



**Vaasan yliopisto**  
UNIVERSITY OF VAASA

Pihla Holopainen

**How can manufacturing companies improve  
production planning resilience against supply chain  
disruptions**

School of Technology and innovations  
Bachelor's thesis in Industrial Management  
Bachelor of Science in Economics and  
Business Administration

Vaasa 2025

---

**UNIVERSITY OF VAASA****School of Technology and innovations**

**Author:** Pihla Holopainen  
**Title of the thesis:** How can manufacturing companies improve production planning resilience against supply chain disruptions  
**Degree:** Bachelor of Science in Economics and Business Administration  
**Discipline:** Industrial Management  
**Supervisor:** Binod Timilsina  
**Year:** 2025                      **Pages:** 50

---

**ABSTRACT:**

Recent disruptions in supply chains (pandemic, geopolitical and logistical) have raised the need to focus on the resilience of production planning in the manufacturing industry. The purpose of this literature review is to examine how manufacturing companies can strengthen the resilience of production planning. A systematic literature review was conducted using several databases covering the years 2020–2025. The criteria for the search were: peer-reviewed, English-language, manufacturing industry and self-performed data extraction and selection of articles.

The most common disruptions were observed to be fluctuations in demand and production caused by the pandemic and logistical disruptions, such as the Suez Canal Blockage. The disruptions were visible in upstream supply, downstream demand and internal processes. The most important tools for resilient production planning were found to be production speed adjustment (inventory and cost control), multi-skilled workforce and redundancy (safety stocks and capacity buffers). The best results came from combining strategies and with proactive, systematic disruption management. Digitalisation (digital twin, CPPS/IoT, analytics and artificial intelligence) improved visibility, collaboration and responsiveness, supporting the development of resilient production planning.

The results provide a concrete framework for companies to develop and prioritize flexibility investments and reinforce disruption resilience in production planning. The results were limited by the time frame of 2020–2025, the use of English and variations in terminology (resilience, flexibility, agility).

---

**KEYWORDS:** production planning, supply chain disruptions, resilience, manufacturing industry, flexibility, digitalisation, redundancy

---

**VAASAN YLIOPISTO****School of Technology and innovations**

<b>Tekijä:</b>	Pihla Holopainen		
<b>Tutkielman nimi:</b>	How can manufacturing companies improve production planning resilience against supply chain disruptions		
<b>Tutkinto:</b>	Kauppätieteiden kandidaatti		
<b>Koulutusohjelma:</b>	Tuotantotalous		
<b>Työn ohjaaja:</b>	Binod Timilsina		
<b>Valmistumisvuosi:</b>	2025	<b>Sivumäärä:</b>	50

---

**TIIVISTELMÄ:**

Viimeaikaiset toimitusketjujen häiriöt (pandemia, geopolittiset ja logistiset) ovat korostaneet tarvetta keskittyä valmistavan teollisuuden tuotannonsuunnittelun joustavuuteen. Tämän kirjallisuuskatsauksen tarkoituksena on tarkastella, miten valmistavan teollisuuden yritykset voivat vahvistaa tuotannonsuunnittelun häiriönsietokykyä. Tutkimus toteutettiin systemaattisena kirjallisuuskatsauksena, jossa hyödynnettiin useita tietokantoja vuosilta 2020–2025. Hakukriteereinä käytettiin vertaisarvioituja englanninkielisiä artikkeleita, jotka käsittelevät valmistavaa teollisuutta.

Yleisimmiksi häiriöiksi tunnistettiin pandemian aiheuttamat kysynnän ja tuotannon vaihtelut, sekä logistiset häiriöt, kuten Suezin kanavan tukkeutuminen. Häiriöt näkyivät toimitusketjun alkupäässä, loppupäässä ja yritysten sisäisissä prosesseissa. Tärkeimmiksi tuotannonsuunnittelun resilienssiä vahvistaviksi työkaluiksi todettiin tuotantonopeuden säätö (varastojen ja kustannusten hallinta), monitaitoinen henkilöstö ja redundanssi (varmuusvarastot ja kapasiteettipuskurit). Parhaat tulokset saavutettiin yhdistämällä strategioita sekä ennakoivalla, järjestelmällisellä häiriöiden hallinnalla. Digitalisaatio (digitaalinen kaksonen, CPPS/loT, analytiikka ja tekoäly) paransi näkyvyyttä, yhteistyötä ja reagointikykyä, mikä tuki joustavan tuotannonsuunnittelun kehittämistä.

Tutkimuksen tulokset tarjoavat yrityksille konkreettisen viitekehyksen seurattavaksi, jonka avulla yritykset voivat kehittää ja priorisoida investointeja joustavuuteen sekä vahvistaa tuotannonsuunnittelun häiriönsietokykyä. Tuloksia rajoittavat aikaväliltä 2020–2025 valikoidut lähteet, englanninkielisten lähteiden käyttö ja terminologian vaihtelut (resilienssi, joustavuus, ketteruus).

