however, the summaries are not included in this report. This resulted in a consolidated summary of issues that occurred due to recent disruptions. The results of the second round of interviews are project descriptions and the effects of the projects on various KPIs.

2.2.3 Documentation

Internal documents, e.g., company and division presentations, supply chain overviews, KPI performance reviews, were used to establish the company description and provide quantitative data as a complement to the interviews. Access to the firm's business intelligence tool was also granted to complement data regarding the supply chain.

2.2.4 Ethics

Assa Abloy AB is a Stockholm stock exchange-listed corporation. Press releases ought to be used to disseminate new information to the public. This thesis shall not contain any confidential supplier or operational information. Assa Abloy Entrance Systems will exhaustively review the thesis to ensure that this is the case.

Bryman and Bell (2011) discuss the significance of not exploiting a position, as a student might do by extracting information from competitors that Assa Abloy Entrance Systems could use to its advantage. All interviewees for this report were internal, therefore, this is not a concern.

3. Theoretical framework

This section seeks to provide an academic literature-based definition of supply chain resilience. It will also include examples of recent supply chain disruptions discussed in the literature and the general effects they have had on supply chains. In addition, common supply chain strategies for enhancing supply chain resilience in the information, logistics, and supply domains will be presented, as will several KPIs that can be used to measure supply chain resilience. The section concludes with a discussion of the trade-offs that arise when developing a resilient supply chain.

3.1 Supply chain resilience

There are numerous definitions of supply chain resilience, but what they all have in common is the ability of supply chains to withstand foreseeable and unforeseeable disruptions to their normal operations (Kummer et al., 2022). There is also a distinct relationship between the definitions of resilient supply chains and time. Resilient supply chains recover to normal or enhanced operations on schedule or as quickly as feasible. According to Andersson (2009), resilient supply chains can both withstand and recover quickly from unanticipated disruptions. Falasca et al. (2008) define supply chain resilience as the ability to reduce the likelihood of disruptions, reduce the impact of disruptions, and increase the pace of recovery. Based on the three pillars of preparedness, response, and recovery, Rahman et al. (2022) compile a definition of supply chain resilience strategies. Ali et al. (2017) define similar dimensions as proactive, concurrent, and reactive. In addition, Kummer et al. (2022) observe that the literature distinguishes a fourth dimension from recovery, which they refer to as growth, or the capacity to emerge from disruption as a more effective organization. The authors of Vugrin et al. (2011) describe three system capacities that a resilient supply chain must possess: absorptive capacity, adaptive capacity, and restorative capacity. Absorptive capacity is defined as the extent to which a system can absorb the effects of disturbances with minimal consequences and effort. According to Vugrin et al. (2011), the difference between adaptive capacity and restorative capacity is that adaptive capacity is more concerned with temporary changes in a situation, while restorative capacity is more concerned with enduring changes in a system's capability.

3.1.1 Supply chain resilience determinants

Supply chain resilience increases as characteristics of resilience are enhanced and vulnerabilities are reduced (Pettit et al., 2019). However, it is difficult to comprehend the disruptions and the consequences of disruptions that firms are able to avoid due to their resilience capabilities, making it difficult to calculate the return on investment of decisions intended to make the supply chain more resilient.

In his research, Andersson (2009) argues that for a supply chain to be resilient, it must possess a combination of robustness, flexibility, and adaptability. The ability of a supply chain to withstand and avoid the effects of unanticipated disruptions serves as a gauge of its robustness. Creating inventory along the supply chain that can be utilized in the event of a production delay could exemplify robustness. Flexibility refers to the supply chain's responsiveness to disruptions and its willingness to alter its original course to accommodate the new circumstances. It could entail replacing a product's component with a comparable one so that supply chain operations can continue as normal despite a severe disruption to the supply chain. The authors of the article by Herold et al. (2021) provide examples of how air transport providers

responded to the COVID-19 pandemic with operational flexibility. They note that DB Schenker modified their passenger aircraft by eliminating seats so that they could transport regular cargo from Asia to the United States and Europe. In addition, Virgin Atlantic redirected one of their passenger planes to transport health supplies between London and Shanghai for the UK Department of Health and Social Care. Consequently, with flexibility, logistics service providers can increase their resilience by developing new capacities for the present circumstances. Adaptability is the capacity to alter operations or strategies in the appropriate direction in response to a disruption (Andersson, 2009). For instance, if a significant portion of the company's structure must be reconstructed, the supply chain can adapt to the prevailing circumstances. Adaptable supply chains have flexible supply chain designs that can alter the supply base, facility location, or even outsource a previously in-house process in response to environmental changes such as market, product, and strategy (Lee, 2004).

Agility is a capability discussed in the literature (Han et al., 2020) and is similar to flexibility, with the distinction that it refers to the speed with which flexible actions are performed in response to, for instance, changes in supply or demand (Lee, 2004). Christopher and Peck (2004) claim that agility is composed of visibility and speed. Visibility is defined as the capacity to have a distinct view of the entire supply chain, including knowledge of the environment and assets throughout the entire supply chain (Christopher and Peck, 2004). The ability to see through the supply chain can aid in identifying vulnerabilities and impending issues (Kummer et al., 2022). According to a McKinsey survey of manufacturers, 48% of businesses are familiar with their tier 1 suppliers, 21% with their tier 2 suppliers, and just 2% with their tier 3 suppliers (Sultan, 2022). Occasionally, supply chain visibility may also encompass the visibility of markets or competitors. Control in terms of monitoring potential disruptions and having the information to act on it is an additional aspect of supply chain resilience (Al-Talib et al., 2020), which is sometimes defined as a subset of visibility (McIntire, 2014). The Internet of Things (IoT) is extensively discussed in relation to this topic, and the benefits of supply chain resilience can be illustrated by using IoT to track shipments and control inventory.

Kummer et al. (2022) include supply chain collaboration among the characteristics of resilient supply chains. Due to the interdependence of businesses, achieving resilience individually is difficult (Cao & Zhang, 2013). Collaboration is characterized by the formation of cooperative, typically long-term relationships. Actors in a relationship can share tangible and intangible resources that complement one another, as well as coordinate activities in an efficient and synchronized manner. Visibility could enable collaborations related to, for example, aligning inventory levels or sharing forecast information. Although collaboration with suppliers is generally viewed as a good thing, there is also the issue of dependability: if the supply chain is too dependent on a single partner, flexibility is compromised (Ralston & Blackthurst, 2020).

The structure of the supply chain plays an essential role in ensuring resilience. Craighead et al. (2007) identify three structural determinants of supply chain resilience: density, complexity, and the number of critical nodes in the network. If a supply chain is dense and has a large portion of its supply base in a single location, it tends to be more vulnerable. As supply chain complexity increases beyond a certain threshold—that is, as the number of flows and actors in the system increases—the likelihood that disruptions will have a significant effect tends to rise. Similarly, the supply chain tends to be more vulnerable the more actors it depends on for its functionality.

The supply chain resilience deterministics discussed in this report are interrelated (Mandal et al., 2016). Visibility in the supply chain facilitates collaboration, as it is difficult to collaborate and improve the supply chain if the relevant actors and information are unknown. Moreover, supply chain collaboration is frequently a requirement for both flexibility and adaptability, as it would be impossible to reconfigure the supply chain or have alternative options if the supply chain partners did not permit it. Similarly, supply chain flexibility is essential for supply chain agility, as agility is defined as the rate at which flexible actions are executed.

Table 5

Supply chain resilience determinants derived from literature review

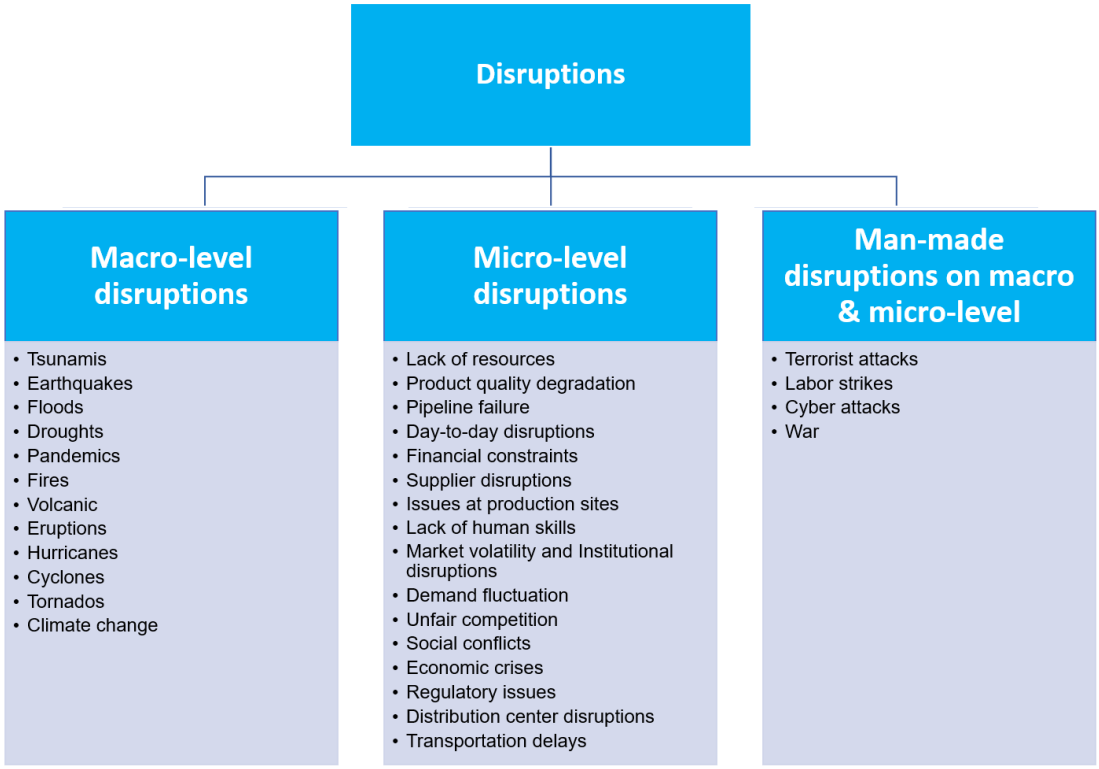
SCRES determinants	Description
Robustness	Coping with disruptions
Flexibility	Changing operations
Adaptability	Changing structure and strategy
Agility	The speed of flexible actions
Collaboration	Degree of resource sharing and coordination
Visibility	Access to information from suppliers and about supplier, about goods and the environment
Structure	Supply chain design

3.2 Supply chain disruptions

There are two categories of disruptions: macro- and micro-level disruptions. According to Rahman et al. (2022), macro-level disruptions have extensive effects on supply chains over an extended period of time and occur infrequently. Micro-level disruptions, on the other hand, occur frequently on a daily basis but affect the supply chain for a shorter period of time. Micro-disruptions are more predictable and easier to recover from. Although Rahman et al. (2022) label all as disruptions it could also be mentioned that some literature makes a distinction between operational disruptions and disasters, where disasters are similar to the macro-level disruptions (Wide, 2021). In Figure 4, examples of disruptions in the two categories are provided. Extreme weather, factory and trucker strikes, trade restrictions, and cyber disruptions were the leading causes of supply chain disruptions in 2022, according to the global value chain barometer for 2022 (Hong & Betti, 2023). According to Hong & Betti (2023), the most important actions towards more resilient supply chains in 2023 are diversifying the supplier base and conducting financial stress tests to comprehend the effects of a recessionary environment.

Figure 4

Examples of macro- and micro-level disruptions (Rahman et al., 2022)



3.2.1 Macro-level disruption: COVID-19

The COVID-19 pandemic, which started at the beginning of 2020, was a challenging time for supply chains globally. The supply side experienced major disruptions, and capacity at supplier sites was drastically reduced due to health-related reasons (Kummer et al., 2022). In addition, there were shortages of raw materials, such as construction materials, and components, such as computer chips. Initially, there was a decline in demand for metals among other commodities, but it soon recovered alongside the price increase (Yu et al., 2021). Numerous commodities, including lumber and concrete, experienced a price increase (Alsharef et al., 2021). Drastically and rapidly changing consumption patterns as well as hoarding tendencies made it even harder to deal with supply shortages for some industries (Kummer et al., 2022). This led to bullwhip effects, which emphasize the importance of supply chain collaboration and information sharing.

Since frequent passenger transport became unprofitable for airlines, the available midsection cargo capacity has been reduced to 25% of the 2019 capacity (Kummer et al., 2020). Approximately half of available air transport capacity is typically devoted to belly cargo. At the beginning of the COVID-19 outbreak, China's ports were closed for approximately two months. The shipping companies also anticipated a significant decrease in demand, so they slowed down, bypassed ports that are typically a part of routes, and decommissioned ships to reduce capacity (Kummer et al., 2022; Zhang & Adrian, 2023). As the demand for maritime transport recovered rapidly, the supply was inadequate, resulting in price increases up to ten times those of 2019 (Kummer et al., 2022). See Table 6 below for a breakdown of route-specific price increases

(Zhang & Adrian, 2021). The rapid recovery of demand led not only to price increases but also to congestion at ports, which lengthened transit periods for ocean transport (Kummer et al., 2022). Simultaneously with COVID-19, the Suez Canal obstruction occurred on March 23, 2021, which had a significant impact on ocean transport congestion and lead times.

Table 6

Changes in spot freight shipping rates. Adjusted from (Zhang & Adrian, 2021)

Route	Change between Nov 2020 and Nov 2021
Shanghai - Rotterdam	522%
Rotterdam - Shanghai	44%
Shanghai - Genoa	373%
Shanghai - Los Angeles	138%
Los Angeles - Shanghai	149%
Rotterdam - New York	204%
New York - Rotterdam	115%
Composite Index	252%

3.2.2 Micro-level disruption: US-China Tariffs

In July 2018, the Trump administration imposed 25 percent tariffs on Chinese-origin commodities imported into the United States (Office of the United States Trade Representative, 2018). Although some tariffs were eliminated by the Biden administration in 2021, there are still tariffs on more than 300 product categories (Lawder, 2022). Various rules determine the country of origin, but ultimately, U.S. Customs and Border Protection determines the country of origin (Yuanyou, 2019). For instance, the country of origin could be determined based on where the majority of the product's value originates, where the most significant transformation occurred, or where the product's harmonized system code was retrieved (Andersson & Olsson, 2021).

3.2.3 Man-made disruptions: Russia-Ukraine conflict

Russia provides 40% of Europe's natural gas and 25% of Europe's oil, which account for 40% and 25% of European consumption, respectively (Ngoc et al., 2022). Consequently, the conflict led to higher energy prices and, as a result, higher transportation and production costs. From the beginning of the conflict in February 2022 to September of the same year, gas and electricity prices in Europe more than doubled (Ferriani & Gazzani, 2022). This has had a significant impact on the financial performance of businesses, according to Ferriani and Gazzani (2022). High gas prices caused a domino effect on other energy sources, such as biomass, resulting in price increases of over 60 percent in Latvia (Prohorovs, 2022). After the conflict, prices of metals, steel, and aluminum, among others, soared; for example, steel

prices increased by approximately 15% per month (Sathe, 2022). Ukraine is a major steel producer.

Russia and Ukraine account for 15% of the global seafarer labor force, which, combined with the rising cost of energy, increases transportation costs and port congestion (Seckute, 2022). The increase in energy prices has affected all transportation costs (Kiss, 2022).

Ports and sea routes in the Black Sea and Sea of Azov have been closed due to military activity (Ngoc et al., 2022; Sathe, 2022). However, freight trains are permitted to proceed through Russia without stopping (Kiss, 2022). The majority of businesses continue to avoid Russia for security considerations. Instead, the central corridor is frequently followed. Additionally, the Russia-Ukraine conflict has resulted in longer transportation routes, which, along with the increase in energy costs, contribute to the price increase.

Figure 5

Part of the middle corridor route which starts at Lianyungang port in east coast China

3.2.4 The discovery of black swans

Long ago, all swans observed in the western hemisphere were white, leading zoologists to believe that all swans were white. Australia was discovered in the 17th century, along with the black swans that inhabited the continent. Taleb (2008) employs the metaphor of the black swan to illustrate how unreliable prior observations can be. This concept can be applicable to supply chain disruptions.

Although the COVID-19 pandemic may not have been completely unpredictable and could have been classified as a "gray swan," it was exceedingly difficult to foresee the global supply chain effects of such an event. A search for the terms "supply chain resilience" AND "pandemic" returned over 4000 results, but only 95 were published prior to 2019. The pandemic could be considered a low-probability, high-impact event. However, it is essential to keep in mind that the set of low-probability, high-impact events may be much larger than imagined, and the probability may be much higher collectively (Taleb, 2007). This is illustrated by a quotation from the supply chain manager at Flextronics: "I have 14,000 suppliers. I guarantee that at least one of the 14000 suppliers is not performing well today." (Sheffi, 2015). If the emphasis

on "I" is disregarded, this quote provides supply chain managers with an important lesson.

According to Taleb (2008), humans are extremely poor at both considering and estimating the effects of black swans; this is consistent with Tang (2006), who suggests that the difficulty of estimating probability and effects is the primary reason resilience efforts are typically ineffective. Table 11 of symptoms of disruptions in Section 4.2 demonstrates that there are a lot of effects to consider, and those are just the known ones. It is simpler to answer the question of what effects any event would have on financials if it disrupts supply, as estimating probabilities is no longer a factor (Simchi-Levi et al., 2014). In addition, humans have a tendency to construct narratives about past events, which can lead us to incorrectly associate causal relationships between events and their effects. This is called the "narrative fallacy" by Taleb (2008).

The approach regarding black swans (Taleb, 2008) suggests preparedness in general. The problem can also be simplified by using extremely conservative estimates, and if the investment in a particular supply chain resilience strategy still provides a strong business case, it should be pursued. As the famous Benjamin Franklin quote "An ounce of prevention is worth a pound of cure" implies, it is generally far more effective to prevent a problem than to respond to it and recover from it. Having a variety of contingency plans in place in advance of disruptions can significantly reduce recovery time and prevent long-term harm to brand image and customer relations (Sheffi, 2015).

3.3 Supply chain resilience strategies

This section introduces supply chain resilience strategies derived from the resilience determinants in section 3.1.1. The following sections aim to exhibit strategies that are related to these determinants.

Table 7

Summarizing table of all resilience strategies

Strategy category	Strategies suggested by literature
Inventory management	Strategic inventory sizing & positioning, time buffers, reserve stock programme, collaborative inventory, vendor-managed inventory, 3PL as inventory manager
Sourcing	Localization, glocalization, flexible supplier base, economic supply incentives, multiple sourcing, dual sourcing, backup suppliers, build outs, supplier backup capacity, supplier diversification, supplier selection on performance, supplier risk awareness
Supply chain design	Several structural supply chains, breaking down supply chains into smaller parts, efficient vs responsive supply chains, identical facilities, additional warehouses, backup routes, backup transportation, choice of 3PL provider
Product Design	Standardization, design for multiple Bill of Materials & alternatives, assortment of diversified items that require different raw materials
Supply chain collaboration	Horizontal and vertical cooperation, create unbreakable relations with key suppliers, integrate systems, distributing power
Supply chain visibility	Information sharing, mapping of a firm's supply chain, mapping of transportation network, IoT, blockchain, big data
Risk management & Culture	Risk management: Scenario analysis & simulations, contingency plans, simplify risk estimations. Culture: Communication, information sharing, rewards and incentives, empowerment & involvement, conditioning, continuous risk management work.

3.3.1 Inventory management

Inventory management is a common strategy for bolstering supply chain resilience. The measurement and placement of inventory throughout the supply chain must be considered (Sengupta, 2022). Peleg-Gillai et al. (2006) and Hopp (2008) state that in

order to achieve flexibility, features such as enhanced safety stock and time buffers can be implemented in order to be able to respond more effectively to large variations in demand or sudden disruptions.

Utilizing inventories to achieve resilience can be a costly undertaking; large inventories should be reserved for particularly strategic components or for limiting bottlenecks (Khojasteh, 2018). Inventories can be very effective, but they have a short-term nature, as no matter how large the inventory is, it will not last forever. As the cost of capital that is tied up increases over time, inventories are most effective as a resilience strategy for imminent and predictable disruptions. Sengupta's (2022) proposal of a strategic reserve stock program, which can be initiated if signs of disruption are detected, is an illustration of such reasoning. Under this program, the company, with the approval of the CEO, purchases a large quantity of reserve stock for relevant components that, under normal circumstances, would be well above inventory guidelines. This concept can be further developed by collaborating with actors within the same supply chain or even outside of it. For instance, Sears and Toyota, which operate in separate industries, were able to share an inventory for a substantial number of items (Tang, 2006). By implementing this methodology with a suitable partner, it is possible to hold a larger stock at a lower holding cost. A vendor-managed inventory methodology could also be used to improve the efficacy and resilience of the supply chain (Khojasteh, 2018). Multiple suppliers are provided with inventory data and a collaborative platform by Walmart in order to prevent stock depletion during disruptive periods. Walmart has had tremendous success with this concept. Although few sources covering the relationship between vendor-managed inventory and resilience have been identified, it is important to note that some sources cannot establish a correlation between methods such as vendor-managed inventories and enhanced supply chain resilience (Brusset & Teller, 2017). In addition, Herold et al. (2021) recommend collaborating with logistics service providers that develop and oversee inventory management for critical supplies in the supply chain to enhance resilience.

3.3.2 Sourcing

Localized supply chains tends to be more resilient and sustainable than globalization, which was the primary focus of the past. Rahman et al. (2022) emphasize the significance of selecting suppliers located close to production sites in order to be more resistant to transport delays. Locally established supply chain networks are advantageous for flexibility in the event of global or local disruptions, according to Sarkar et al. (2022), due to reduced lead times and the possibility of having buffers close to manufacturing. However, even if the manufacturing is located in close proximity to the supplier base, the supplier may be sourcing from a distant region, which would merely shift the bottleneck (Pickett, 2003). In their article, Spieske et al. (2022) state that it is promising to consider near-shoring and localization in preparation for pandemic challenges. However, "glocalization" as the new buzzword is also mentioned, which is a combination of localization and globalization, indicating that organizations are not prepared to go completely localized in the future and will instead use a combination of these strategies (Spieske et al., 2022). Longer lead times increase the supply chain's susceptibility to disruptions and fluctuations, highlighting the significance of reducing lead times to enhance resilience (Tang, 2006). This is possible by reorganizing supply chain networks. The article by Tang (2006) describes a case in which all phases of a textile supply chain were relocated to a single geographic region, resulting in a reduction of the lead time from concept to sale from ten to fifty weeks to less than sixty days.

Utilizing a flexible supplier base is an effective method for mitigating unforeseen disruptions (Tang, 2006). The 1997 devaluation of the Indonesian Rupiah was mitigated by the contribution of the supply chain management corporation Li and Fung. Due to their inability to afford the increased cost of imported components, it was difficult for Indonesian suppliers to complete their productions during this period. At this time, The Limited and Warner Bros outsourced their sourcing to Li and Fung. They in turn had a vast supplier contact network, which allowed them to transfer suppliers and utilize some that were operating in other Asian nations. At the same time, Li and Fung could assist their Indonesian vendors with, for instance, loans so that they could eventually resume delivery as planned (Tang, 2006).

In many instances, the number of suppliers on the market is limited, and it is not possible to have a flexible supplier base (Tang, 2006). In order to increase flexibility in these situations, economic incentives can be used to encourage the entry of new suppliers into the market. Intercon Japan responded to a key supplier's "monopoly attitude" by assisting a new supplier, Nagoya Steel, to enter the market through the use of economic incentives. The objective was for Nagoya Steel to develop a process technology that differed from that of the previous key supplier in order to generate competition and maintain affordable prices for both suppliers.

Dual or multiple sourcing are frequently employed methods for constructing resilient supply chains. Multiple sourcing, according to Namdar et al. (2018), can help an organization manage both macro and micro risks, such as natural disasters, component shortages, strikes, and technological uncertainty. The production volume can then be increased at a different supplier and shifted back when feasible, resulting in an improved service level. Sengupta (2022) asserts that single sourcing is a thing of the past, and that it should only be used when a second source is either unaffordable or unavailable. If single sourcing is chosen, which sometimes makes economic sense, Picket (2003) suggests that it must be monitored, with supplier data and relationships evaluated frequently and contingency plans based on the critical suppliers. There are numerous examples of businesses choosing single-sourcing despite being aware of the hazards (Sheffi, 2007). For instance, Unilever ran out of Q-tips because a hurricane destroyed the only facility that produced them. Despite this, Unilever decided to restore the plant and continue using a single supplier following the hurricane. Instead of transitioning to a strategy of multiple sourcing, they decided to increase their inventory levels by 10% and establish barge-based backup transportation routes.

Multiple sourcing can also reduce the possibility of price hikes (Zillner, 2022). It is recommended to pursue a multiple procurement strategy in conjunction with price comparison and cherry-picking the lowest price as opposed to pursuing volume discounts through fewer commodity supplier relationships. In transactions with commodity suppliers, supply contracts can be made more robust by establishing the price for a predetermined period of time in the future. Similarly, it can be fixed to a certain range based on an agreement between the parties or the current open market price. Zillner (2022) refers to these contract configurations as "forward contracts," "escalator clauses," and "window clauses."

Partnering with and collaborating with backup suppliers are additional methods to create flexibility (Rahman et al., 2022). According to Hosseini and Barker (2016), it is advantageous for a supplier and manufacturer to contract with backup suppliers prior to disruptions in order to be able to fulfill consumer orders in the event of a strike. Namdar et al. (2018) note in their study that it is common practice for the consumer to reserve a predetermined quantity of capacity from the backup supplier in exchange for a reservation fee. If the reserved capacity is not utilized, the purchaser

will incur a penalty fee. This strategy is effective when combined with other strategies, such as procurement from the spot market and a long-term supplier, where the trade-offs between increased resilience and higher cost can be mitigated (Namdar et al., 2018). A comparable alternative to backup supply is to construct recovery sites that can be utilized in the event that the primary site is interrupted (Sengupta, 2022). This could be accomplished through a joint investment by the company and its supplier.

Coordination and planning of backup capacity at the supplier's manufacturing facilities is another approach (Rahman et al., 2022). Firms should routinely assess their capacity levels to identify potential constraints and excess capacity in the supply chain (Hoppe & Podkowiak, 2021).

According to Earring (2010), supplier diversification and ensuring that a business has suppliers from multiple geographical regions is one strategy for enhancing resilience. Consequently, risks associated with disruptions that strike particular regions, such as natural disasters and geopolitical tension, can be mitigated. (Hong & Betti, 2023; Sengupta, 2022; Earing, 2010). This is supported by Kazemian et al. (2022), who note that diversification strategies may be applied to supplier bases, distribution sites, and manufacturing facilities.

There are also suggestions to select suppliers based on their performance rather than their cost-effectiveness to reduce supply-side risk (Rahman et al., 2021). Regarding selecting suppliers based on performance, "suppliers' risk awareness" is an important factor to consider when selecting suppliers. If a key supplier fails, the entire production can be jeopardized, making this a crucial aspect of the supply chain (Kazemian et al., 2022). In terms of supplier criticality, it is common practice to concentrate risk management efforts on suppliers whose financial impact or component supply is particularly crucial. However, it is crucial to keep in mind that suppliers of low-cost commodities, for example, can cause significant disruptions if their supply is interrupted (Simchi-Levi et al., 2014). After a comprehensive investigation of Ford Motor's supplier risk, it was discovered that some suppliers of low-cost commodities with lower volumes were overlooked due to standard practice, despite the fact that these suppliers posed the greatest risk in the event of a supply disruption.

3.3.3 Supply chain design

Ivanov (2022) discusses the prospect of having multiple structural supply chain designs to deal with various situations. The idea is to have a single structure for periods of economic expansion and low disruptions. The supply chain should then be designed to attain a high level of product variation in order to accommodate customization and satisfy the needs of customers. In addition, a second supply chain design should be available for use in scenarios such as natural disasters. This design is intended to be adaptable so as to be able to respond to such local events; it includes the storage of excess inventory, plans for fallback suppliers, and the possibility of adjusting production capacity. In the event of larger disruptions, such as the COVID-19 pandemic, a third form of structure is suggested as a design option. Then, the supply chain should have the ability to adapt production to a new demand type. During the COVID-19 pandemic, for instance, logistic providers altered their operations to transport medical supplies rather than passengers. It could also refer to reducing the variety of products to ensure customer delivery.

Malik et al. (2011) discuss the fragmentation of vast supply chains into more manageable chunks. The article uses a case study in the US as an illustration. The

company decided to divide their supply chain into four sections because they had reached a point where forecasting and customer service were difficult to get right due to the increased variation in customer demand. Each component was uniquely structured based on the degree of demand volatility relative to weekly sales volume. High-volume products with stable demand continued to be manufactured in China, whereas high-volume and low-volume products with volatile demand were designated to be manufactured in North American facilities. The argument for increasing production in a high-cost nation such as the United States was that inventory and delayed sales could be reduced and the products could reach the market more quickly, which would be economically beneficial.

Strategic priorities should be considered when designing a product's supply chain (Sáenz & Revilla, 2014). Two Cisco routers had significantly different supply chains. For one router, the client prioritized service levels; consequently, a flexible and resilient supply chain was developed. For a more fundamental router, the consumer placed a premium on price, so the supply chain had fewer flexible options. This method of thinking is comparable to Fisher's (1997) supply chain framework, which suggests that stable-demand commodity products should have efficient supply chains with a focus on cost. Conversely, more innovative products necessitate a flexible, agile, and resilient supply chain, which Fisher (1997) refers to as "responsive supply chains." Cohen et al. (2022) introduce the "Triple-P" framework, which extends Fisher's (1997) framework. It suggests that not only the product but also the firm's product portfolio as a whole should be considered; if a company has a portfolio with thousands of products, it is difficult to have the requisite power, visibility, and collaboration to implement resilience strategies. Suppliers should also be considered; the number of available suppliers and the number of suppliers a company works with can limit the scope of potential supply chain resilience strategies.

Having identical designs, processes, and facilities for multiple plants is another method to increase the flexibility of supply chain components (Kazemian et al., 2022). It indicates that, in the event of a disruption, partners in the supply chain are able to work together and transfer products between each other to accommodate disruptions and fluctuating demand. Intel ensures that the layout, required machinery, and process for enabling flexible capacity switches are identical (Khojasteh, 2018). Smith & Wesson utilizes excess factory space and capacity for injection molding, forging, and heat treatment, which they sell as a service to other companies (Smith & Wesson, 2022). A strategy can be derived from the Smith & Wesson case: for supply chains that are designed with excess capacity in the form of additional or larger factories for reasons of resilience and flexibility, the excess capacity can be used to offer manufacturing services to reduce the trade-off between cost and flexibility.

Furthermore, flexibility and adaptability must be considered during the design phase of warehouses (Schuhmayer, 2022). This could take the form of a potential expansion area that can be utilized if another facility is disrupted, or simply contemplating the possibility of natural disasters and adding warehouses to the network accordingly. The robustness of the warehouses can be greatly impacted by exercising due diligence when selecting locations. The selection of distribution centers should also be made with reliability in mind (Rahman et al., 2022). Fattahi et al. (2017) emphasize the significance of locating them near to customers to reduce the likelihood of significant transport disruptions upstream in the supply chain. In designing warehouse structures, there is a trade-off between scale economies and resilience (Schuhmayer, 2022). Ericsson has decided to operate three warehouses despite the fact that a single warehouse would suffice in the current situation. In addition, contractual employees can provide additional flexibility to respond to

downturns and upturns. As it is simpler to terminate a warehouse contract than to sell a fully owned warehouse, outsourcing warehouse operations can also increase flexibility.

Rahman et al. (2022) propose having alternative routes to protect against transportation disruptions. According to Kumar et al. (2014), the choice of transport mode is significant, and the article argues that multicarrier and multimodal transportation are preferable, as well as the use of multiple routes to prevent transport delays. One company had prepared an ocean transport route in the event of road transport disruptions; when they did occur, the ocean transport route was faster (Azevedo et al., 2013). Establishing close relationships with airlines and airline brokers in advance, despite the fact that air travel is not the primary mode of conveyance, is an additional method for enhancing the resilience of logistics (Hoppe & Podkowiak, 2022).

According to Zhen et al. (2016), secondary transportation is a resiliency-enhancing strategy. When a distribution center has backup transportation, it can allow other distribution centers to transport its products or components within the company or to its consumers in the event of a disruption. However, because these parties are frequently subsidiaries or competitors, enabling these transports incurs a higher cost due to charges for overtime, alterations in delivery schedules, and overall additional fees.

Other authors, such as Liu and Lee (2018), discuss the benefits of utilizing a well-established third-party logistics provider. According to the third-party logistics industry, internal integration is more essential than external integration when it comes to enhancing the resilience of supply chains. Internal integration could be accomplished through the use of "integrated logistics operation systems", which would enable the third-party logistics provider to be more agile in their processes and better able to react to disruptions. To accomplish supply chain resilience, organizations must improve not only their internal integration, but also their collaboration with other logistic actors and their customer integration.

3.3.4 Product design

A large body of research demonstrates that communication between supply chain operations and research and development departments can yield a plethora of robust strategies (Simchi-Levi et al., 2015; Hoppe & Podkowy, 2022; Lee, 2004). Changing the design of a product is sometimes preferable to investing in inventory redundancy (Simchi-Levi et al., 2015).

The more customized a product is, the more difficult it is to reconfigure it for other sources of supply. If components, particularly critical components, can be standardized through design changes, it is easier to locate multiple sources of supply, thereby reducing the likelihood of component shortages (Hoppe & Podkowiak, 2022). A factory that supplied Nokia and Ericsson was destroyed by fire in March of 2000. In five days, Nokia received supplies from Japan and the United States after standardizing the design of the chips (Lee, 2004). Ericsson, on the other hand, had eliminated all of their backup suppliers in an effort to reduce costs, and they were unable to modify the design, resulting in months of factory downtime and delays in the release of a new product.

In the food industry, it is common for there to be multiple listed recipes that satisfy the same product specifications and yield extremely similar products (Sengupta, 2022). If a manufacturing company could apply a similar concept to their Bill of

Materials, components, or raw materials, it would be extremely advantageous during shortages. Sengupta (2022) provides examples of heavy plastics replacing light metals and piatex replacing leather. The majority of the time, it is crucial that a change in the product's material does not result in any visual differences. Similarly, design can be used to reduce price risk; if a product can be designed so that the base material can be switched, for example, from aluminum to steel, it can add flexibility to the supply chain and drastically reduce the risk of commodity price increases because the cheapest of the two can be chosen (Pellegrino et al., 2019). A diversified assortment of articles that consist of different raw materials can also create a hedge against commodity price fluctuations (Zillner, 2022). Another method to hedge against commodity prices is to use options or futures contracts. For example, if a manufacturer is highly dependent on steel prices, it might purchase options or future contracts that benefit from increases in steel prices. Even though commodities are in fact commodities that tend to be easy to get hold of, some manufacturers whose profitability depends on commodity prices hold strategic stocks of commodity products that they purchase when prices are good enough (Zillner, 2022).

3.3.5 Enhance supply chain collaboration

In their work, Kazemian et al. (2022) emphasize the significance of power distribution among supply chain partners. Due to the fact that each party can make their own decisions and does not need to wait for other key partners to give instructions, this can result in much faster reaction times. Consequently, the effect of disruptions can be mitigated. Liu et al. (2021) examine empowerment through the lens of Chinese logistical platforms like JD Logistics and Cainiao. Through technology and the vast amounts of data at their disposal, these participants can empower supply chain partners to make independent decisions. Empowerment is a highly effective tool for achieving a high degree of interorganizational collaboration in a supply chain (Liu et al., 2021).