---

**AVAINSANAT:** production planning, supply chain disruptions, resilience, manufacturing industry, flexibility, digitalisation, redundancy

## Contents

1	Introduction	6
1.1	Background of the study	6
1.2	Objectives and research questions	7
2	Research Methodology	8
2.1	Design & Scope	8
2.2	Data sources and search strategy	9
2.3	Data extraction & Analysis	11
2.4	Quality, Validity & Limitations	12
3	Literature review	14
3.1	Types, causes and impacts of disruptions	14
3.2	Production planning flexibility	16
3.2.1	Strategic aspects	16
3.2.2	Operational aspects	19
3.2.3	Structure and algorithmic management	21
3.3	Digitalisation and resilience in manufacturing	23
3.3.1	Introduction to digitalisation and resilience	23
3.3.2	The role of digital technologies in resilience	24
3.3.3	Smart systems and data-driven approaches	26
3.3.4	Supply chain resilience through digitalisation	27
3.3.5	Industrial applications	27
3.3.6	Summary of literature review	28
4	Findings	30
4.1	Common supply chain disruptions	30
4.2	Strategies to improve production planning flexibility	31
4.3	Role of digitalisation in risk management	32
5	Summary and Conclusions	35
5.1	Key findings	35
5.2	Practical recommendations	36

5.3	Limitations	39
5.4	Future research	39
	Appendix	41
	List of reviewed articles	41
	References	47

# 1 Introduction

## 1.1 Background of the study

Production planning has become an increasingly important aspect of industrial operations. The business environment is changing rapidly, and companies must be able to adapt and respond more quickly in order to remain competitive. Supply chain disruptions such as delivery delays, material shortages and sudden changes in demand can affect the entire production process. To adapt to such conditions, quick response and flexible planning are essential.

Recent global crises have exposed weaknesses in production chains and systems. COVID-19 in particular has disrupted industrial operations all over the world. According to a survey by Make UK (Shi et al., 2025, p. 1), nearly 80% of manufacturing companies reported a decrease in sales and orders during the COVID-19 pandemic. According to Shi et al. (2025, p. 8) companies with higher degree of operational flexibility had more abnormal inventory increases, fewer layoffs or job reductions, and greater operational efficiency than companies with a lower level of operational flexibility during the pandemic. The degree of flexibility in operations can determine the extent and impact of supply chain disruptions. Flexibility can increase customer satisfaction for manufactures, firm growth in sales, employment and profit (Shi et al., 2025, pp. 12–13). Shi et al. (2025, p. 14) emphasize that operationally flexible companies are better able to respond to large-scale supply disruptions and adapt to changes in their business environment. Production planning should therefore emphasise flexibility in addition to efficiency, as it enables companies to better prepare for a rapidly changing environment and the supply chain disruptions it may cause. This thesis compiles a framework for production planning flexibility by combining recent research findings on flexibility and digitalisation.

## 1.2 Objectives and research questions

The objective of this thesis is to identify and synthesise (i) the most common supply chain disruptions in the manufacturing industry, (ii) strategies that increase the flexibility of production planning in order to mitigate the effects of disruptions and (iii) tools of digitalisation that can be used to support production planning in the event of disruptions.

Based on this objective, the thesis aims to answer the following research questions:

1. What are the most common supply chain disruptions affecting manufacturing companies?
2. What strategies can companies use to improve flexibility in production planning to mitigate supply chain disruptions?
3. How does digitalisation contribute to production planning flexibility and mitigate risks from supply chain disruptions?

The scope of this study is limited to the manufacturing industry and peer-reviewed, English-language sources published between 2020 and 2025. In this thesis the term “flexibility of production planning” is used specifically in relation to capacity, labour and scheduling.

## 2 Research Methodology

### 2.1 Design & Scope

The aim of this research was to understand how industrial companies can develop the resilience of their production planning against disruptions in supply chains. This topic requires a broad understanding of existing research data, as it is multifaceted and topical, and therefore there is a great deal of information available on it. This thesis has been conducted as a systematic literature review focusing on supply chain disruptions, production planning flexibility and digitalisation (RQ1–RQ3). This thesis does not collect primary data but systematically analyses and synthesises existing peer-reviewed studies. The aim is to integrate previous findings and identify themes and gaps related to the research topics.

Review protocol:

- Type: systematic literature review.
- Time window: Jan 2020–Jul 2025
- Last search date: 10 Jul 2025
- Databases: ABI/INFORM (ProQuest), Business Source Premier (EBSCO), Emerald Insight, ScienceDirect, Taylor & Francis Online
- Research questions covered: RQ1–RQ3 (disruptions, planning flexibility, digital enablers)
- Inclusion: peer-reviewed, English, manufacturing context, relevance to RQ1–RQ3
- Exclusion: non-peer-reviewed, language ≠ English, not manufacturing context

The aim was not to examine all available information, but to look at the key themes of the topic. This thesis covers various topics such as production planning, supply chains, flexibility and digitalisation. Studying these topics gave me a deep understanding of the subject. This review enabled me to familiarise myself with the solutions proposed in studies for managing supply chain disruptions in production planning. The aim of this

this thesis was to understand how industrial companies develop their resilience. The scope of the study is the manufacturing industry, excluding supply chains related to other contexts. The sources are from 2020–2025, meaning that this thesis is based on recent information. The themes of supply chain disruptions, flexibility and digitalisation that appear in the thesis are based on research questions RQ1–RQ3.