In order to improve the resilience of the supply chain, there are also strong recommendations for enhancing supplier relationships and expanding collaborations with suppliers (Rahman et al., 2022). According to Christopher and Peck (2004), supply chain collaboration and investment in stronger partnerships are very advantageous for mitigating risks and minimizing the impact of disruptions. The authors (Christopher and Peck, 2004) use the term "supply chain intelligence" to describe the objective of fostering a higher level of collaboration, greater transparency, and information sharing among supply chain partners. Kazemian et al. (2022) argue that collaborative relationships across supply chains are one of the most influential factors that can increase the resilience of an entire supply chain. Schumayer (2022) identifies horizontal and vertical cooperation as the two types of collaboration. Although it requires a great deal of trust, some businesses engage in horizontal collaboration, in which two firms that are normally considered competitors assist each other when stock runs out at one business. The actors in the supply chain engage in vertical cooperation; discussing capacities and inventories along the supply chain can make it significantly more resilient. In addition to production processes, the concept of bottlenecks also exists in supply chains. If bottlenecks can be identified, the supply chain can collaborate by, for instance, sharing investment costs for additional capacity or inventory.

Kazemian et al. (2022) note that a close relationship with key suppliers in the supply chain can be advantageous because business continuity is frequently reliant on these suppliers. By establishing unbreakable relationships, the entire supply chain can be made more resilient, and disruptions can be dealt with more effectively. The

primary activities and factors that foster collaboration and strong relationships are incentive and goal alignment, mutual dependence, resource and information sharing, communication, collaborative learning, and finally collaborative decision-making (Scholten & Schilder, 2015).

3.3.6 Increasing supply chain visibility

Integrating systems to gain visibility into transactions throughout the supply chain was one of the top initiatives to improve supply chain visibility (Heaney, 2013). Sengupta (2022) suggests that software that displays a map of the company's supply chain as well as ongoing geopolitical risks is an additional means of enhancing visibility. Mapping transportation networks can increase resilience in the same way that mapping supplier networks can increase the visibility of their networks. Hoppe & Podkowik (2022) recommend identifying nearby airports, road and rail transport carriers that operate in the local region, analyzing customs' capabilities, etc.

According to Chopra (2013), effective information sharing can improve the utilization of supply chain assets and make this process significantly more efficient. In addition, it can improve the supply chain's coordination of flows, resulting in lower costs and greater flexibility. Sharing information throughout the supply chain can also help identify weak links, prevent overreactions, and provide information about component shortages, thereby reducing unproductive decision making in a high-risk environment (Namdar et al., 2021). In addition, the supply chain benefits from reduced uncertainty and whiplash effects (Christopher and Peck, 2004; Namdar et al., 2021).

The Internet of Things (IoT), blockchains, and big data can help make the supply chain more transparent and facilitate the sharing of high-quality information both upstream and downstream. Consequently, concerned actors can obtain more accurate and up-to-date information, which will assist them in making the right decisions and acting more proactively, allowing them to recover from disruptions more quickly (Rahman et al., 2022).

3.3.7 Risk management & Corporate culture

Important to supply chain resilience is a strategy that includes assessing and managing risks in a company's supply chain to mitigate the effects of disruptions (Kumar et al., 2014). Depending on the type of product, whether the probability of disruption is high or low, and whether the consequences of a disruption would be mild or severe, different strategies that strike a balance between these parameters are suitable.

Another approach is to examine and improve the adaptability of organizational change management systems (Kumar et al., 2014). One way to improve the processes is to conduct disruption simulations as a form of scenario analysis to determine whether the organization can effectively implement its crisis management plans. In this way, many new lessons can be learned without actually experiencing a crisis, and they can contribute to the improvement of the infrastructure associated with supply chain flexibility. Supporting this notion, there appears to be a clear relationship between resilient companies that handle high-impact events well and companies that deal with almost daily small disruptions (Sheffi, 2007). Kazemian et al. (2022) emphasize that the entire supply chain should have a business continuity management system as a safeguard against disruptions. Christopher and Peck (2004) argue that, when addressing business continuity management, risk mitigation should go beyond the organizational level and encompass the entire supply chain. After recovering from a disruption, a company and its supply chain should review and

update their contingency plans in order to handle future disruptions effectively (Hoppe & Podkowiak, 2022).

The estimation of probabilities and the economic impact of disruptive events present a challenge for risk management, making it difficult to calculate the expected return on investment (Tang, 2006). To simplify the issue, Simchi-Levi et al. (2014) created a model that did not take probabilities into account but instead focused on answering the question of what the impact would be and how long it would take to recover if the supply of a particular component or material ceased.

Literature acknowledges that culture plays a significant role in the efficacy of risk management and the majority of resilience dimensions (Christopher & Peck, 2004; Kumar & Anbanandam, 2020; Pickett, 2003; Sheffi, 2007). Even Pickett (2003) acknowledges that culture is the most effective resilience strategy.

Sheffi (2007) identifies four characteristics that comprise the organizational culture of resilient organizations:

1. Frequent internal communication and information sharing - Information about the state of the company in form of KPIs and reports of the current situation. A culture where information sharing is emphasized and employees feel safe to share signs of risk and bad news increases supply chain resilience as it enhances the dimensions of supply chain resilience (Kumar & Anbanandam, 2020).
2. Empowerment by distributing power - It is probably not management who encounters a disruption first and therefore it is important that the employees who do can act on it (Sheffi, 2007). It is important to connect rewards and align employees with the strategy.
3. Care for the success of the organization
4. Experience and conditioning from previous disruptive events: industries whose daily operations are frequently disrupted are typically better equipped to handle low-probability, high-impact events.

Christopher & Peck (2004) suggest two measures for enhancing the culture of risk management: involving supply chain management in crucial cross-functional decisions and establishing a team with a focus on supply chain risk that reports to the board. Pickett (2003) adds that, over time, a resilient mindset and culture can be cultivated by remaining vigilant for potential disruptions.

3.4 Measuring supply chain resilience

Measuring supply chain resilience should also be regarded as part of a strategy towards resilience. Cisco monitored its resiliency by compiling an index that evaluated its capabilities in four dimensions: product design, supply chain design, manufacturing, and testing (Sáenz & Revilla, 2014). To fully comprehend if a supply chain is improved, performance metrics must improve; most organizations fail to consider resilience because, due to its dynamic nature, they fail to develop performance metrics for it (Singh et al., 2019). Resilience key performance indicators should support a chosen strategy and assist with its implementation (Han et al., 2020). Thus, one KPI may be appropriate for measuring one strategy but not another.

Few studies have been conducted on resilience metrics (Han et al., 2020). This is likely due to the difficulty of measuring supply chain resilience, and the fact that an organization's true supply chain resilience is only revealed after a disruption amplifies the difficulty of measuring it (Guoping & Xinqui, 2010). Second, Hosseini et al. (2020) note that ripple effects make it more difficult to predict how a disruption may impact the supply chain.

This section introduces and summarizes a variety of performance metrics that could be used to measure supply chain resilience. The performance metrics are related to the supply chain resilience determinants presented in Table 5 of Section 3.1.1. Although there are other methods to structure the evaluation of supply chain resilience, such as evaluating on a system level such as logistics, procurement, and production (Guoping & Xinqui, 2010), these are the most common. In addition, there is a plethora of literature on simulations and quantitative modeling that aims to quantify the supply chain resilience of firms (Agarwal et al., 2022; Ribeiro & Barbosa-Povoa, 2018). Nonetheless, it is essential that measurements be both easy to understand and resistant to manipulation (Singh et al., 2019).

3.4.1 Robustness

From a preparedness perspective, robustness can be measured as inventory levels throughout the supply chain or as excess capacity available, which can also be expressed as a utilization rate (Werner et al., 2021). Ivanov (2019) suggests order fill rate for measuring inventory levels, while Rajesh (2016) adds inventory accuracy rate to prevent being misled by inventory data in the system. Werner et al. (2021) add that the inventory could be advantageously divided into critical and low-risk component inventories.

Simchi-Levi et al. (2015) introduce two resilience-related concepts: time to sustain (TTS) and time to recover (TTR). The time to endure is defined as the amount of time a node, such as a supplier, can meet demand during a disruption, whereas the time to recover is the amount of time it would take to resume normal operations following the disruption. Therefore, if the TTS is longer than the TTR, the node is robust and disruption would have no effect on performance if it is longer than the TTR. Using a combination of these metrics and the cost of disruption during a specific time period, the most vital suppliers in the supply chain were subsequently identified. Suppliers need a budget to be able to recover, so the financial health of a supplier can be seen as a metric of robustness (Hosseini & Barker, 2016).

Supplier reliability (Ivanov et al., 2019) and supplier rejection rate (Karl et al., 2018) can be used to evaluate robustness at supply sites and the focal factory. By continuously measuring suppliers' dependability and other performance metrics, it is possible for a business to determine which suppliers to continue working with and which to end relations with (Huang & Keskar, 2007). By collaborating with higher-performing suppliers, it is likely that the supply chain will also perform better during disruptions. Simatupang and Sridharan (2005) suggest using a supplier scorecard approach for this benchmarking procedure.

3.4.2 Flexibility

To measure flexibility, the number of incidents handled through flexible actions in the process or product is suggested by Rajesh (2016), although it is not explained how such a metric would be constructed in practice or how the data would be collected. Hosseini & Barker (2016) introduce rerouting options for transportation and resilience metrics when selecting suppliers. Having the ability to alter delivery dates can also

indicate flexibility that can be measured (Vargas & González, 2016). There is also an opportunity to be creative and adapt company-specific metrics not only for flexibility but for supply chain resilience in general. As an illustration, Hosseini et al. (2020) emphasize a variety of resilience metrics for an inland port, such as space utilization and additional handling equipment, that would be irrelevant at other companies.

3.4.3 Adaptability

A measurement of adaptability found in literature is planning cycle time, which is derived from the frequency of S&OP meetings in the organization (Chae, 2009). Adaptable supply chains have the option of reconfiguring, so measuring available alternatives per supply category is relevant (Carvalho et al., 2012).

3.4.4 Agility

To evaluate agility, Lin et al. (2006) create an agility index based on a multitude of attributes, such as the time of decision-making and the rate at which information about demand and supply is captured. Supply chain agility is abstract in nature and highly uncertain to measure, and the authors highlight this using terminology like "fuzzy". Other agility metrics found in the literature are upside and downside flexibility, which aim to answer the question of how much of a demand increase or decrease the supply chain can sustain in 30 days (Bauer & Göbl, 2017). As an illustration, a supply chain that currently meets a monthly demand of 1,000 units but could produce 1,500 units if the demand increased has 50% upside flexibility. This measurement could also be inverted to determine the number of days required for the supply chain to accommodate a specified percentage increase in demand.

Short lead times relate to agile supply chains (Singh et al., 2019). A positive correlation between lead time and supply chain resilience has been shown by multiple studies in the literature, which imply that lead time should be measured as part of supply chain resilience (Han et al., 2020). Lead time variance is a good complement to understanding how the lead time varies (Ivanov, 2019). Carvalho et al. (2012) suggest measuring the lead time between a supplier and facility when the supplier is "new", i.e., purchased due to a disruption.

3.4.5 Collaboration

The collaboration index developed by Simatupang and Sridharan (2005) takes into account information sharing, incentive alignment, and decision synchronization. If incentives are not aligned, it is difficult to collaborate, which can contribute to conflict and poor results. The alignment of incentives includes sharing of results, such as the sharing of increased inventory costs or inventory savings. The synchronization of decisions incorporates elements such as assortment alignment, inventory levels, forecasting, and order quantity. Moreover, Ramanathan et al. (2011) argue that distinct collaboration metric complexity levels should be utilized based on the relationship stage. When the relationship is more advanced and long-term, investments in technology, for instance, should be monitored, according to Ramanathan et al. (2011).

3.4.6 Visibility

Supply chain visibility is part of supply chain resilience, and it is also highly related to information sharing (Karl et al., 2018). To measure it, a visibility index based on the quantity and quality of supplier information can be used (Caridi et al., 2010) to enable an analysis of the different types of information it can be categorized into.

1. Event information regarding shipping details, order changes, etc.
2. Status information regarding current stock levels, capacity, etc.
3. Specification information regarding technical details such as life cycles, shelf lives, etc.
4. Plan information regarding what they plan to produce, forecasts, future investments, etc.

Supply chain managers can then assign a score to each type of information from the different suppliers based on the quantity and quality of information they have access to, i.e., whether the information was received on time and how accurate it was (Caridi et al., 2010). Furthermore, there is the issue of defining what information is essential to receive, which varies by company (Kalaiarasan et al., 2022).

Forecasting is an essential element of planning, and accurate forecasts result in more resilient supply chains because the supply chains are able to be proactive; therefore, forecast accuracy is a crucial indicator of resilience (Patidar et al., 2022).

3.4.7 Supply chain structure

In this report, supply chain density, complexity, and node criticality are included in the supply chain structure dimension.

Supply chain density can be measured as the average distance between nodes in the supply chain (Craighead et al., 2007). Similarly, Patidar et al. (2022) suggest measuring the distance between manufacturers and suppliers as part of resilience assessments. Choudhary et al. (2021) refer to supply chain density as spatial complexity and measure the share of the supply base in specific geographic regions.

On a national level, the world risk report produces an annual world risk index that combines the likelihood of a country being hit by a natural disaster with the resilience of the country (United Nations Office for the Coordination of Humanitarian Affairs, 2022). In terms of logistics, the World Bank has created a Logistics Performance Index (LPI) for countries, which ranks countries in terms of resilience-related dimensions such as quality of infrastructure and delivery accuracy (The World Bank, n.d.). Resilience was one of many important aspects considered when constructing the logistics performance index (Arvis et al., 2018).

Supply chain complexity can be measured by the number of nodes and flows in a supply chain. Kim et al. (2015) suggest that complexity needs to be balanced and that there are studies showing a positive correlation between resilience and both high and low complexity. Choudhary et al. (2021) take a supply network point of view and establish the measure average degree, which is calculated as the number of relationships in the network divided by the number of nodes. They further discovered a negative correlation between average degree and supply network resilience. Further on, they propose that the optimal structure of a supply network seems to follow the 20/80 rule, where 20% of facilities have relationships with 80% of the rest of the network, as this seems to be an appropriate complexity level that allows supply networks to adapt and handle disruptions at critical nodes.

3.4.8 Common characteristics of supply chain resilience metrics

When measuring supply chain resilience, metrics are often compared to a baseline case that attempts to establish what the performance would be if no disruption occurred (Behzadi et al., 2020). For example, measuring the supply rejection rate for

a baseline case and comparing it to the supply rejection rate during disruption. A related general concept is recovery level, which can be used with multiple metrics such as cost of goods sold or service level and analyzes what percentage of performance remains after a certain time period has elapsed since a specific disruption (Behzadi et al., 2020). Additionally, because the definition of supply chain resilience also includes how long it takes to recover, the time aspect should be considered when measuring resilience. In relation to time, Behzadi et al. (2020) use net present values when calculating lost profits due to disruptions, as some disruptions are more likely to occur more frequently than others. The usage of indexes is common as many dimensions, for example, collaboration and visibility are qualitative. Ivanov et al. (2019) propose the performance impact index, which compares the budgeted sales projections to the actual sales during the disruption. This could be used to compare supply chains internally.

3.4.9 “SMART” framework for Key Performance Indicators

Almström et al. (2017) recommended that KPIs be designed according to the “SMART” framework: *Specific, Measurable, Achievable, Relevant, Time-bound*. It should be measurable and assignable to an employee who can collect the data and calculate the KPI, and it must measure a specific area that you wish to improve. KPIs should either be aligned with the overarching strategy or serve as a performance indicator for the strategy; therefore, they are often paired with goals that ought to be realistic and time-specific.

In addition to the "SMART" framework, Almstrom et al. (2017) discuss additional characteristics that KPIs should ideally possess, including that they should be relative and not absolute. KPIs can have dependencies; for instance, an increase in units produced does not necessarily mean the production is more efficient, as more resources may have been used. By assessing KPIs as ratios, such as the number of units produced per hour worked, the KPI serves as a more accurate indicator of efficiency.

Additionally, KPIs should preferably aid in the comparison of performance between internal sites and external competitors’ sites (Almström et al., 2017). Furthermore, the KPI should be as simple as possible and clearly defined to avoid misunderstandings and divergent interpretations of the measure throughout the organization. In addition, the bare minimum of KPIs should be used to avoid information overload.

Table 8

A consolidation of KPI dimensions from Almström et al. (2017)

Dimension	Description
Strategy	KPI's should either be in line with the strategy or confirm if the strategy is working
Relative	Ratios are preferred over absolute numbers
Clearly Defined	Avoid different interpretations
Simple	Avoid misunderstandings
Few	Too many KPI can easily get out of hand
Comparable	Aid comparison between internal sites and competitors
SMART framework	
Specific	KPI reflecting clear area of improvement
Measurable	Make sure it is possible to measure
Assignable	Assign someone in the organization to measure and follow up
Realistic	Connected goal is achievable
Time-specific	State when the goal should be achieved

3.5 Trade-offs when creating a resilient supply chain

In traditional supply chain management, managing cost and service level has been the main goal for supply chain professionals, but in more recent developments, sustainability has also become a primary dimension for many companies (Ivanov et al., 2019). Recent times, even before COVID-19, have been turbulent for supply chains, and it has become evident that supply chain professionals have to manage an additional dimension, resilience (Ivanov et al., 2019). Trade-offs between all the dimensions frequently occur in decisions; a reduction in cost can lead to negative impacts on service levels, and vice versa. When evaluating cost trade-offs, the total cost should be considered (Jabbarzadeh et al., 2018). It is important to note that trade-offs can also occur between resilience determinants (Tukamuhabwa et al., 2015).

Figure 6

Supply chain management triangle based on Ivanov et al. (2019)

4. Empirical data and analysis

This section is based on empirical data derived from Assa Abloy's website and interviews with employees at Assa Abloy Entrance Systems. Firstly, a description of the company is provided. Thereafter, a symptomlist is presented showing effects from relevant disruptions between the years 2019-2023. Lastly, two case projects A and B are explained and explored from the interviewees perspective. The interviewees can be seen in Table 4, section 2.2.1.