## **2.2 Data sources and search strategy**

Sources were searched in several different databases, such as ABI Inform Complete (Proquest), Business Source Premier (EBSCO), Emerald Journals, ScienceDirect (Elsevier) and Taylor & Francis Online Journal Library. Sources were sought from these databases because they are recommended for industrial management and business research and contain high-quality, peer-reviewed studies. Using multiple databases keeps the information broader and ensures that it is not based on a single perspective.

Only peer-reviewed articles were included in the search results to ensure high-quality sources. The publication year was limited to 2020–2025 to ensure that the information was up to date. Inclusion criteria included: peer-reviewed, English, 2020–2025, relevant to RQ1–RQ3 and manufacturing context. The exclusion criteria included: non-peer reviewed, language ≠ English, no full text, irrelevant to the topic. Even after narrowing down the search, there were still dozens of articles, but not all of them were relevant for this thesis' research questions. The search results were transferred to an Excel spreadsheet, where they could be viewed by the titles and authors, the publication years, concepts, and abstracts of the articles. In the first stage, the abstracts and titles were read from the Excel spreadsheet. After this, it was possible to divide them into categories according to how relevant they were for this thesis. The irrelevant articles were removed from the spreadsheet, leaving a smaller number of publications that could be examined more closely. Excel made it easy to return to potentially suitable articles. Search strings, which are presented in Table 1. Search strings and filters were formed using Boolean operators according to the themes (RQ1-RQ3).

**Table 1.** Search strategy and screening.

Theme	Search string	Database	Filters	Hits	Title/abstract screened	Included
RQ1	“supply chain disruption” AND manufacturing AND resilience	ScienceDirect	Peer-reviewed; Article/Review ; 2020–2025; English	35	35	5
RQ2	“production planning” AND flexibility AND manufacturing	ScienceDirect	Peer-reviewed; Article/Review ; 2020–2025; English	106	100	8
RQ3	“digitalisation” AND “production planning” AND manufacturing	ScienceDirect	Peer-reviewed; Article/Review ; 2020–2025; English	87	87	10

Searches were also conducted in the Business Source Premier (EBSCO), Emerald Insight and Taylor & Francis Online databases, however, ScienceDirect was chosen for reporting because it provided the most high-quality results suitable for the work. Sometimes the search resulted in too many hits, in which case the search terms were refined or narrowed down using filters. The “hits” section of the table shows all results obtained from ScienceDirect for the search term. “Screened” contains articles that were transferred to Excel for further examination based on their title and abstract. “Included” contains all articles from ScienceDirect selected for analysis, which can be found in the

appendix and references. This method enabled a consistent selection of suitable articles.

### **2.3 Data extraction & Analysis**

The same content was extracted from each selected article. Basic information such as author, year, title, keywords, database, journal and DOI/URL was extracted from the articles. In addition, a description of the theme was formed based on the article, and it was noted whether the article would be included in the study (yes/maybe/no). This approach made it possible to compare articles according to their suitability for RQ1, RQ2 and RQ3, which means the final analysis was conducted by theme rather than simply listing articles.

The following table 2 presents three main themes, their connection to RQs, key concepts and sources representing them.

**Table 2.** Themes selected from the literature and their relevance to the research questions.

Main theme	Related RQ	Key concepts	Sources
Common supply chain disruptions in manufacturing	RQ1	<ul style="list-style-type: none"> <li>• Classification: Upstream/internal/downstream</li> <li>• COVID-19, Suez Canal blockage, ripple effects, supply/demand fluctuations</li> </ul>	Solari et al., 2024; Kudakwashe & Poee, 2024; Peukert et al., 2020; Ranaboldo et al., 2024.
Strategies to improve production planning flexibility	RQ2	<ul style="list-style-type: none"> <li>• Production rate flexibility</li> <li>• Multi-skilling &amp; labour flexibility</li> <li>• Redundancy</li> <li>• Real options valuations</li> </ul>	Glock & Grosse, 2020; Afshar-Nadjafi, 2021; Kuhn et al., 2024; Mraih et al., 2023; Yang et al., 2024.
The role of digitalisation in risk mitigation and production planning	RQ3	<ul style="list-style-type: none"> <li>• Visibility &amp; collaboration</li> <li>• Digital twin, CPPS/IoT, AI/ML, cloud, blockchain</li> </ul>	Alshawabkeh et al., 2024; Zaid et al., 2024; Malburg et al., 2023; Feddoul et al., 2025; Lee et al., 2022.

These themes form the subchapters of chapter 4; the results of the analysis are presented in this order.

## 2.4 Quality, Validity & Limitations

The reliability of the study is reinforced by the use of multiple databases (ProQuest, EBSCO, Emerald, ScienceDirect, Taylor & Francis). Clearly defined search terms (see table 1). A systematic selection process that made it easier to find suitable sources. Excel spreadsheets enabled comparison of articles.

The validity of the study was ensured by setting a time frame, selecting the years 2020–2025 to guarantee up-to-date material. Only peer-reviewed articles were selected for the study. The searches were focused on the context of the manufacturing industry. By detailing the search strategy and criteria in the study, the validity of the study can also be strengthened.

The limitations of the study included, for example, only English-language articles; other languages were excluded. The time frame of 2020–2025 left out older classic articles. The results may have a limited perspective, as positive results are more likely to be published. There is also variation in concepts, for example: resilience, flexibility and agility. These limitations are considered in the interpretation of the results and conclusions.

### **3 Literature review**

#### **3.1 Types, causes and impacts of disruptions**

Solari (2024, p. 7) discusses how the impact of Covid-19 on logistics and supply chain processes has significantly increased interest in supply chain disruptions since 2021. On the other hand, Solari also points out that the peak of publications will be reached in 2023, which indicates how active research is in this field. Solari (2024, p. 19) notes that COVID-19 related topics were the most prominent in recent years, leading to significant increase in the use of keywords related to crises, disasters and health related topics such as drug shortages and vaccine distribution. Therefore the most frequently studied supply chain disruptions in recent years are highly related to the effects of COVID-19.

Solari (2024, p. 2) states that the first studies on disruptions began to appear in the late 1990s, focusing on the Millennium bug. In 2004 research began to focus on the war in Iraq and the SARS epidemic in Asia. Between 2017 and 2023, studies focused on Brexit, which affected political and trade balances in the European Union and globally. Recently attention has shifted to the impact of COVID-19 on global supply chains, in particular the challenges faced by Chinese migrant workers in low-wage sectors. Over the past two years, attention has focused on the war between Russia and Ukraine, which led to disruptions in trade relations among global players and raw materials and energy resources supply. These events illustrate the vulnerability of interconnected supply chains. They also point to the fact that supply chain disruptions have been studied for decades, with research typically focusing on the most significant disruptions at a given time.

The following section discusses the most common types of disruptions, their underlying causes and their impact on manufacturing.

Solari et al. (2024, p. 2) presents a variety of major disruptions such as the COVID-19 pandemic, Brexit, the war between Russia and Ukraine and climate-related risks. The war between Russia and Ukraine caused serious disruptions within trade relations among global players and raw materials and energy supply. These examples represent various types of disruptions: technological risks, geopolitical conflicts, health crises and natural or climate-related threats. The supply chain disruptions are not limited to developed economies. According to Kudakwashe and Pooe (2024, p. 8), studies show that there are many uncertainties in South Africa's fast moving consumer goods and retail industry. The study suggested possible resilient strategies to cope with disruptions. Nel (2024, p. 1) found a clear difference in how firms used agility and flexibility, collaboration and redundancy in their supply chain risk management strategies to manage disruption. Those who collaborate more and implement redundancy strategies are better prepared to respond to disruptions. Overall, disruptions are often caused by global dependencies, limited arrangements and political or environmental instability. Together and separately, these factors increase the uncertainty of supply chains.

Shi et al. (2025, p. 1) cite a Make UK survey which found that an estimated 80% of manufacturing companies reported a decline in sales and orders during the COVID-19 pandemic. COVID-19 has therefore contributed to the collapse of industrial production, due to its uncertainty. The pandemic had serious consequences for companies' operations, as they might reduce their production outputs or inventories due to possible severe reduction in demand and high demand uncertainty (Shi et al., 2025, p. 2). These disruptions affect supply chains, as companies have to react to uncertain situations, for example by reducing production and inventory. This is further supported by Solari et al. (2024, p. 2), who highlights that constant disruption and high uncertainty can have a huge impact on production chains, as the failure of one element can cause the failure of the whole chain (ripple effect). The effects are not only economic, such as lost sales and

increased costs, but also more operational, such as inventory turnover, workforce instability and chain reaction disruptions in global networks.

Supply chain disruptions vary and arise for different reasons, such as geopolitical conflicts, global crises, technological disruptions, and environmental risks. Their effects vary; some affect operations, such as delivery delays and production stoppages, while others affect the economy, such as increased costs. Understanding these disruptions is important in terms of the resilience strategies (3.2) and the impact of digitalisation (3.3) discussed in the following chapters.

## **3.2 Production planning flexibility**

This section discusses ways to increase production planning flexibility and resilience. The chapter includes key strategies which can be classified into strategic, operational and structural approaches. Digital methods are addressed in section 3.3. According to Guzman et al. (2021, p. 1) manufacturing companies must aim to produce products with as few resources as possible to meet high quality standards and respond quickly to changing market needs. Production planning flexibility means the ability to react quickly to changes in demand without wasting too many resources. In today's world, the market environment includes uncertainty and changing customer needs, which requires more efficient planning.