4.1 Assa Abloy

Since the founding of Assa Abloy in 1994, they have made over 300 acquisitions, which is an essential part of Assa Abloy's strategy (Helgesson, F., personal communication, 23 January 2023). The company is divided into smaller divisions that focus on different products and operate in different parts of the world. See the structure of the Assa Abloy divisions in Figure 7.

Figure 7

Assa Abloy divisions

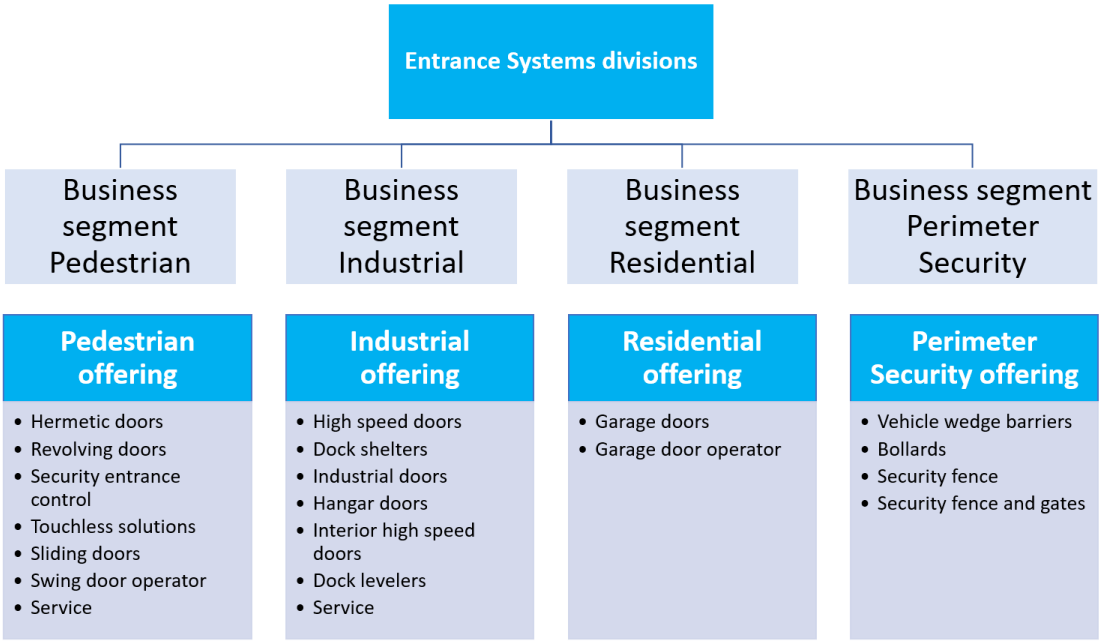
ASSA ABLOY	Regional divisions			Global divisions	
Product offering	Door openings and access control			Identification and access management	Entrance automation
Organization	Opening Solutions Americas 23%	Opening Solutions EMEIA 18 %	Opening Solutions Asia Pacific 7%	Global Technologies (HID and Global Solutions)	Entrance Systems
% of Group sales	48%			16%	36%

4.1.1 Assa Abloy Entrance Systems

Assa Abloy Entrance Systems is a large division, and the over 15000 employees at Entrance Systems achieved revenues of 42,8 billion SEK in 2022 (Assa Abloy, 2023). The division Entrance Systems provides door solutions and is the leader in the European and North American markets (Helgesson, F., personal communication, 23 January, 2023). The European and North American market represent 40% and 54% of the division's sales, respectively (Assa Abloy, 2023). The Entrance Systems division is further divided and consists of four segments focusing on separate products: residential, pedestrian, industrial, and perimeter security. These segments produce everything from garage doors for homes, security doors, revolving doors for stores, and the largest hangar doors in the world. Assa Abloy Entrance Systems divisions and their product offerings are shown in Figure 8.

Figure 8

Assa Abloy Entrance Systems Divisions and their segment product offerings



The segments all share a centralized KPI pack for which they can easily generate results. The collection of KPI includes: *loss to injuries, order fill rate, cost of poor quality, productivity, material throughput time* and *staff turnover.* However, Assa Abloy Entrance Systems is in general a decentralized organization partly in line with their acquisitions strategy and segments could establish other KPI which are not part of the bundled KPI.

4.1.2 Assa Abloy Entrance Systems supply chain

Assa Abloy Entrance Systems has component and assembly factories, each with their own supplier networks. Component factories supply not only assembly factories but also other component factories in the Assa Abloy Entrance Systems division (Helgesson, F., personal communication, 15 May 2023); thus, their reliability is vital.

Figure 9

Assa Abloy Entrance Systems supply chain (manufacturing structure)

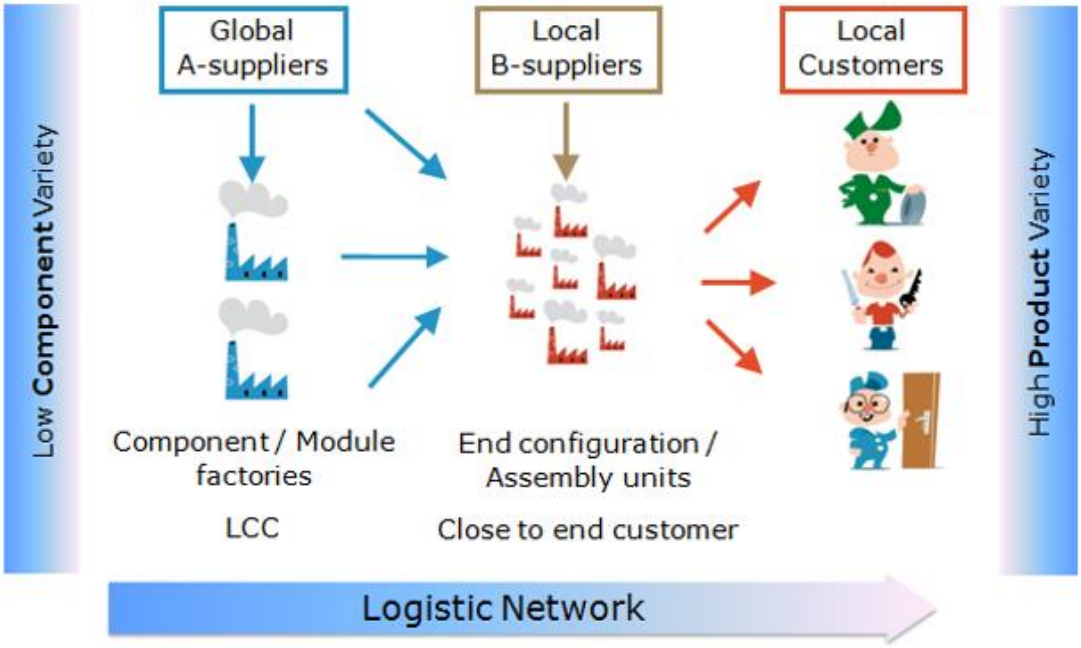


Table 9 includes three factories from the pedestrian, industrial, and residential segments of Assa Abloy Entrance Systems. The pedestrian factory in the Czech Republic has the majority of its suppliers located outside of Europe, while the industrial factory in the Czech Republic has most of its suppliers located within Europe. The residential factory in the Netherlands has global suppliers and is a significant supplier to many other Assa Abloy Entrance Systems entities.

Table 9

Description of three case supply chains

Location	Type of factory	Type of product	Number of items, RM/Comp	Supplier base	Lead times (S/M/L)	Lot sizes (S/M/L)
Czech Republic	Component /Module factory	Pedestrian doors & operators	3000 SKUs (Components/ Sensors/ Alu)	160 suppliers (EU/APAC)	M/L 1-130 wd	M/L 40% of SKUs > 100 wd
Czech Republic Ostrov	Component /Module factory	Industrial Operators	773 SKUs	74 suppliers (EU/APAC)	M/L 3-160 wd	M/L 31%of SKUs > 100 wd
Netherlands	Component /Module factory	Residential SDC	1698 SKUs	19 suppliers (EU / APAC)	M/L 9-184 wd	M/L 27% of SKUs > 100 wd

4.1.3 Assa Abloy Entrance Systems Industrial Ostrov Factory

The Assa Abloy Entrance Systems Ostrov factory consists of three factories producing for different Assa Abloy Entrance Systems segments. The Assa Abloy Entrance Systems Industrial part produces motors and control units, which include plenty of electronics (J. Hofmann, Personal communication, 21 february, 2023). The operations currently performed in the Ostrov Industrial Factory were located in Strömstad, Sweden, which was moved to the Czech Republic in 2012 as part of a consolidation project. Approximately 20 employees are part of the team at Ostrov Industrial.

The factory turns over around 15 million euros per year with around 12 million euros in direct material costs (J. Hofmann, personal communication, February 21, 2023). The supplier base is localized, with only a small percentage of suppliers located outside of Europe. Approximately 75% of the suppliers Ostrov purchases from are

suppliers for other nodes within the Assa Abloy Group as well. In terms of unique items purchased, about 70% are from a single source.

Table 10

Data for Ostrov factory suppliers

Country	Avg Lead time, days	Spend %	WRI (World risk index)	LPI (Logistics performance index)
Belgium	20	-	4,16	4,04
Hungary	16	-	0,97	3,42
China	36	-	28,7	3,61
Czechia	13	-	1	3,68
Germany	21	-	3,92	4,20
Netherlands	16	-	4,04	4,02
Italy	0	-	9,37	3,74
Poland	32	-	4,63	3,54
Sweden	17	-	2,06	4,05
Slovakia	31	-	1,03	3,03
Austria	13	-	1,14	4,03
Denmark	20	-	1,03	3,99
Spain	40	-	9,68	3,83
Lithuania	16		2,24	3,02

4.2 Symptoms of disruptions on Assa Abloy Entrance Systems supply chain

Table 11 presents a summary of the different symptoms that came up while interviewing several employees at Assa Abloy Entrance Systems with different roles. The symptoms are described more thoroughly further down in the text through references from the interviewees.

Table 11

Symptomlist of disruptive events year 2019-2023 at Assa Abloy Entrance Systems

Disruption	Symptom	Interviewee
COVID-19		
	Component shortage	(1), (2), (3), (4), (7), (9), (10), (11)
	Price increases on raw material and components	(2), (3), (6), (9), (10), (11)
	Procurement from the spot market	(1), (3), (6) (9), (11)
	Delayed transport & volatile lead times	(1), (3), (4), (6), (7), (9), (10), (11),
	Spike in freight prices and volatile prices	(7)
	Time consuming activities	(1), (2), (4), (7)
	Change in power balance between buyer and seller	(7), (9)
Russia-Ukraine war		
	Supplier shut down	(1), (3), (4)
	Increased price of raw material	(2), (3), (4) , (6), (10)
	Transport route blockage	(1), (7), (9)
US-China tariffs		
	Redesign	(1), (6), (7)

4.2.1 COVID-19

Component shortage

Component shortage is one of the most common issues mentioned by interviewees. The electronic components have been particularly affected by this matter. Prior to COVID-19, the electronic components had experienced supply issues due to the general problems in the electronic industry, with lead times reaching nearly a year (1). There had also been other disruptions including a snowstorm in Texas, flooding in Europe, and a factory fire in Japan (1, 9). The pandemic worsened preexisting problems through increased demand from various industries and supplier shutdowns due to labor shortages (1). Assa Abloy Entrance Systems were initially not heavily

affected at the start of COVID-19 because they had a good handle on inventory and the situation of their first-tier suppliers. However, previously unknown second-tier suppliers began failing to deliver, which affected the first-tier suppliers (3). Prior to the shortages, a cable from China had a lead time of four weeks, but in the first half of 2022, the lead time increased to 104 weeks (10). Assa Abloy Entrance Systems products do not require a lot of volume of electronic components and therefore their position is weak compared to other actors that operate in for example the automotive industry (1). Assa Abloy Entrance Systems did not commit to a capacity or volume, making it more difficult to supply the products with necessary components (11).

Assa Abloy Entrance Systems electronic components are legacy products (2). Since suppliers have begun to invest capacity in new technology, it is more difficult to obtain priority for legacy components; consequently, the shortage of legacy components remains (1). The process of adapting Assa Abloy Entrance Systems products to the new technology is difficult and time-consuming because the company must obtain test certificates for new components (2). The components are included in doors with sensors, and it is crucial that they function properly.

There was also a global container shortage that is believed to be caused by transport imbalances, with most shipments going from China to the US, as well as demand spikes (7). Price increases accompanied the shortage. Prior to COVID-19, the price of 40-foot containers was approximately 3000 US dollars, while after COVID-19 it was approximately 12000 US dollars (7).

To guarantee the availability of components, the factory in Ostrov constructed additional stockpiles. Customers' on-time delivery was maintained at the expense of increased capital commitments. The material throughput time increased by a third and still has not recovered fully, being about 15% higher than levels prior to COVID-19 (4).

Price increases on raw material and components

Component shortages have a strong correlation with price increases. Most components and materials experienced price increases, including printed circuit boards, wood, which increased packaging costs, and steel (2, 3, 6). Comparing the same order quantities before and after COVID-19 (3), the cost of printed circuit boards increased by approximately eightfold. The price of steel tripled from 2019 to 2021 (6). The price increases have a dramatic impact on the cost of a product; in one instance, the cost of door openers increased by 15% due solely to price increases in electronics (6). These cost increases have ultimately been passed on to the final consumer (3, 6).

Procurement from spot market

Increased procurement on the spot market was a typical COVID-19 pandemic effect. As an illustration, Assa Abloy Entrance Systems factory in Ostrov previously purchased microchips from Taiwan at a standard price per order quantity of $36,000. As a result of the microchip supplier's shutdown during COVID-19, Assa Abloy Entrance Systems was forced to purchase the same quantity of chips on the spot market at a tenfold higher price. Therefore, they were forced to choose between shutting down the Ostrov plant for six weeks, which would disrupt other parts of Assa Abloys supply chain as Ostrov also supplies other Assa Abloy plants, or purchasing microchips at ten times the cost (3). The cost of downtime exceeds the additional cost of purchasing components at inflated prices from the spot market, which led Assa Abloy Entrance Systems to use the spot market instead of closing any of their

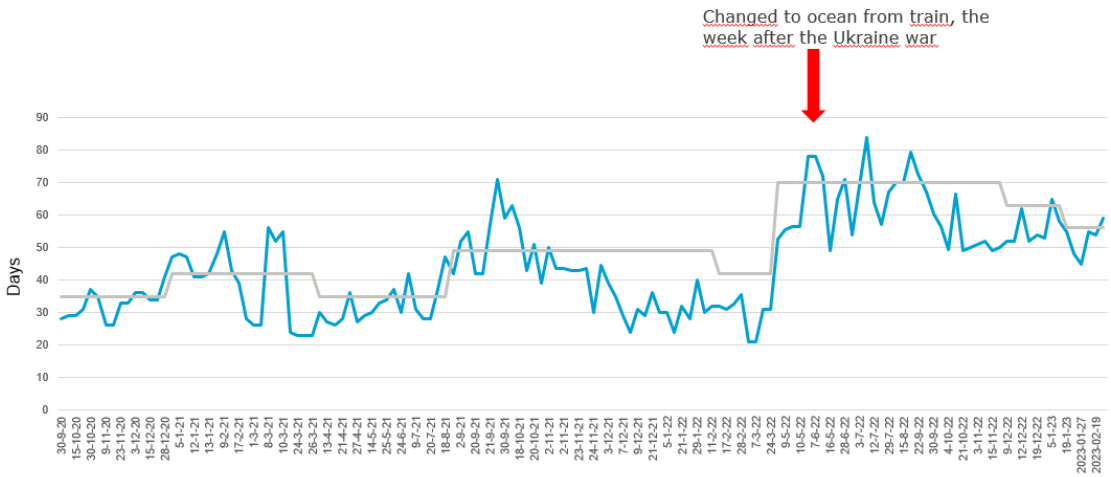
plants (9). Assa Abloy Entrance Systems suppliers did not want to sell to the actors that resell at inflated prices on the spot market; they would much rather sell to serious long-term customers, so they actively sought out the resellers (9). In 2022 and 2021, Assa Abloy Entrance Systems expenditures increased by 13% of its annual revenue (3), as a result of price and transport cost fluctuations. In addition to increased costs, goods from the spot market increased the supplier rejection rate, as they did not always meet the requirements because the source was only responsible for their stake and not the repercussions if the performance affected the quality of the final product (6).

Delayed transport & volatile lead times

During the COVID-19 period, train and ocean freight lead times increased. In the case of the Ostrov factory, the average lead time for transportation increased by 20% (4). It is believed that port congestion and a lack of labor are the primary causes of the increase in lead times (4, 7). Transport lead times fluctuated drastically during the COVID-19 era, and it was extremely difficult to forecast the lead time and provide an estimated time of arrival to a factory. During the COVID-19 pandemic (7), lead time reliability was at an all-time low.

Figure 10

Graph illustrating the volatility of lead times



Note. This is a graph adjusted from Assa Abloy Entrance Systems internal documents.

Importantly, other disruptions, such as the blockage of the Suez Canal, occurred simultaneously. As a result of the Suez Canal Blockade, Assa Abloy Entrance Systems was required to purchase duplicate components (1).

Due to increased lead times and decreased dependability, Assa Abloy Entrance Systems was forced to rely heavily on air freight in order to maintain service levels and delivery precision for their customers (1, 6). PCB suppliers who supplied the Ostrov plant experienced difficulties during COVID-19, resulting in longer lead times. Therefore, the Ostrov plant had to use air transport to acquire PCBs; otherwise, they would not have been able to manufacture (3). However, this did not entirely resolve the issue; on one occasion, they had to wait four weeks for a spot on a cargo plane, as Assa Abloy Entrance Systems was not the only company increasing its use of air

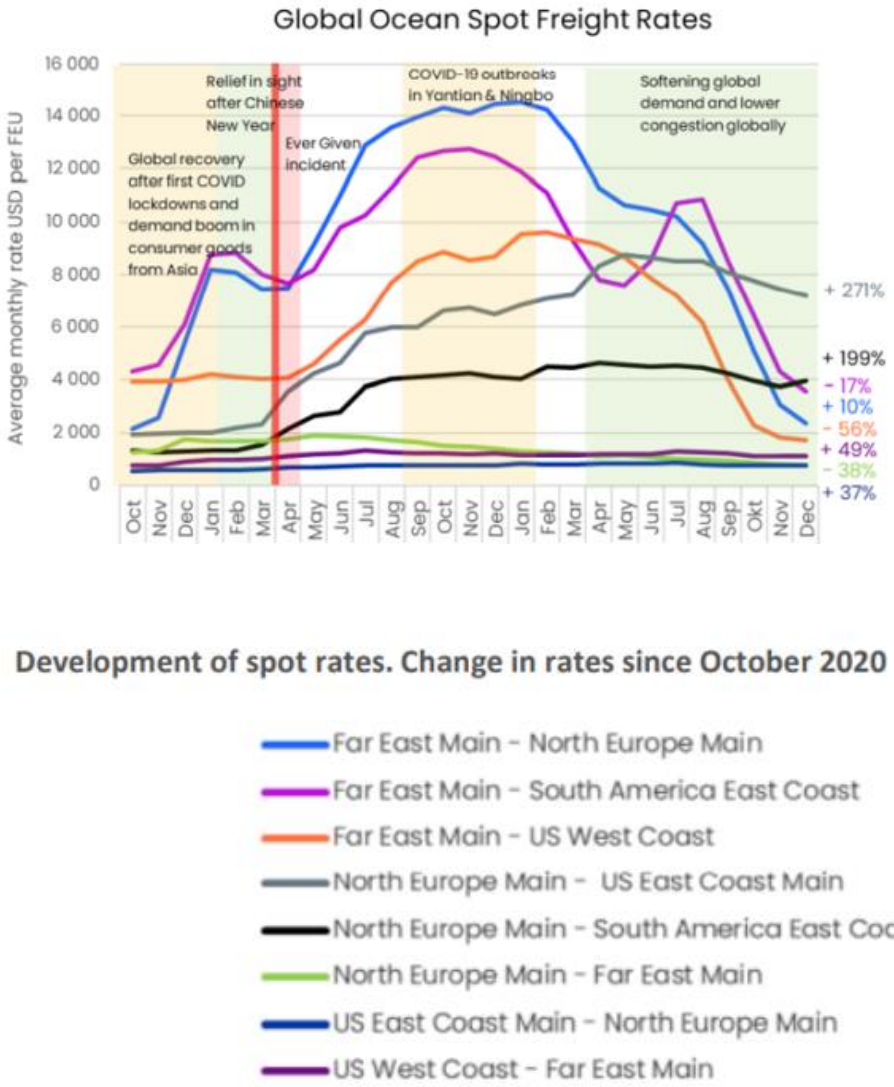
transport and belly cargo capacity on passenger planes was virtually nonexistent. In order to avoid factory shutdowns, the Ostrov factory frequently utilized air transport instead of the usual maritime route, particularly for shipments from Asia. This prevented shutdowns but severely impacted margins (4).

Spike in freight price and volatile prices

After COVID-19 struck, prices became increasingly volatile and unpredictable, fluctuating every week or even hour (7). The cost of train, air, and maritime transportation increased. Since the beginning of 2022, ocean spot freight rates have been in free fall, whereas train transportation costs remain elevated. As a response to the price increases, Assa Abloy Entrance Systems has increased their prices as well.

Figure 11

Freight price



Time consuming activities

COVID-19 has been described by Assa Abloy Entrance Systems employees of all divisions and positions as the most time-consuming disruption of their careers. It required extensive communication between carriers, suppliers, and even internal departments such as sourcing and research and development (2, 3, 4, 7). On the supply side, it is important to follow up with steel, plastic, and electronics suppliers in an effort to identify alternative components that can be used in long-lasting products (2, 3, 4). For logistics, there was extensive communication with numerous carriers in order to resolve transportation problems (7). Even though these are collaborative activities, the COVID-19 pandemic may have caused some gaps in supplier relationships due to the impossibility of face-to-face meetings; this has been particularly apparent when suppliers have exchanged owners or contact points (1).

Change in power balance between buyer and seller

The occurrence of component shortages appears to have altered the relationship between supplier and buyer. The interviews have provided two examples of this. Assa Abloy Entrance Systems is currently being phased out (6) as a result of the decision by two large electronic distributors that they do not want them as a customer because of their relatively low purchasing volume. Similar behavior was observed with the carriers (7). Prior to COVID-19, Assa Abloy Entrance Systems typically sent quarterly requests for quotations and received inquiries from forwarding agents requesting to ship Assa Abloy Entrance Systems volume. During the COVID-19 era, freight carriers set the prices, while Assa Abloy Entrance Systems had to pursue transportation opportunities. Freight carriers no longer possess the same level of influence as they did during the COVID-19 era; the situation is slowly returning to its previous state.

4.2.2 Russia-Ukraine War

Supplier shutdown

The primary effect of the Russia-Ukraine war on the supply chain was the complete shutdown of suppliers due to a lack of workers. Ukrainian neon suppliers, who account for fifty percent of the global market, were forced to cease production (1). Likewise, a Ukrainian transformers supplier had to stop operations, but fortunately, another supplier had been established for quality and cost reasons (3). Due to the testing process, the recovery time would have been three months had this not been the case. The Czech factory Ostrov was unable to continue purchasing plastic granulate from a Russian supplier. They discovered two new suppliers in different parts of the world, but the abrupt switch resulted in significant price increases because they lacked contracts with the new sources and have not yet concluded price negotiations.

A supplier of plastic components in the Czech Republic had a primary source of plastic granulate in Russia, from which they could no longer obtain supplies (3). This led to price increases as they had to track down plastic granulate suppliers. They located suppliers in China and Italy. The plastic issues have not fully recovered, the prices are still significantly higher, and they have not finished price negotiations.

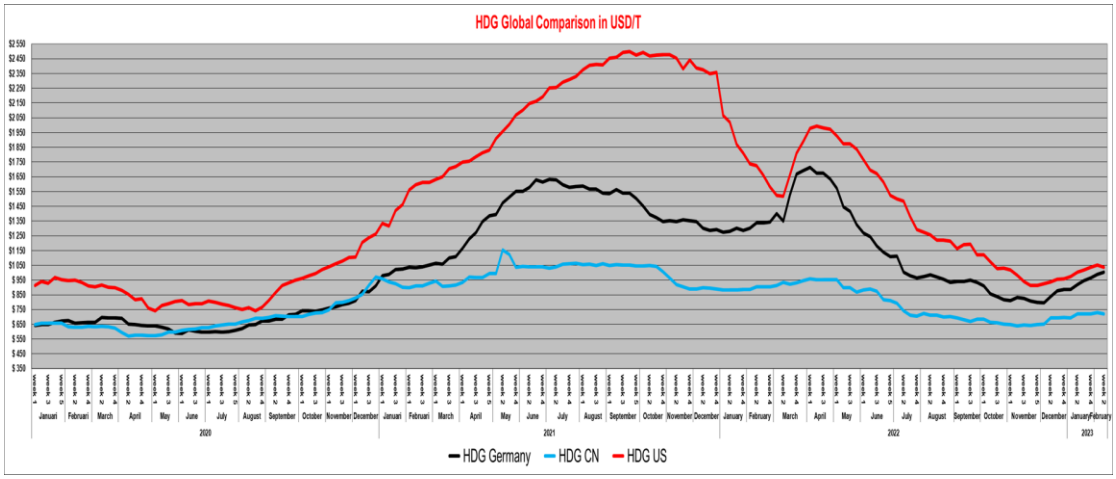
Increased price of raw material

Steel component prices have more than doubled as a result of the Russia-Ukraine war (4), which is a major consequence of the conflict between Russia and Ukraine. Prior to the outbreak of war, steel prices were already on the rise; they reached their peak in 2021, but experienced a brief local maximum just after the outbreak of the war (6). During a period when steel was scarce, Assa Abloy Entrance Systems small size could be advantageous because their volumes are smaller and easier to store (1). Some components also increased in price due to the increase in copper prices, as their copper supply came from Russia (3).

The war between Russia and Ukraine has also led to a significant increase in energy prices. This has caused ripple effects such as a 30–50% increase in the price of glass in 2022 (6).

Figure 12

Steel prices



Transport Route blockage

Due to the war, train routes are no longer viable for Assa Abloy Entrance Systems, resulting in an increase in the use of sea and air transport, which has increased lead times, material throughput times, and costs (1, 9). Some companies continue to use routes through Russia; however, Assa Abloy Entrance Systems avoids this possibility because their primary logistic partners do not accept rail orders on this route (7). Due to the fact that they had based their stock levels on train lead times prior to the war, they now had a six-week gap when using ocean transport, which had to be filled by air freight.

4.2.3 US-China tariffs

Redesign

As a result of the added 25% tariffs, Assa Abloy Entrance Systems was forced to redesign their supply chain for US imports (1). Some products are entirely manufactured in Canada and exported to the United States via a free trade agreement. For other components, they were required to ship them from China to Switzerland, where they assembled the product and changed the country of origin to

Switzerland, thereby avoiding tariffs (7). This increases the complexity of the supply chain as well as the lead times and transportation costs (1, 6).

4.3 Case projects

This section describes Assa Abloy Entrance Systems two case projects, including the implementation process and the projects' effects on their performance. An important step before Project A and B was that of an implementation of a Demand Driven Material Requirements Planning (DDMRP) system. This is perhaps not a necessity, however very beneficial when implementing these projects.

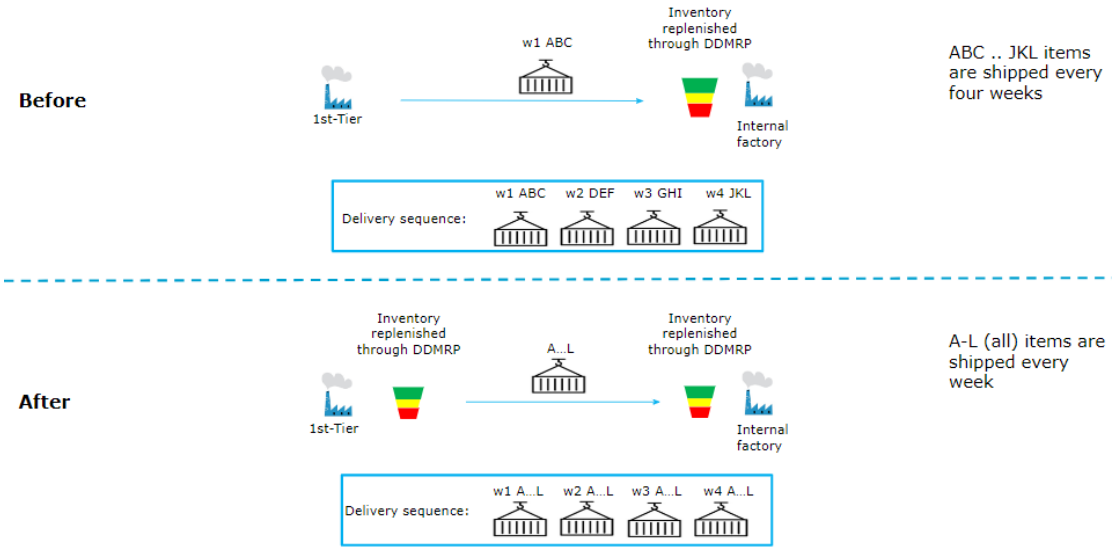
4.3.1 Project A - Inventory placement and sizing

To understand Project A, the previous state must be understood. Before Project A was implemented, the factory held all the inventory, and the supplier had no finished goods inventory. Components were delivered from the supplier in large batch sizes, three component types at a time, in parallel with the suppliers' production batches.

In Project A, inventory was built at the first-tier supplier. Once the initial inventory build-up phase was over, Assa Abloy Entrance Systems could order smaller batches of every component in one container. The inventory at Assa Abloy Entrance Systems could then be reduced as all components are delivered at a weekly frequency. The replenishment occurs through a demand-driven material requirements planning system, which is not fully covered in this thesis but is basically about strategically planning inventory levels for components and ordering material once the inventory is below the decided level. The supplier and Assa Abloy Entrance Systems monitor the order levels together. The first-tier supplier in Project A is an internal supplier, part of the Assa Abloy Entrance Systems division, which could have simplified the implementation process.

Figure 13

An illustrative example of the flow before and after implementation



Implementation process

To increase the value of the reduction in material throughput time, it is necessary to identify suitable items for the project; ideally, these items are of high value. Additionally, suppliers with short setup times who can accommodate the new delivery sequence are preferred, as the project could result in an increase in inventory levels otherwise. As of the writing of this report, Assa Abloy Entrance Systems has initiated a similar project with an external supplier; for that project, the supplier required economic incentives in order to agree to hold the additional inventory.

Strategic inventory levels, order size, and packaging size will have to be calculated when implementing the project. Some components will likely need adjustments to packaging in order to fit into a single container. During the implementation of Project A, the first-tier supplier also had to change the sizes of components and packaging from the second-tier suppliers as well.

Table 12

Effects of project A

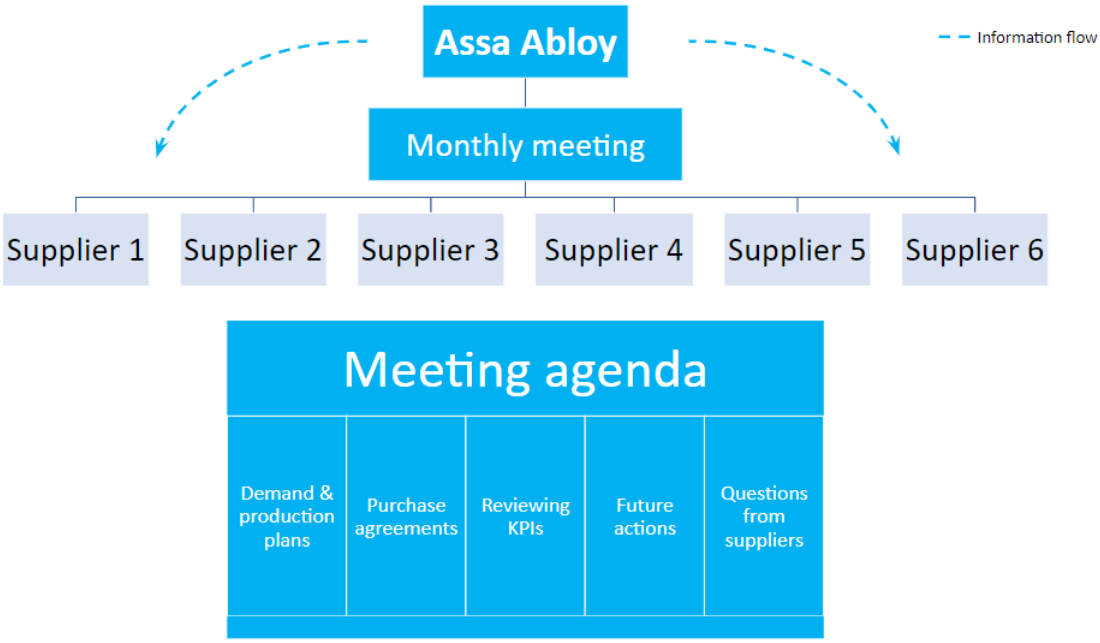
Benefits
~9% increased on-time delivery from supplier
~35% reduced lead time
Lower inventory at Assa Abloy Entrance Systems factory.
Same inventory at 1st tier supplier.
~35% reduced number of transactions
Added visibility for the supplier and therefore better planning
Disadvantages
Initial increased picking time at supplier
Worsened cash flow for suppliers
Difficulties to get suppliers onboard without economic incentives

4.3.2 Project B - Supplier involvement initiative

The objective of the supplier involvement project was to increase collaboration and visibility between the Assa Abloy Entrance Systems IDS factory in Romania and some of their critical suppliers. To determine which suppliers to include, they evaluated those with long lead times and the potential to reduce inventory levels; those with low delivery performance who can improve their order fill rate (OFR); and the highest-value suppliers in terms of inventory. So far, six suppliers have been selected to participate in the project, and their procedure is to hold monthly meetings where Assa Abloy Entrance Systems shares information about demand and production plans, purchase agreements and when they should be renewed, various KPIs related to the specific suppliers, such as lead time, inventory values, quality, and rejections, as well as discussions about future actions to be taken and questions from the suppliers. The flow of information from Assa Abloy Entrance Systems to suppliers is one-directional, and if Assa Abloy Entrance Systems requires specific information from a supplier, this is handled outside of the monthly structure.

Figure 14

An illustrative example of scope



Implementation process

The majority of suppliers have been enthusiastic about the project's impact on their operations. The most difficult aspect of the implementation has been scope creep; suppliers typically request that a great deal of information be added to the meetings, information that simply cannot be covered during their monthly meetings. In addition, there is a possibility that the meeting's intended purpose will be obscured by the volume of information requested, thereby rendering the meeting ineffective. Due to

recent high employee turnover among material planners, it has been difficult to incorporate new suppliers into the project. Furthermore, an unanticipated obstacle was a fear of presentation and negotiation that caused some employees to feel uneasy and, as a result, not support the involvement projects fully. This could, according to our interviewee, be a cultural issue that can be explained by the Romanian education system, which does not reward or emphasize oral presentation skills.

Several factors must be considered to enhance the implementation procedure in the future. It would be advantageous to include colleagues from the sourcing department because they possess a unique skill set, particularly in negotiation. They are also able to make decisions concerning the supplier. Agendas and materials should be standardized to a degree in order to prevent issues with scope creep and an increase in workload that would make involvement meetings unsustainable. This is also important in regards to employee turnover, to ensure the replacement process does not take too much time. The advantages and disadvantages of the projects are summarized in Table 13.

Table 13

Effects of project B

Benefits
Inventory mix improved
Strengthening of relationships - secured components during COVID-19
Added supply chain visibility, for example information regarding location of 2nd tier suppliers have been revealed.
Disadvantages
Workload for employees in terms of preparation
Employee turnover leads to potential impairment of relationships when key contacts leave.