### **3.2.1 Strategic aspects**

Nel (2024, pp. 5–6) presents three key strategies for reducing supply chain risks: agility, collaboration and redundancy.

According to Nel (2024, p. 5) agility is about the ability of a firm to respond quickly to disruptions, while flexibility helps to prepare for future disruptions. Flexibility can be improved by investing in infrastructure, adaptive production systems and employee skills (Nel, 2024, p. 5). Agility is therefore beneficial in rapidly changing situations, such

as those where disruptions can occur simultaneously in different parts of the supply chain. For instance, if the delivery of parts needed for production is delayed, an agile company is prepared to change suppliers. Flexibility, on the other hand, means the ability to prepare for the future and adapt. For example, if a company has production lines that manufacture several products, it can respond quickly to changes in demand.

According to Nel (2024, p. 5) supply chain collaboration requires close cooperation between independent companies to implement relevant supply chain strategies. Information sharing is an important part of forming this collaboration. Nel suggests that visibility, which refers to a company's ability to view the entire supply chain, improves collaboration. Visibility is important because when companies have information about the entire supply chain, they can collaborate to develop strategies for managing supply chain disruptions. Technology also significantly improves collaboration, which will be discussed in section 3.3.2.

Redundancy refers to maintaining excess capacity and inventory (Nel, 2024 p. 6). Other examples of redundancy as a strategy for supporting supply chain resilience mentioned by Nel are multi-sourcing, including stockpiling inventories and having reserve capacities available. Redundancy can prevent production standstills. Inventory types such as safety stock and buffer inventory can be used to prepare for supply chain disruptions. Although maintaining excess resources requires capital investment and can lead to inefficiency, excess capacity can be crucial in ensuring continuity of production in a crisis situation.

Lou et al. (2024, p. 2) states that manufacturers can reduce the risk of supplier disruption through investment or diversifying supply disruption risk through a dual sourcing strategy. The combination of these two strategies is more effective in reducing the risk of interruption. Dual sourcing and buffer stocks are examples of how redundancy can be implemented. Lou points out that, in general, the selection and implementation of resilience strategies is complex and that the results of investments will influence companies' future decisions on strategies. Companies need to take into account factors such as supplier relationships, product quality, procurement costs and the possibility of

supplier failure. Although dual sourcing and the use of buffer stocks increase costs and may lead to inefficiency, they improve delivery reliability and reduce risks.

Nel (2024, p. 1) concludes that firms that are agile and flexible, collaborate with supply chain partners and adopt redundancy strategies tend to be better equipped to deal with disruption. Therefore companies that know how to combine agility, collaboration and redundancy as strategies are better prepared to adapt to disruptions and prevent them. Peukert et al. (2020, p. 1) state that current disruption management is often based solely on experience and intuition, leaving out some important partners and influencing factors, which prevent optimal results from being achieved. This clearly shows how essential a proactive and systematic approach is. Recent studies indicate that effective disruption management also requires a comprehensive, planned and well-integrated approach. Instead of traditional, reactive approaches, the focus should be on proactive planning.

Kuhn et al., 2024, p. 1404) states that the valuation of real options allows the costs and benefits of investment to be assessed on the basis of different future developments. Production flexibility can lead to increased costs, and its full benefits are not necessarily evident under stable conditions. Instead, the more unstable the future becomes, the more valuable flexibility can become (Kuhn et al., 2024, p. 1404). Therefore, flexibility is an investment which increases in value when uncertainty increases. In times of stability, it can be costly and may be perceived as useless, but in times of crisis it is the key to continuity. Crisis resilience needs to be included in production planning in order to be able to operate effectively to the unexpected. Under stable conditions, such investments may generate small losses, but under uncertain and volatile conditions they may have significant return potential. Real options valuation is a strategy that allows a company to economically evaluate flexibility investments for different situations. This strategy helps in making decisions on financially significant and long-term investments.

Kuhn et al. (2024, p. 1404) also indicates that production resource flexibility cannot be implemented in an economically viable way without sufficient evaluation of costs and

benefits. Implementing flexibility therefore requires specific calculations and research, which are usually not sufficiently considered. Systematic evaluations enable flexibility to be achieved economically.

Glock & Grosse (2020, p. 703) suggest that adjustable, or variable, production rates offer production planners better opportunities to manage inventory build-up and drawdown and to control costs more flexibility. The adjustment of the production rate is therefore a tool to control stock levels, and the costs involved. This demonstrates that managing production parameters is essential to managing resilience. In open production systems or batch-based production scheduling, slowing down the production rate can reduce inventory levels and therefore reduce costs. On the other hand, in uncertain production environments, increasing speed can increase safety stock, which helps the firm to protect itself against disruptions. Production rate flexibility is therefore a proactive strategy, meaning that disruptions can be prevented. Variations in production rates can have an impact on a number of performance measures, such as storage costs, machine operating costs and downtime costs (Glock & Grosse, 2020, p. 710). It is therefore an important part of the strategy for increasing flexibility.