4.4 Mitigating strategies and future initiatives at Assa Abloy Entrance systems

As part of the semi-structured interviews, multiple mitigating solutions used by Assa Abloy Entrance Systems to resolve or mitigate problems caused by disruptions were discussed. Even though this was not the primary objective of the interviews, they

serve as support to the strategies that came up in the literature, and add a context for how the strategies have been used in a real context and how they have affected the company. Furthermore, future initiatives were discussed by the interviewees which can be used as a great inspiration for recommended actions that Assa Abloy Entrance Systems may take in the future. In Table 14 and 15 below, all solutions and initiatives discussed are presented in a consolidated format.

Table 14

Mitigating solutions used at Assa Abloy Entrance Systems

Disruption	Mitigating strategies	Interviewee
COVID-19	Recent filling of inventory, and large inventory in transit	(4)
	Fast decisions to order from spot market prevented production shutdown	(1)
	Reassessment of supplier base before COVID-19	(4), (3)
	Reactive alternative supply search	(3), (2)
	Close supplier relations	(2), (10)
	Direct contact with 2nd tier suppliers.	(11)
	Worked with socially important products that were prioritized to be produced	(2), (6)
	Weekly meetings with R&D	(9), (11)
	Weekly meetings with critical suppliers	(9), (10), (11)
Russia -Ukraine	Supplier change already initiated due to cost and quality issues at Ukraine supplier	(3), (4)

Table 15

Future initiatives in the minds of the employees

Future initiatives	Interviewee
Close supplier relations	(1), (2), (10), (11)
Integrate several roles in cross communication between supplier and company	(10)
Face-to-face meetings (procurement, magic happens by the production line)	(1), (10)
Information sharing	(2)
Improve forecasting	(1)
Alternative components in products	(1), (6), (11)
Increased standardization of products	(6)
Reduce product complexity in terms of number of components	(2)
Movement of supply base	(1), (3)
Collaboration between business segments	(2)
Spread information through the organization	(2)
Nearshoring	(2), (6)
Dual sourcing	(6), (10), (11)
Reduce dependency on supply from China & supplier diversification.	(6), (11)
Risk assessment of suppliers	(2)
Develop contingency plans	(6)
Enable usage of new technology in the components to follow the investments by suppliers	(9)
Be part of suppliers' variable costs	(10)
Consider risk for disruptions in decisions	(11)
Commit to volume or capacity	(11)

4.5 Gap analysis of absent supply chain resilience strategies at Assa Abloy Entrance Systems

The hivemind of Assa Abloy Entrance Systems covered a lot of resilience strategies; this section will compare those to strategies covered in literature to uncover gaps and strategies that were not mentioned during interviews and which can be of help in answering research question three. Table 16 below lists the supply chain resilience strategies mentioned in the literature that were not identified from the data collection at Assa Abloy Entrance Systems.

Table 16

Adjusted version of Table 7 excluding the strategies brought up during interviews with Assa Abloy Entrance Systems employees

Strategy category	Strategies suggested by literature
Inventory management	Reserve stock programme, Collaborative inventory, Vendor-managed inventory, 3PL as inventory manager
Sourcing	Flexible supplier base, economic supply incentives, backup suppliers, build outs, supplier backup capacity, supplier selection based on performance, supplier risk awareness
Supply chain design	Several structural supply chains, efficient vs responsive supply chains, identical facilities, additional warehouses
Product Design	Assortment of diversified items that require different raw materials
Enhance supply chain collaboration	Horizontal cooperation, integrate systems, distributing power
Increasing supply chain Visibility	Mapping of transportation network, IoT, blockchain, big data
Risk management & Culture	Risk management: Scenario analysis & simulations, simplify risk estimations. Culture: Rewards and incentives, empowerment & involvement, conditioning, continuous risk management work.

5. Discussion

This chapter will present and discuss the study's findings in relation to its objectives and research questions.

5.1 Improving supply chain resilience

Supply chain resilience is the ability for a supply chain to be prepared for disruptions, respond to disruptions, and recover from disruptions. Seven determinants that further illustrate supply chain resilience have been identified and consolidated into Table 5 in Section 3.1.1. This section aims at answering the first research question.

RQ1: *How can organizations improve the resilience of their upstream supply chains?*

5.1.1 Supply chain resilience strategies

There is an abundance of strategies discussed in the literature that can increase the resilience of supply chains. In Figure 15, the strategy categories have been connected to the supply chain resilience determinants to establish a connection and get a sense of what the sets of strategies aim to improve. However, the determinants are interrelated and the strategy categories are large, which makes the framework broad and leads to many strategy categories covering most of the supply chain resilience determinants.

Figure 15

Supply chain resilience determinants connected to supply chain resilience strategies

	Strategy Category						
	Strategic inventory sizing & positioning, time buffers, reserve stock programme, collaborative inventory, vendor-managed inventory, 3PL as inventory manager	Localization, glocalization, flexible supplier base, economic supply incentives, multiple sourcing, dual sourcing, backup suppliers, build outs, supplier backup capacity, supplier diversification, supplier selection on performance, supplier risk awareness	Several structural supply chains, breaking down supply chains into smaller parts, efficient vs responsive supply chains, identical facilities, additional warehouses, backup routes, backup transportation, choice of 3PL provider, rent out excess capacity	Standardization, design for multiple Bill of Materials & alternatives, assortment of diversified items that require different raw materials	Horizontal and vertical cooperation, create unbreakable relations with key suppliers, integrate systems, attitude, distributing power	Information sharing, mapping of a firm's supply chain, mapping of transportation network, IoT, blockchains, big data	Risk management: Scenario analysis & simulations, contingency plans, simplify risk estimations. Culture: Communication, information sharing, rewards and incentives, empowerment & involvement, conditioning, continuous risk management work.
SCRES Determinants	Inventory management	Sourcing	SC design	Product design	SC collaboration	SC visibility	Risk management & culture
Robustness	X	X	X		X	X	X
Flexibility	X	X	X	X	X	X	X
Adaptability		X	X	X	X	X	X
Agility			X	X	X	X	X
Collaboration	X	X			X	X	X
Visibility					X	X	X
Structure		X	X				

In order for a business to identify the most appropriate strategy to implement, it must first evaluate its process, product, and partner complexity, geographical spread among other data. However, some general conclusions regarding resilience can be drawn after completing the literature review and compiling the interviews with Assa Abloy Entrance Systems employees. To establish a robust, flexible, and adaptable supply chain, which are important qualities from a resilient point of view, lead times and order frequency are of great importance regardless of the supply chain environment. With short lead times and high order frequency, it will be easier to respond to changes in demand, macro and micro disruptions, and variability in general. If, for example, one transport is delayed, with high order frequency the next one will soon be on its way. If the lead times are short, the recovery will be faster as well. Adding strategic inventory placed both at the supplier and at the factory will result in an inertia factor absorbing the delays in the two nodes, which increases the robustness. The supplier will consequently be more protected against, for instance, shortages of material, disturbances in manufacturing, or delays from their suppliers and can ship components straight from their stock regardless of minor disruptions. If there are delays between the supplier and the factory, there is built-in stock at the factory to absorb those delays. A second-order effect of having this system is that by having high delivery precision, hoarding and overall increased inventory levels along the supply chain are avoided, which can potentially decrease inventory costs substantially. To further protect against unforeseeable disruptions, dual or multiple sourcing are proven strategies that can be implemented where possible. If not feasible, taking a look at product design and allowing for alternatives in the Bill of Material is highly efficient and increases flexibility and the ability to respond to shortages of material, price increases, or severe delays.

Analyzing the strategies reveals that creating a resilient supply chain is not a one-person job dependent on a single function; rather, it requires the collaboration of multiple functions, both internally and externally. For instance, to develop product alternatives, the factory manager and category manager must collaborate, with R&D developing the alternative after identifying the need. To create identical facilities internally that can meet demand, sourcing and identifying the need are likely prerequisites, followed by the factory's ability to construct them. To establish a collaborative supply chain, the sourcing department, the factory, and the external supply partner with whom both functions have relationships must collaborate. If an unimaginable sort of disruption hits, such as the COVID-19 pandemic, close supplier relations have been found to be priceless, sharing the responsibility of common interests. Having good supplier relations can also result in the possibility of planning long-term procurement of critical components. An important insight from the COVID-19 pandemic was the importance of committing to order volumes beforehand to not lose priority for critical components. It decreases the flexibility of the company; however, securing the components is likely of higher importance than a potential decrease in costs because of cancellations.

In this report, two case studies that have previously been conducted at Assa Abloy Entrance Systems have been analyzed. The projects are examples of strategies that have been mentioned in the literature and have a clear relationship to the supply chain resilience determinants.

Figure 16

Effects from case project with regards to the supply chain resilience determinants

	Case projects	
SCRES Determinants	Case project A	Case project B
Robustness	X	X
Flexibility	X	
Adaptability		X
Agility	X	X
Collaboration in the SC	X	X
Visibility	X	X
Structure		

Project A comprises an example of strategic inventory included in the inventory management category in Figure 15. A first-order effect of project A is reduced lead times. By designing their supply chain to include strategic inventory at the supplier, it is possible to have weekly shipments of all products. Ordering from a finished stock enables products to be shipped immediately, as opposed to having to wait for the product to be manufactured and then shipped. Sharing production plans and increasing visibility between Assa Abloy Entrance Systems and the supplier improves supply chain agility. The production plans provide the supplier with greater support to forecast their production, which makes them more flexible because, as long as they maintain an agreed-upon stock level, they can optimize their production volumes according to their needs and capabilities. The disadvantage is that it may be difficult to gain the support of suppliers for this idea, as it could worsen their cash flow by requiring them to maintain inventory, which in turn increases their costs. Additionally, the fact that every item is shipped every week could increase the picking time, at least initially. However, the ability to optimize their production flows and increase the precision of their shipments is enormously advantageous. For Assa Abloy Entrance Systems, shorter lead times allow for the possibility of maintaining lower inventory levels at their factories and significantly improving delivery precision for their customers.

Project B belongs to the categorization of supply chain collaboration covering the strategy of vertical cooperation between Assa Abloy Entrance Systems and their suppliers. The initial effect of a higher level of collaboration is improved visibility with critical suppliers. The collaboration fosters trust and makes information sharing more accessible for both parties, allowing them to act more quickly and adapt more easily to changes in the supply chain. The interviewee, who was responsible for Project B, mentions that due to their closer relationship, they were given priority during COVID-19 and were able to secure vital components. This improves robustness and can be seen as a second-order effect from vertical cooperation in the form of creation of “unbreakable relations with key suppliers”, incorporated in Figure 15. With a stronger relationship, there is a greater understanding of one another and a higher level of trust, which makes it more difficult to break deals and leads to the parties supporting one another through difficulties. A disadvantage of these bonds is that they potentially reduce the flexibility of the individual company. However, the ability to secure critical components during difficult times and to have an agile supply chain

significantly outweighs many of these disadvantages in terms of the desirable characteristics of modern supply chains that must survive in environments that are becoming increasingly variable.

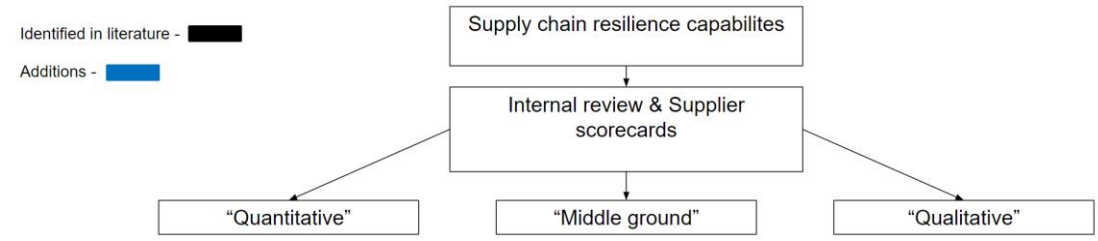
5.1.2 Measuring supply chain resilience

Measurement is an integral part of an improvement process and therefore it is a natural part in answering the question of how a firm can improve its supply chain resilience, as former CEO of General Electric, Jack Welch said so well “What gets measured gets done”. Based on the literature regarding the seven determinants, 34 metrics of supply chain resilience have been identified. Out of those metrics, 27 have been discussed in the literature identified in this study; further explanations of the metrics can be found in Section 3.4. The overarching expression is that the literature does not go into depth on how supply chain resilience could be measured. There is, however, a large quantity of articles based on quantitative models and simulations of supply chains during disruptions. It could be argued that these models and simulations are not understandable and are manipulable. Besides, it is probably difficult for supply chain professionals in an organization to conduct the same simulations and update the models as the supply chain evolves.

Our reasoning is that an improvement in the metrics provided, especially when combined, is indicative of increased supply chain resilience and can therefore simplify understanding of what supply chain resilience is. The metrics have been categorized according to related determinants, but as the determinants are interrelated, it is possible to argue that this categorization is not fixed. Furthermore, the metrics have been separated into quantitative and qualitative metrics, along with a middle ground that is quantitative in nature but requires qualitative assessments. This classification also reflects the amount of work necessary to measure; creating a collaboration index by surveying supply chain professionals within an organization requires significantly more effort than, for example, extracting data from the system to calculate lead time.

Figure 17

Metrics identified in literature and additions



Robustness	Utilization rate, Excess capacity, Order fill rate, Inventory accuracy, supplier rejection rate, Financial health metrics	Time to survive, Time to recover, Cost of disruption based on time to survive and time to recover	
Flexibility	Nr of order delivery changes, late order changes	Nr of incidents handled through flexible actions, Alternative components	
Adaptability	Alternative suppliers per supply category, Planning cycle time, Contract time		
Agility	Lead time, Lead time variance, Lead time for new supply.	Upside & Downside flexibility	Agility Index
Collaboration		*Share of suppliers with established communication channels*	Collaboration Index
Visibility	Forecast accuracy, 2nd-tier and 3rd-tier suppliers known per 1st-tier supplier.		Visibility Index
Structure	Geographical spread, Number of nodes and flows in supply chain, Supply chain density, Average degree	World risk index * Geographical spread, *Logistics performance index * Geographical spread*	
General		Recovery level, Performance impact index	

Note. The blue metrics were not identified in literature and are discussed below.

As a result of our research and understanding of the determinants of supply chain resilience, we propose seven new metrics that were not identified in the literature. The flexible action of changing the design to allow for different components is widely discussed in the literature as an effective resilience strategy; however, no metric was discovered during the literature search. Moreover, multiple Assa Abloy Entrance Systems interviewees brought up the topic of alternative options. The number of alternative components at the item level is therefore proposed as a new metric. Late order changes are proposed as well as a resilience metric within the flexibility dimension. Similar to delivery modifications, the capacity to modify order quantities or items signifies flexibility.

Adaptability is the capability to reconfigure the supply chain, long contract duration and volume commitments might make reconfiguration impractical. As a result, contract duration is suggested as a metric of resilience. Assa Abloy Entrance Systems Project B is all about involving the supplier and establishing channels of communication. A simple metric is to count the number of suppliers with whom you've established communication channels as opposed to focusing solely on order-based communication. In the literature on the visibility dimension, which discusses the integration of systems and mapping of suppliers, one interviewee also mentions the sudden disruption caused by unidentified second-tier supplier problems. Consequently, a metric measuring, for instance, the number of known second-tier

suppliers is proposed. However, the metric is not relative and merely being aware of the supplier's existence does not improve supply chain resilience if it is not evaluated and collaborated with if deemed necessary.

Literature references the world risk index and logistics performance index. Although, there was no application of these metrics in the literature discovered. Our suggestion is that the indices could be combined with geographical spread to provide supply chain managers with an indication of how susceptible the supply chain is to natural disasters in the case of the world risk index and logistical disruptions in the case of the logistics performance index. Although past observations may not be a true representation of the future, the metrics provide a method to outsource the identification of risk to an actor with vastly more data points to analyze than a single firm has access to. The weighting of the indices could, for instance, be based on the proportion of spending per country or the share of critical articles per country. The world risk index provides a consolidated metric that includes dimensions such as the probability of disasters, the impact of disasters, and a nation's capacity to respond to and recover from natural disaster damage. However, it is also possible to disassemble the index and use the individual values (Humanitarian Data Exchange, 2023). In the context of a supply chain, it may be most important to consider the probability and impact of natural disasters over the nation's ability to respond to them. On the other hand, there is value in keeping things straightforward by utilizing the consolidated index.

Figure 18

An illustration of how the world risk index (WRI) and logistics performance index could be used

Country	Spend %	WRI (World risk index)	LPI (Logistics performance index)
Belgium	-	4,16	4,04
Hungary	-	0,97	3,42
China	-	28,7	3,61
Czechia	-	1	3,68
Germany	-	3,92	4,20
Netherlands	-	4,04	4,02
Italy	-	9,37	3,74
Poland	-	4,63	3,54
Sweden	-	2,06	4,05
Slovakia	-	1,03	3,03
Austria	-	1,14	4,03
Denmark	-	1,03	3,99
Spain	-	9,68	3,83
Lithuania		2,24	3,02

Weighted average LPI	Assa Abloy LPI / global average
3,79	132,13%

Weighted average WRI	WRI Risk category
6,31	Low-end High

Note.The spend is not revealed as it is not necessary to illustrate the use case.The categorization of the WRI is included in the world risk report 2022 (United Nations Office for the Coordination of Humanitarian Affairs, 2022).

5.2 Disruption impacts on Assa Abloy Entrance Systems supply chain

In order to understand how to improve Assa Abloy Entrance Systems supply chain resilience, this report includes an analysis in Chapter 4 of how they have been affected by different disruptions historically. The purpose of this section is to present an answer to research question two.

RQ2: What impacts have previous disruptions had on Assa Abloy Entrance Systems supply chain?

5.2.1 Consolidated symptoms

The purpose of the interviews was to determine the consequences of recent disturbances. Nonetheless, some interviewees expressed uncertainty regarding the source of the problems during multiple interviews. For instance, the problematic shortage of electronic components is likely the result of a combination of COVID-19 and supplier shutdowns, as well as hoarding tendencies and other disruptions such as floods, fires, and snowstorms, among others. Assa Abloy Entrance Systems have been affected by macro, micro, and man-made disruptions and have experienced similar effects as the general effects from previous disruptions described in Section 3.2.