### **3.2.2 Operational aspects**

Concrete evidence illustrates how operational flexibility supports strategic flexibility in practice. Shi et al. (2025, p. 1) highlights that during the COVID-19 pandemic, firms with greater operational flexibility tended to experience higher than normal inventory growth, maintain more stable employment levels, and achieve better operational efficiency. Therefore, the pandemic has provided concrete evidence of the impact of strategies on continuity and maintaining efficiency in times of crisis.

According to Afshar-Nadjafi (2020, p. 1) multi-skilling can be divided into vertical, horizontal and depth skills, all of which have different effects on labour costs, efficiency, quality and production flexibility. This kind of multi-skilling increases the flexibility of production. For example, it is possible to change tasks without interrupting production.

Employee diversity improves their accessibility to different functions and thus their responsiveness to disruptions. Multiskilling refers to the effective planning, scheduling and allocation of diverse employee resources to take advantage of their flexibility to perform tasks (Afshar-Naadjafi, 2021, p. 2). Multi-skilling therefore requires comprehensive planning and efficient use of resources, targeted in the right way. This should be included to the planning of employees' flexibility as a part of production planning.

Mraihi et al. (2024, p. 9) points out that the use of worker flexibility allows the scheduling algorithm to flexibly allocate tasks according to worker skills and task requirements. This task allocation strategy that focuses on allocating employees by their abilities leads to an optimal use of resources, especially in a large organisation. For example, data collected on employees can be used to allocate tasks efficiently within the organisation in a systematic way. Yang et al. (2024, p. 318) highlight how supply chain resilience can be strengthened through, for example, flexible shift scheduling, transferable production resources such as human resources, technology and processes and operational diversity, which means alternative pathways and diverse skill sets. The possibility of transferring employees between different work systems allows a rapid reorganisation of production if necessary. Operational diversity allows the company to increase flexibility even if a resources changes. Consideration of worker flexibility has a significant impact on the scheduling of decentralised production systems (Mraihi et al., 2024, p. 9). Employee flexibility is not just additional feature, it is a key element of planning, especially in a large organisation. It also has an impact on the scheduling, capacity and expenses.

Flexible firms can strategically reallocate labour and other resources rather than reducing them. Such operational flexibility can mitigate the negative effects of severe supply chain disruptions (Shi et al., 2025, p. 2). Flexible operations support crisis situations where rapid adjustments are needed to adapt operations to the situation. Shi et al. (2025, p. 4) also point out that operational flexibility allows responding to disruptions through, among other things, flexible employment contracts and multi-

skilling. Multi-skilling and flexible employment contracts are an essential part of the operational ability to respond to challenging events. The ability to respond to challenging situations is achieved by planning workforce availability and HR policies proactively. Developing flexibility can mean investing in training and skills upgrading and adopting flexible employment contract models (Shi et al., 2025, p. 14). Operations flexibility therefore requires preventive investments such as training, flexible working contracts and process redesign, it is therefore a long-term strategy. Shi et al. (2025, p. 5) hypothesise that firms with high operational flexibility experience fewer job losses or staff layoffs during major disruptions. Companies with flexible operations therefore have a better chance of being able to maintain their workforce in times of crisis.

### **3.2.3 Structure and algorithmic management**

Structural flexibility is the ability of the supply chain to adapt to major changes in the business environment. Such forms of flexibility include postponement, outsourcing, multichannel sourcing, flexible shift scheduling and resource allocation (Yang et al., 2024, p. 319). Structural flexibility is built in, allowing for rapid and effective adaptation to changing circumstances. In other words, it is achieved by planning in advance strategies and structures that can be adapted quickly if necessary. Structural flexibility is therefore preventive not merely reactive.

Flexible Process Planning (FPP) includes three types of flexibility, which are processing flexibility, which means alternative production methods, sequencing flexibility and operational flexibility, which means the choice of resources and machines. Sequence flexibility refers to the organisation of selected work steps in such a way that production costs are kept to minimum and workflow requirements are met (Ma et al., 2025, pp. 1–2). FPP will therefore help to adapt to the changing production process.

Real options valuation allows the economic valuation of investments in situations where in a stable environment the investment may cause a small loss, but in conditions of increasing uncertainty it may have a significant return potential (Kuhn et al., 2024, p.

1403). Real options valuation provides a way of comparing different scenarios where flexibility pays in a stable situation but helps in a crisis.

According to Kuhn et al. (2024, p. 1403) in strategic production planning, the assessment of flexibility can be implemented in a four-step process. The evaluation process begins with the identification and description of uncertainties. Uncertainties may be related to demand, resource availability or geopolitical risks, for example. Companies need to be able to understand their uncertainties in order to assess whether flexibility in planning is needed. Uncertainties in different parts of the production process are combined using Monte Carlo simulation to account for statistical dependencies. The simulation results in uncertainty distributions of capacity demand and supply for critical production segments, which are used to build lattice-based scenario models for future planning (Kuhn et al., 2024, p. 1407). This allows flexibility to be assessed in an uncertain environment, as it combines statistical forecasting with economic decision making.

To address uncertainties, measures are identified which exploit flexible production resources (Kuhn et al., 2024, p. 1403). Therefore, the next step is for the company to determine what measures are to be taken to achieve flexibility. Flexibility measures are identified from two sources. The first is based on a systematic literature review, which has identified a set of measures that are generally applicable to most manufacturing companies. The second source is an expert review to identify company-specific and less common flexibility solutions (Kuhn et al., 2024, p. 1407). This method combines a theoretical and practical approach, making it ideal for production planning within a wide range of companies. Kuhn et al. (2024, p. 1403) introduces a final step in which, based on the previously discussed uncertainty factors, the flexibility of production resources is assessed by means of a real options assessment. The real options method allows decisions to be made, considering extreme scenarios and effect on the investment. Kuhn (2024, p. 1404) points out that the investments under consideration may cause a small loss in stable conditions but have the potential to create significant benefits in situations

where the future is uncertain and variable. Companies should evaluate investments including scenarios, not just calculations.

Elyasi et al. (2023, p. 157) presented a study that presented a heuristic algorithm based on column generation. The results show that the optimisation model achieves an average deviation of less than 6% from the optimal solution and reduces the average cost of production by more than 12% compared to conventional systems without flexible manufacturing system (FMS). These results show that a flexible manufacturing system and an optimised model can reduce production costs, compared to systems without FMS.

### **3.3 Digitalisation and resilience in manufacturing**

#### **3.3.1 Introduction to digitalisation and resilience**

Saarikko et al. (2020, as cited in Caon et al., 2024, p. 216) define digitalisation as a process that uses advanced technologies to transform organisational structures, business models, and the products or services offered. Digitalisation means more than just adopting technology. It helps to transform the organisation. According to Caon et al. (2024, p. 216), digitalisation is a continuous process of change that enables resilience by speeding up anticipation and adaptation. Caon et al. also highlight how technological development can improve operational efficiency, enable data-driven management and help companies adapt to rapidly changing market demands. The ability to adapt quickly is an important part of resilience and with the help of technology, a company can anticipate and change its operations before a disruption occurs. Utilizing data enables faster analysis of trends and risks, allowing for proactive action. These characteristics are related to the absorptive and adaptive dimensions of resilience (Lee et al., 2022, p. 21).

The COVID-19 pandemic accelerated digitalisation but at the same time highlighted the vulnerabilities of micro and small businesses (Caon et al., 2024, p. 217). Crises reveal the true capabilities of organisations. Digitalisation can improve the ability to change, but its effective utilization depends on the capabilities of the organisation. COVID-19 is a good

example of how companies that lacked expertise fell behind despite technological developments.

Caon et al. (2024, p. 218) also points out that during crises, so called “antifragile” companies among small businesses took advantage of the situation as an opportunity to improve their competitiveness through digitalisation, which led to permanent strategic changes. Resilience is therefore not just about recovering from a crisis, but about the ability to change one’s actions and grow stronger through the crisis. Organisations that had the ability to learn and a strategy were able to utilize digitalisation to strengthen their competitiveness. Certain organisations adopted a reactive stance, investing in technological solutions to ensure survival. In contrast, others succeeded in proactively developing their own capabilities at the same time. Achieving antifragility requires a strategy, not just individual technical solutions.

### **3.3.2 The role of digital technologies in resilience**

According to Zaid et al. (2024, p. 2), previous studies (Piramuthu et al., 2015; Rejeb et al., 2020; Bertolini et al., 2013) have shown that digital technologies support the development of smarter supply chains, promote operational excellence and collaborative processes and improve real-time visibility and coordination between marketing and production. Digital technologies are not only tools for storing and transferring data but also make the supply chain intelligent and capable of learning. Real-time visibility enables quick decision-making based on real-time data. Visibility allows disruptions to be identified in time, production planning easier and enables faster adaptation to changes. With these technologies, the benefits are seen across the entire system, not just at the individual level. Kudakwashe and Pooe (2024, p. 2) emphasize that some studies suggest that the adoption of blockchain technology can strengthen supply chain resilience, especially in conditions of increased risk and uncertainty. According to Swan (2013, as cited in Kudakwashe & Pooe, 2024, p. 2) blockchain is a new organisational model that enables the coordination of all human activities and value transfers on a significantly larger scale. The implementation of blockchain will improve

the transparency and traceability of materials, information and finances in the supply chain (Etemadi et al., 2021, p. 7). Blockchain can, for example, help track where delays occur in the supply chain during disruptions.

Alshawabkeh et al. (2023, p. 1) found in their study that analytical capability (AC) has a significant positive impact on digital collaboration (DC) and supply chain resilience visibility (SCRES). According to their research, digital collaboration increased the speed and flexibility of the supply chain. Alshawabkeh et al. define visibility as the ability to detect disruptions in time, velocity means rapid response to disruptions and flexibility means flexibility in process changes. They also show why analytical skills are emphasized in practice, as data collection must be followed by analysis because it provides a basis for drawing conclusions. Alshawabkeh et al. (2024, p.1) point out that analytical capabilities between companies enable digital collaboration. They also emphasize that AC and DC are key elements in improving supply chain resilience and organisational performance. Together these capabilities make responses faster and more targeted. According to RBV theory they presented, strategic competitive advantage comes from internal resources. It is therefore about utilizing data and collaborating to build resilience. Digitalisation is thus a capability that creates adaptability and stability.