The symptomlist presented in Section 4.2 were organized according to particular disruptions. To avoid the narrative fallacy and to acknowledge that multiple disruptions could have affected the situation, the effects of disruptions have been condensed into a list of effects that one could typically anticipate from any disruption.

Table 17

Consolidated symptomlist

Symptom
Component shortage
Price increases and price volatility of raw material, components, and freight
Change in power balance between buyer and seller
Delayed transport, route blockage & volatile lead times
Time-consuming activities
Forced reconfiguration of supply chain

The consolidated effects could derive some suitable strategies that can be applied to Assa Abloy Entrance Systems. Component shortages have been one of the main symptoms that they have dealt with. The effects of the shortages could, for example, be mitigated by collaborative inventory, a proactive search for alternative components, multiple sourcing, or the establishment of backup suppliers. Some of these strategies could also serve as mitigating strategies for the significant shift in the power dynamic between buyer and vendor that occurred during the COVID-19 pandemic and decrease the risk of price increases caused by a lack of competition among suppliers.

As price increases of materials have been a common issue, the strategies of creating a diversified assortment that requires different raw materials or creating a design that could use multiple raw materials could be relevant. However, this would have to be analyzed at the product level.

Delayed transports and volatile lead times could also generally be addressed by a plethora of strategies, such as localizing, inventory sizing, warehouse and inventory placement, backup transport and routes, and backup suppliers, among others. Furthermore, due to the China-US tariffs, there has been a forced reconfiguration of the supply chain, which highlights the importance of creating a generally flexible supply base with facilities spread over multiple locations and applying multiple sourcing strategies, etc.

Numerous additional strategies, such as the Internet of Things (IoT) and blockchain, are cited in the literature as essential and could also be used to mitigate the effects; however, they are beyond the scope of this discussion. These are examples of supply chain strategies that facilitate information sharing and greater visibility, thereby reducing supply chain risk, enabling more accurate forecasting, and potentially reducing time-consuming activities.

5.3 Improving Assa Abloy Entrance Systems supply chain

This section is intended to answer research question three. To ensure that the recommended focus areas are appropriate, this section provides a combined set of recommendations that incorporate aspects of the literature and Assa Abloy Entrance Systems' current situation, how they have historically been affected by disruptions and what they have done in the past to mitigate the effects, as well as employee beliefs. What strategies are appropriate varies depending on the product, suppliers, and corporate strategy. Therefore, the section could be considered explorative and illustrates how the lists of strategies and metrics could be used in combination with the context of data and strategy.

RQ3: What are the main areas and actions Assa Abloy Entrance Systems may focus on to prepare for future supply chain disruptions?

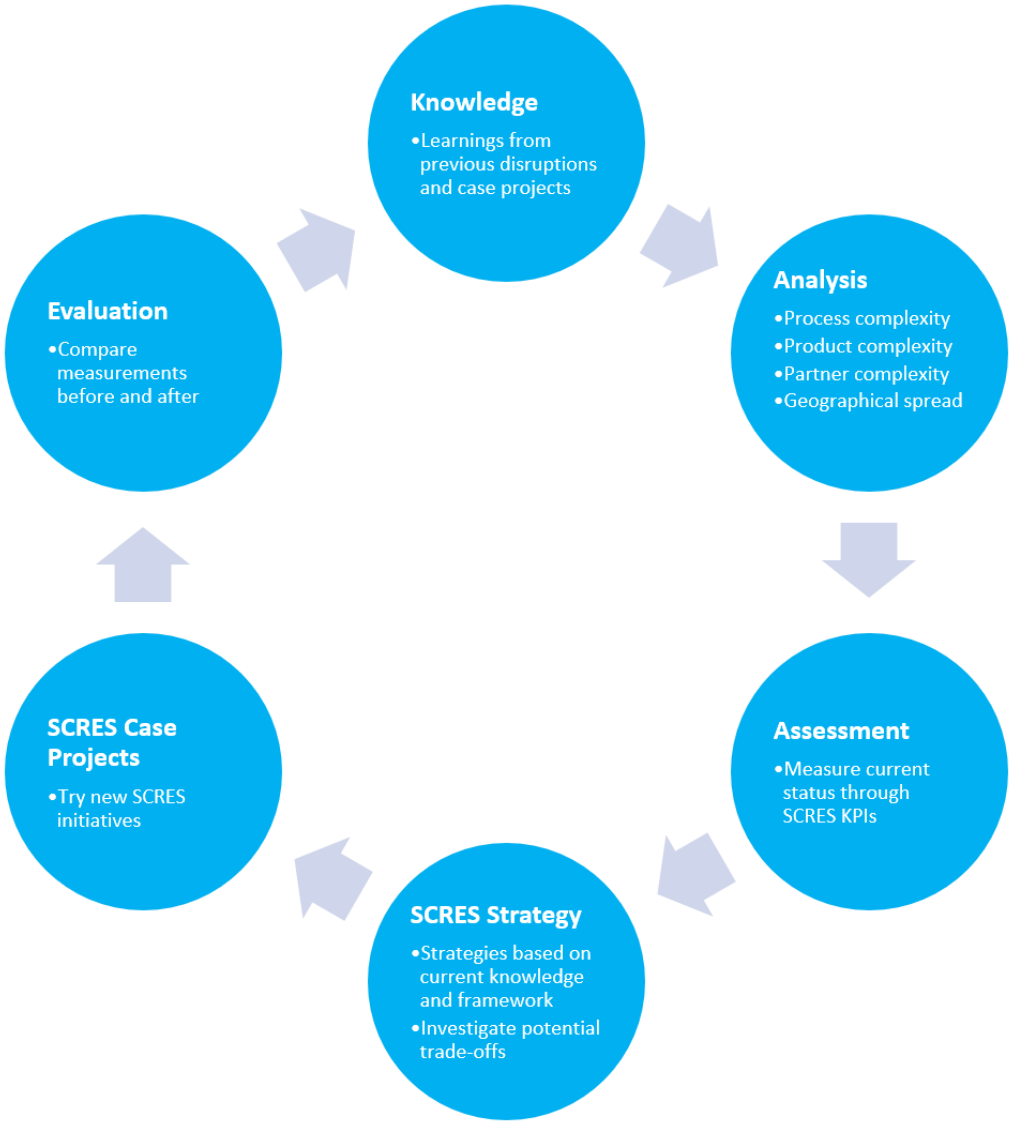
5.3.1 Appropriate supply chain resilience strategies for Assa Abloy Entrance Systems

This chapter proposes supply chain resilience strategies that could be applied to the division in general. In Figure 19, a suggested general framework of how to assess and improve supply chain resilience in a company is presented. This is a guideline for Assa Abloy Entrance Systems to follow to make sure all steps are included to be

able to achieve improved supply chain resilience.

Figure 19

General framework of how to assess and improve supply chain resilience in a company



Looking at the three segments of Assa Abloy Entrance Systems included in this scope, there are some differences. Regarding the business segment pedestrian, lead times are perhaps of higher priority with a large supplier base operating in Asia, resulting in longer minimum lead times and stressing the fact that variations in lead time throughout the supply chain can have a huge impact in the final delivery precision. The industrial business segment, having a major part of their suppliers in Europe, works largely with the electronics category, which has been dealing with a shortage of components since before the COVID-19 pandemic. Because of the general problems of dealing with a scarce source of material and suppliers in this category, perhaps the highest priority for this segment is creating strong supplier relations to be able to secure components. Another important aspect is product design, where there are possibilities to develop towards including new technology to

follow the investment trend of suppliers extending their capacity for new technology prior to the old even though component shortages of the old technology are still lagging. It also adds flexibility to allow for alternative components and materials if disruptions occur. In addition, the industrial segment has by far the fewest Stock Keeping Units (SKUs), which indicates that it is, at least relative to the other segments, easier to work with product design strategies. Regarding the residential business segment, they are deeply entangled through collaborations with Assa Abloy Entrance Systems own factories and could be regarded as a component factory for the other segments' factories, enforcing the importance of high delivery precision. They also have a large share of supply in Asia which leads to long lead times. This points in the direction of prioritizing short lead times and building in strategic inventory to maximize delivery precision at internal units. Due to their importance internally, it could arguably be seen as the segment where resilience is most important to invest in, even though higher costs as a trade-off might incur. The introduction of internal backup facilities or identical factory designs that allow for the same production at multiple sites seems suitable for the residential segment, as a disruption at a residential site could imply a bottleneck issue for many component factories in the Assa Abloy Entrance Systems division. The residential segment only has 19 suppliers, which is relatively few and means that they are working in an environment with less process complexity. Therefore, there might be possibilities to establish strong relationships with the majority of suppliers and achieve greater supply chain visibility to enable the discovery of vulnerabilities in lower tiers.

Generally for all three segments, is the strategy to commit to volume and capacity which has not been done before at Assa Abloy Entrance Systems as mentioned by interviewee 11. This caused issues during the recent disruptions and therefore It seems reasonable to commit to volumes in the future to not get deprioritized again in the event of a disruptions. An added benefit could also be closer relationships with the supplier as they feel more secure. Further on, the literature on metrics mention the planning cycle time as frequency of S&OP meetings as a metric related to adaptability. Currently, Assa Abloy Entrance Systems does not have an S&OP planning process and it could be considered as a potential addition in all the segments as S&OP involves steps such as capacity planning which is clearly related to resilience.

5.3.2 Exemplifying resilience strategies at Ostrov factory

Strategies pursued should vary with the context of the factory, to exemplify this the Ostrov factory has been chosen as an example. The report has covered projects A and B, which have demonstrated significant supply chain resilience benefits, including shorter lead times, an increase in deliveries made on time, and securing critical components during disruptions, among others. With evidence of their positive effects on supply chain performance, these tried-and-true projects could likely be beneficially applied to the Ostrov factory context as well. One interviewee suggested integrating the purchasing department into Project B in order to broaden the negotiation and decision-making knowledge base. To preserve the relationship in the event of employee turnover, another interviewee gave the example of integrating multiple roles in cross-communication between the supplier and company. This could also result in a more refined exchange of knowledge when multiple roles participate and share their experience.

Currently, the Ostrov factory is proactively searching for alternative components for the critical items to prevent future disruptions from having a significant impact. 70% of the items used in the factory are single sourced, indicating that this is an effective

strategy that is also frequently praised in the literature. Theoretically, it would increase supply chain resilience if a second source for the items could be identified, even for non-critical items that can also cause production to stop. However, the complexity and quantity of items, the number of available suppliers, and the associated costs impact the viability of dual sourcing. The items could be categorized, in which case they could be prioritized. Time to survive and time to recover could be used to calculate the cost of disruption in order to categorize the items and suppliers. However, for items that dual sourcing is not feasible for, we recommend that the Ostrov factory proceeds to investigate the possibility of opening up their Bill of Materials to allow for alternative components and materials.

Collaborative inventory was a strategy that was not discussed in any of the interviews as identified in the gap analysis. Since approximately 75% of Ostrov's suppliers are also Assa Abloy Group suppliers, it may be possible to share inventory with other Assa Abloy units within the Entrance System division or the group as a whole. Ostrov could also investigate collaborations with external companies; for instance, the literature covered the collaborative inventory strategy between Toyota and Sears, two seemingly unrelated companies. This appears to be especially advantageous for the electronics industry, which has experienced supply constraints multiple times in the past. During one interview, the interviewee spoke about a partnership between Assa Abloy Entrance Systems and Tetrapak, in which they shared information on how to enter the Indian market. The interviewee had contacts at Tetra Pak from prior employment that were useful. It could be a good starting point for the Ostrov factory to determine whether it has established relationships within Assa Abloy or with suitable external companies that they could collaborate with. We believe that strong relationships are required if a collaborative inventory strategy is pursued, as there may be instances in which both actors require the same components and inventory is insufficient. Therefore, it is safer to collaborate with other Assa Abloy units; however, there are examples of successful collaboration with external parties. A similar concept to that of Project B with an external collaboration partner could serve as the basis for this strategy.

Our recommendations for strategies to be implemented by the Ostrov factory are summarized in Table 18. We believe it would be beneficial for the employees of Ostrov to have Figure 15's comprehensive list of supply chain resilience strategies as inspiration, as well as our recommendations. The recommendations are meant to be a refined version highlighting a mix of already proven strategies by Assa Abloy Entrance Systems, an example of suggestions from the employees themselves, and a pinch of inspiration including an example derived from the literature.

Table 18

Potential resilience strategies appropriate for Ostrov factory to implement

Strategies for Ostrov Factory to implement	Aim
Project A, strategic inventory including implementation of DDMRP system	Improved forecasts, shorter lead times → better service level
Project B, vertical cooperation	Enhanced supplier relation → secure critical components and increase visibility in the supply chain
Alternatives in the Bill of Material	Enable component and material alternatives in product design → less vulnerable to component shortage, shift in power balance, and price increases
Collaborative inventory	Increased inventory of critical components → less vulnerable to component shortage

5.3.3 Introducing resilience metrics

Assa Abloy Entrance Systems currently measures a plethora of supply chain-related KPIs through business intelligence tools. These are displayed through KPI dashboards, which contain multiple KPI but also have dedicated dashboards analyzing, for example, lead time or spend. We propose a similar approach, using the existing business intelligence system, to add a set of resilience metrics; much of the data needed is already inside the data model. There are multiple benefits that could come from this. Creating and displaying metrics related to resilience is a way to bring the subject into the discussion. According to literature, one of the most common reasons supply chain resilience is often unacknowledged is that performance metrics that can be monitored are missing.

Creating and following up on supply chain resilience metrics in combination with the regular performance metrics is also part of the structuring toward an organization that cultivates an appropriate risk management culture while keeping the performance trade-offs in mind. In an interview with interviewee 11, it was discussed that, in the year before 2019, it was difficult to present a business case for a project that would increase resilience but slightly increase cost. Although this has gotten better over time due to the acknowledgement of recent disruptions, once the dust has settled, it is not for certain that this will continue to be the case. A dashboard for resilience would be a good reminder of the importance of being prepared for the next disruption that we know for certain will come at some point in the future.

The metrics also provide a way to observe improvement, in this case over a long time horizon. On a more speculative note, even the Hawthorne effect might be in play, meaning that the act of measuring supply chain resilience is recognized, and since it is observed, the resilience is improved over time. Finally, when the improvement is noticed, it enables creating rewards for such decisions and also makes it possible to incentivize even further improvements. Costs and service levels

should, of course, not be replaced by the elimination of risk, but it is important that the opposite is not true as well. Imagine an insurance company with the incentive to earn a certain amount of revenue. They are likely to issue risky insurance that is way too risky, which comes with a negative expected return. The supply chain parallel would be a supply chain that rewards cost reduction to the degree that small cost decreases are pursued at the expense of extreme cost in the event of a disruption. Such developments can even be rewarded if luck is involved and a large disruption does not occur; what did not happen is easily forgotten when evaluating results. Resilience metrics are hopefully a way to avoid this phenomenon and award the otherwise unnoticed supply chain heroes that prevent the extreme disruption cost from occurring in the future.

The current set of KPIs for Assa Abloy was introduced in Section 4.1.1, and there are indications of resilience within those metrics. Lead time correlates strongly with supply chain resilience, and one of Assa Abloy's key metrics is material throughput time. In addition, order fill rate, which reflects inventory levels and is related to supply chain resilience, is measured. However, according to this research and our established supply chain resilience determinants, the KPI pack does not cover certain aspects of resilience, such as collaboration, visibility, and structure. It is probably not a good idea, when constructing a centralized KPI pack at a high level, to include a metric for every determinant. Consistent with previous discussion, it would be advantageous to include at least one metric at this level to include resilience in the discussion. We believe that a weighted average world risk index, as illustrated in Figure 18, could be included in the KPI pack as it is easy to standardize the generation of the metric and it reflects geographical spread and relates it to the risk of some disruptions in the country. A second option that might be harder to implement but, at the same time, could be great to measure is to create a metric that measures the share of vulnerable items. A vulnerable item could be defined as those items that have no design alternative, no supply alternative, and a lead time longer than a certain established lead time threshold that is deemed fast enough, following the mindset of “An ounce of prevention is worth a pound of cure”.

The remainder of the resilience metrics covering the various determinants could be incorporated into the decentralized KPI at a lower level. For a logistics manager, it is essential to delve deeper into the robustness, adaptability, and agility determinants and measure metrics such as inventory levels at supplier sites, upside or downside flexibility, and complementary metrics that measure the quality of the data, including inventory accuracy and lead time variance. Sourcing managers may instead concentrate on metrics related to visibility, collaboration, adaptability, and structure, such as alternative suppliers, geographical spread, the quality of information, and supplier collaboration. As sourcing is accountable for supplier evaluations, a supplier scorecard approach could also be considered for implementation. In contrast, a category manager might focus on the number of alternative components within their category.

5.3.4 Exemplifying resilience metrics at Ostrov factory

The KPIs that are ultimately chosen should vary along with the strategy, to be able to exemplify this the Ostrov factory has been chosen as an example. The Ostrov factory is currently working to proactively establish supply alternatives for components. This suggests that the number of alternative components should be measured; following the "SMART" framework, the metric could also be adjusted to show the share of components with an alternative instead. Furthermore, 70% of items for the Ostrov factory are single-sourced, which does not have to be a problem in itself. However, if there are no alternative components established, the suppliers only have a single

facility, and the lead times are long, then the cost of disruption is likely to be high. Consequently, Ostrov could, on a supplier level, measure metrics such as excess capacity, lead time, order fill rates, and the number of nodes, i.e., facilities, per supplier. The metrics discussed above also provide a basis for trying to estimate the time to survive and the time to recover. If the time to survive is lower than the time to recover, then the cost of disruption should be estimated to identify which supplier has the highest financial impact in the event of a disruption.

To cover the remaining determinants of supply chain resilience, Ostrov could construct a visibility or collaboration index with the methodologies provided by Caridi et al. (2010) and Simatupang & Sridharan (2005), respectively. This would most likely require significantly more work than the other metrics suggested. Not only strategy determines what KPIs should be followed, but also the priority of resilience and the amount of information that is deemed reasonable to display. If there is a wish to simplify the measurement of supply chain resilience, Cisco's methodology for creating a resilience index provides some inspiration. The supply chain resilience strategy categories provided in Section 3.3 can be the base for the index, with the different categories being individually assessed and then weighted and consolidated into an index.

During the literature study and the interviews, it became clear that some problems can be completely unknown and arise from second-tier suppliers and below. It has also been discussed that metrics should be applied at the supplier level to ensure resilience throughout the supply chain. Our metric suggestions are mostly covering internal and first-tier suppliers, and the task of applying the metrics at an even lower level is daunting. However, if project B is implemented, it might enable a resilience kpi and resilience mindset further upstream to the 2-nd and n-tier suppliers. This might affect the selection process further down the supply chain and put stress on lower-tier suppliers to follow the mindset as well.

The suggested KPIs can help identify supply chain weaknesses and highlight strategies that can strengthen the supply chain. Similar to the process of projects A and B, strategies that are chosen can be implemented on a smaller scale so that the effect can be observed by comparing the KPI before and after implementation with limited downside.

Table 19

Potential resilience metrics that are related to Ostrov factory's current situation

SCRES determinants	KPI at Ostrov
Robustness	Excess capacity, Order fill rate ,Cost of disruption based on time to survive and time to recover
Flexibility	Alternative components
Adaptability	Alternative supply options
Agility	Lead time
Collaboration	Collaboration index
Visibility	Visibility index
Structure	Number of facilities per supplier

6. Conclusion

This study set out to dissect supply chain resilience and illustrate it in a concrete manner. Supply chain resilience has been categorized into seven determinants: *robustness, flexibility, adaptability, agility, collaboration, visibility, and supply chain structure.* Within these categories, 34 metrics have been suggested. Supply chain resilience strategies were gathered into seven broad categories: *inventory management, sourcing, supply chain design, product design, supply chain collaboration, supply chain visibility, and risk management and culture.* The supply chain resilience strategies were compared to the two case projects analyzed as part of research question two as well as mitigating and future solutions covered during interviews at Assa Abloy Entrance Systems. The study found that all the strategies that arose during the interviews were part of the literature framework created beforehand. This strengthens the viability of the framework in terms of including a wide range of strategies. Furthermore, the impacts of disruptions experienced by Assa Abloy Entrance Systems were summarized in a list of symptoms.

6.1 Managerial implications

Prior to this study, a comprehensive collection of metrics had not been found. The insights gained from this study may be of assistance to managers by providing an inspirational list of 34 metrics related to supply chain resilience that could be implemented in their organization if they are aligned with their current objectives.

The empirical data contributes to existing knowledge of supply chain resilience by providing real-life examples of strategies implemented by managers. Furthermore, the literature strategy framework presents inspiration from a wide range of available alternatives that managers can further reflect upon and apply. A limitation of the study is that the discussion on strategies does not cover how they should be implemented or what effects they would imply both in the short and long term. Managers will have to assess the feasibility of specific strategies in their situation through reflection, calculations, and observations.

The framework in Figure 19 for how to assess and improve supply chain resilience in a company can contribute to a better understanding of what is an appropriate order and way to assess current resilience in a company and how to improve it further. It can be used to preserve knowledge and shape a template to start from when issues of resilience are brought up in new areas. This way, different divisions of Assa Abloy can take advantage of each other's experience from pilot projects and start from their level when starting new projects.

The symptom list and analysis of disruptions provided in this report might increase our understanding of how future disruptions might play out. For example, ripple effects and problems at unknown lower-tier suppliers are likely to be issues in the future as well. However, it is important not to forget that the future might not be a reflection of the past. A general preparedness should be built into the supply chain, not only a preparedness for the effects of recent disruptions.

6.2 Further research

This report provides a generalized framework of available strategies that affect supply chain resilience according to literature and what could be done at the Ostrov factory. However, appropriate strategies tend to vary depending on product, partner,

and process complexity. Therefore, further research could be done at a higher level of detail on either of these categories to further analyze what strategy is best for a specific item and what trade-offs it would imply. Furthermore, detailed research on how the strategies should be implemented could be done. For example, how can the set-up of backup suppliers be done, or what agreements should a collaborative inventory partnership include? The value and applicability of the newly proposed metrics could also be explored further to confirm their usefulness and feasibility.

Future improvements for Assa Abloy Entrance Systems could include adding a function in Qlik Sense that summarizes important data related to resilience. Furthermore, this function could use this data to make an assessment of a company’s strengths and weaknesses and return suitable suggestions of strategies to improve their resilience.

This report's scope was limited to first-tier suppliers, and the difficult task of analyzing resilience further upstream was only touched upon briefly. However, the application of resilience metrics at lower tiers appears extremely challenging and, as a result, requires additional study. In addition, the downstream side of the supply chain, such as distribution and service, was not included in the report's scope and is another area worthy of further investigation.

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Appendix 1

Interview guide symptomlist, Covid and Russia-Ukraine war and US-China tariffs were discussed sequentially using the

1. What were the effects and in what part of the supply chain did these occur?
    a. Supply
    b. Information
    c. Logistics
    d. Other
2. Do the effects differ in terms of region?
3. Do the effects differ in terms of product / product categories
4. Which process/supply chain took the longest time to recover?

5. Did you have a contingency plan before the disruption?

6. Was there any process in place before the disruption that worked well or made the supply chain recover surprisingly well?

7. Are you doing something differently today with regards to resilience strategies? Have you added any new processes?

8. If you were to do a project to make the supply chain more resilient, what would it be?

Interviewguide for case projects

1. Describe the project.

2. Benefits with the project. What effects have you seen so far and do you expect more benefits in the future?

3. Disadvantages with the project.

4. Implementation process

5. Difficulties with implementation

6. Any tips you would give to a department that tries to clone this concept? Anything you would change if you were to redo it?

Appendix 2

COVID-19

Component shortage

(1) New capacity invested in new technology, old technique lagging problem, Assa falls behind.

(10) Lead time of a cable from a German supplier but manufactured in China had regular lead times of 4 weeks but in the first half of 2022 it had 104 weeks lead time.

(1) Demand variation and surge. Slashed Capacity of suppliers. Smaller disruptions before COVID-19 weakening the SC. Electronics in general have had issues for a long time due to long lead times among others. Supplier side needs 26 weeks, contract manufacturers need 12 weeks, shipping another 8 weeks.

(3) There are a lot of problems in regards to electrical components that comes from the position that they have in comparison to other actors ordering components from the suppliers. The volume that Assa Abloy Entrance Systems provides to the suppliers is nowhere near the volumes actors like Samsung and Automotive.

(3) At the start of COVID-19 they had inventory in both the plant and in transit so they felt quite safe since there were no lockdowns in Thailand and Malaysia at the time. However, they soon realized that the 2nd tier suppliers that they did not know about were experiencing issues which in turn caused difficulties for their first tier suppliers and made them unable to deliver for some time.

(4) To increase resilience with regards to component shortages they for example entered negotiations with one supplier and demanded that they find more alternative suppliers for laminates.

(1) What caused the lack of supply was firstly that factories had to lock down and caused a shortage of components, and also shortage of workforce due to sickness.

(2) To change components in electronic control, it can be difficult to find alternatives due to the fact that they need test certificates for new components. The components are included in doors with sensors that are important that they work otherwise people can get stuck or squeezed. Further on, Assa Abloy Entrance System's electronics are “legacy products”, which has made it more difficult to get priority on such supplies.

(9) The capacity issues with electronics actually had its inception when a supplier in Japan suffered a factory fire before COVID-19.

Price increases on raw material and components

(3) A pre-COVID-19 order quantity of PCB’s cost about 25k euro while normal levels were about 3k euro, more than an 8 times increase. This cost had to be transferred to their customer.

(2) Another shortage that arose was that of wood. When people started to work from home, they started to build stuff such as terraces among other stuff. This resulted in a shortage of packaging material and also an increase in cost.

(4) Another supply-side issue was price increases of plastics Assa Abloy Entrance Systems used in their products, the same plastics were used for medical equipment used for COVID-19 relief efforts which were prioritized and therefore plastic supply drastically decreased.

(6) Prices of steel increased drastically starting in the second half of 2020. It varied depending on region but in some regions, price increases were almost 3x in 2021. Similar effects were seen for aluminum. The material at Assa Abloy Entrance Systems is purchased when needed rather than strategically when there is an average price or below-average price. What they speculate on is available and if they need to create buffers.

(6) Prices of electronic components in control units have been widely discussed in many interviews, information showcasing the effect of these price increases on the total cost of a component (door opener) were provided. Between 2021 and 2022 the cost of the door opener increased ~15% basically only driven by price increases in the control unit.

(11) Assa Abloy Entrance Systems did not commit to capacity or volume which caused further issues when trying to supply electronic components.

Procurement from spot market

(3) One example is that of microchips that they bought from Taiwan at a standard price per order quantity of 36k usd, the supplier of microchips had closed down and then they had to order the same order quantities at a 10x price.Then they either had to make a decision to either stop the plant for 6 weeks and therefore disrupt Assa Abloy Entrance System's supply chain as Ostrov supplies to other plants part of the Assa Abloy group or purchase microchips at 10x the price. The purchase price variations along with transport cost variation increased spending of over 2 million euro in 2022 and 2021, that is 13% of the yearly turnover.

(9) Electronics suppliers had capacity issues and were not able to deliver, therefore spot market purchases were frequent and components that normally would cost 50 cents could sell for 8 dollars.

(9) The cost of downtime is larger than the added cost from purchasing components at inflated prices from the spot market. Assa Abloy Entrance System's suppliers did not actually want to sell to the actors that resell at inflated prices at the spot market, they would much rather sell to serious long-term customers and therefore they actively tried to identify the resellers.

(6) Goods from the spot market increased the supplier rejection rate as they were not always fulfilling the requirements due to the fact that the source did only have responsibility for their stake and not the consequences if the performance affected the quality of the end product.

Delayed transport & volatile lead times

(7) Transport Lead times during the COVID-19 period varied drastically and it was extremely hard to forecast what the lead time would be and then give this ETA to a

factory. The reliability of the lead time was record low during the COVID-19 pandemic.

(7) It was also difficult to move between districts and get permission to drive in for example China, which made it hard to get products to the harbors from the factories.

(7) Because of COVID-19, containers were stuck in harbors due to lack of workforce (capacity of manhours and equipment) and space, sometimes up to 15 days, and ships were stuck waiting to be loaded outside of harbors. Lead times increase material throughput time which is a high priority for Assa Abloy Entrance Systems as they are a capital intensive organization that want to do a lot of acquisitions.

(4) There were lots of times when ports were overloaded and lead times increased by around 30 days because of this, on average the transport lead times increased by about 20% for the Ostrov factory. Because of the added lead time, they had to use air transport on multiple occasions instead of the usual maritime route to avoid standstills in the factory. This hurt margins a lot. The logistical problems occurred mainly for shipments from Asia.

(1) There were other disruptions than COVID-19 at the same time, the suez canal. They had products on the ship that were stuck for a long time. When the ship was solved and not stuck anymore, there were other issues regarding responsibility and ownership of the products which took a long time to solve. Accordingly, they had to buy duplicates of everything that was stuck on the ship which resulted in increased costs.

Air transport

(1) Had to use expensive transport to save delivery precision

(6) To maintain service levels towards their customers during COVID-19, they had to use air freight to a large extent.

(3) Since the PCB suppliers had issues it led to longer lead times and therefore the Ostrov plant had to use air transport to receive their PCBs otherwise they would not have been able to produce. However, this did not completely resolve the issue, one time when they had to wait 4 weeks until they got a spot on a cargo plane since Assa Abloy Entrance Systems was not the only one having this idea and that belly cargo capacity on passenger planes was next to none.

Container shortage

(7) Difficult to get containers. Closed harbors, demand unbalance “Furthermore it was much more beneficial to send containers in the direction China to the US which has resulted in containers going empty one way” , spike in demand (“bored americans”).

(7)Spike of prices of containers, For containers, the price was about 3000 us dollars for one 40 feet container and in the end of COVID-19 it was about 12000 us dollars.

(1) There was a general global shortage of containers due to a spike in demand from products in China to the US that arose in a later stage of COVID-19, which added to an imbalance in transport.

Time consuming activities

(7) All the communication with different carriers, forecasting variance, problem solving has been extremely time demanding for the logistics organization, the period has been the most hectic in (7)s career.

(3) Pre-COVID-19 they experienced shortages for some components on a quarterly frequency but during as COVID-19 hit component shortages related to the PCB became an almost daily issue. They would get lists from the suppliers containing all the components that they were missing and then deciding what they would do about it.

(3) The workload for white collar workers exploded as they had to constantly resolve shortage issues. A lot of cooperation between material planners and R&D took place to try finding alternative components that can be used. They have found a lot of alternative products that they can use during the last three years. They are now trying to proactively find alternatives, specially for critical customized products.

(4) A major part of 4's work days were such follow-up meetings regarding electronic components and steel and plastic material.

(2) When there started to be a shortage of components, people working with purchasing had to start doing a lot of work coordinating all the suppliers and hunting for information regarding lead times, capacity, and collecting information whether the suppliers could deliver or not.

(1) Extra evident when a supplier swaps owners and contact persons. Gap in the relationship when not able to meet in person.

Change in power balance between buyer and seller

(7) The freight rates overall were very steady before the COVID-19 pandemic. Assa Abloy Entrance Systems could use the opportunity to do an RFQ every quarter to find best prices for our power lanes. They were reconfigured every quarter but stayed pretty much the same. The power balance changed and prices were now dictated by the suppliers and forwarding agents. During this period with COVID-19 it was all about chasing transport possibilities, previously, and now starting again, Assa Abloy Entrance Systems received phone calls from forward agents asking to ship some of Assa Abloy Entrance Systems volume.

(6) There are interesting power dynamics in the electronics category, the two suppliers Scanfield & Flextronics decided that they do not want Assa Abloy Entrance Systems as their customer due to their location and relative purchasing volume. Phasing these suppliers out is ongoing and they will after this process have a single source (IMI, China).

Spike in freight price and volatile prices

(7) The freight price increased drastically

(7) After a while when COVID-19 had struck, prices got more and more volatile and unpredictable and could change every week or even hour. The price for train transport increased as well. However, this has not decreased as the ocean rates. We did not face any issues finding spots on airplanes, however, the prices have increased a lot. The dependency and volume have increased and so increased their costs from 1.1 millions to 2,6 millions. To deal with the price increases Assa Abloy Entrance Systems has responded with an increase in their prices as well.

Related to volatile prices:
(7) Assa Abloy Entrance Systems have recently started a new contract with Maersk which was under the market price. Now however, prices for containers have had free fall. The contract does include quarterly prices according to a market index.

Increased tied-up capital

(4) Although the on-time delivery was upheld it came at a price of increased tied-up capital, material throughput time increased by a third and still has not recovered fully by being at about 15% higher than levels previous to COVID-19.

Russia-Ukraine

Supplier shutdown

(1) Neon supplier had to stop production, ukraine represented 50% of global market. Transfomer productin had to stop operations due to work force shortage

(3) THey had a supplier of transformers in Ukraine, the factory didnt get bombed but they had to stop completely since they had a lack of employees and supplies. They were however lucky and had just finalized testing at another supplier due to cost and quality issues at the Ukraine supplier. Jakub mentions that the testing process takes about 3 months , therefore the time to recover if they had still single sourced from Ukraine would have been very long.

(3) A supplier of plastic components in Czech republic had their main supplier of plastic granulate in Russia and they could not get supplies from there anymore. This led to price increases as they had to chase suppliers of plastic granulate. They found a supplier in Italy and China. The plastic issues are still not fully recovered , the prices are still much higher and they have not finished negotiations of prices.

Transport Route blockage

(1) Routes with trains are no longer possible to use. Sea and air instead which have significantly increased LT and Cost.

(7)We avoid using rail since it pass through Russia and our main logistic partners does not accept orders for rail on this route due to company policies.

Some of their competitors are still managing to use the railway through Russia, however Assa Abloy Entrance Systems took the decision to not include any business that could potentially help Russia in any way.

(9) Before COVID-19 Assa Abloy Entrance Systems had transitioned from ocean to rail transport for the Suzhou - Ostrov route. During COVID-19 they still used rail and did not experience any notably large issues with this mode of transport. However, when the Russia-Ukraine war started they had to transition back from rail to ocean transport

(9) Since they had calculated their stock levels based on train lead times they now had a 6 week gap when using ocean transport and this gap had to be closed by air freight. Ocean freight contributed to an increase in material throughput time.

Increased price of raw material

(4) The price of steel based components more than doubled.

(3) Some components also increased in price due to copper price increases since they got their copper from Russia.

(1) For a while the source of steel was scarce, and in Assa Abloy Entrance Systems case, it could be an advantage to be small because their volumes are lower and easier to squeeze in.

(6) The steel prices were increasing already before the war was initiated, it was a high in 2021, but experienced a short term local maximum just after the initiation of the war.

Energy prices rose a lot due to the Russia - Ukraine war and this had ripple effects increasing the price of glass by ~ 30-50% during 2022.

US-China tariffs

Added cost & complexity

(1) It gets much more complicated and expensive to import components produced in China to Assa Abloy Entrance Systems factories situated in the US.

(6) Because of the added tariffs on products produced in China and imported to the USA, products had to go through other countries to be reclassified before entering China. Subsequently, lead times for Assa Abloy Entrance Systems increased by about 5 weeks and resulted in larger transport costs due to increases in transportation distance. However, the biggest effect was seen on flexibility due to longer lead times. There was also subsequently greater capital captured on boats which increased their material throughput time which is an important KPI for Assa Abloy Entrance Systems. They work a lot with acquiring businesses which makes the cash flow important.

Redesign

(7) Fully produce in Canada to avoid tariffs through FTA. Or another example is assembly in Switzerland.

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF SERVICE MANAGEMENT AND LOGISTICS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
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