Disruptive technologies such as the Internet of Things (IoT), artificial intelligence, blockchain technology and big data are central to the digitalisation of supply chains and can support organisations in achieving sustainable supply chain performance (Zaid et al., 2024, p. 1). AI enables efficiency and flexible operation of the supply chain operations even during disruptions. Artificial intelligence can help in automated decision making in crisis situations so that emotions do not influence decisions.

Shahab et al. (2025, p. 1) recommend a service configuration strategy that will improve the resilience of cloud-based manufacturing networks. Their model utilizes subentropy to handle uncertainties in various scenarios. Cloud manufacturing is used to manage resources and capacity. In this model, resources are provided as services through the

cloud. The services that help achieve the production target are selected. This considers which service is most likely to succeed. In other words, it measures the uncertainty of the service and identifies the best option, resulting in a resilient solution.

Feddoul et al. (2025, p. 1) present the augmented perception approach, which is based on digital twin technology and improves the perception capabilities of robots by combining virtual elements with the robot's map view. Augmented perception enables robots to better perceive changes in layout, for example, adding flexibility and proactivity. The robot adapts better to changes in the environment because the virtual elements are linked to an internal map.

### **3.3.3 Smart systems and data-driven approaches**

Modern technological solutions promise to improve operational efficiency, enable data-driven decision-making, and help companies adapt to rapidly changing market conditions (Caon et al., 2024, p. 216). Technological systems are therefore based on the use of data in decision-making. Using data allows for quick, in real-time and logical decisions. It allows organisations to adapt to changing circumstances and improve their operations continuously. Due to these characteristics, they support resilience and adaptation.

Industrial knowledge graphs (iKGs) are used to combine and present industry-specific knowledge and for graph-based reasoning to identify and learn new connections (Lim et al., 2024, p. 2). IKG combines information and helps to make decisions based on it. The system supports resilience in supply chain disruptions, as it can suggest alternative courses of action in changing situations. The solution options are scored using transparency labels, which promotes clarity in decision-making and supports informed choices (Lim et al., 2024, p. 2). IKG therefore proposes solutions from which a choice can be made by examining the reasons it provides. This allows for a quick response to situations with justification.

Zaid et al. (2024, p. 2) point out that digital technologies improve real-time visibility and coordination between marketing and production. These systems increase visibility and collaboration within the organisation. This enables feedback that facilitates learning. These features allow smart systems to improve over time, which enables resilience and continuous learning within the organisation.

### **3.3.4 Supply chain resilience through digitalisation**

Kudakwashe and Pooe (2024, p. 2) note that, according to some studies, the adoption of blockchain technology can strengthen supply chain resilience, particularly in situations where risks and uncertainties are heightened. Blockchain technology helps strengthen resilience when the environment is uncertain, especially in crisis situations.

### **3.3.5 Industrial applications**

Geurtsen et al. (2023, p. 171–172) show that adopting usage-based maintenance instead of time-based maintenance significantly improves production line throughput. They also mention that enabling maintenance flexibility and taking the condition of production machines into account when scheduling maintenance measures strengthen these improvements more. According to authors digital solutions such as deep reinforcement learning-based maintenance planning are a good example of how digitalisation can increase efficiency and flexibility. Because of the technology maintenance can be scheduled based on machine condition and production needs. This increases the speed of production lines and prevents unnecessary stoppages. They also explain in more detail that the DRL method can work particularly well on multi-machine production lines, where it is difficult to manually monitor machine maintenance.

According to Malburg et al. (2023, p. 1) to build intelligent and flexible production systems, production capacity and capabilities must be used as efficiently as possible, especially in the event of failures or unexpected situations. They emphasize that due to digitalisation, production systems operate proactive, meaning they can anticipate

disruptions and adapt to the changes they cause. For example, AI-based tools enable continuous replanning in production. This adaptability is important in crisis situations, as the order of priority in production may change. In addition, people do not need to spend time on these problems as the systems take care of them

Several technologies, like digital twins, cyber-physical systems, IoT sensors, robots, edge computing, artificial intelligence and big data are seen as promising solutions to help meet industrial demand (Ranaboldo et al., 2024, p. 16). Demand-side flexibility gives a solution for the flexibility gap, especially because of its low marginal costs (Ranaboldo et al., 2024, p. 2). These technologies are especially relevant in energy-intensive industries, because they adjust companies' electricity consumption to price changes.

Lee et al. (2022, p. 27) gives a practical example of this digital transformation. Compared to traditional automated production facilities, lights-out factories have increased production efficiency by 30%, reduced inventory turnover time by 15%, and cut unnecessary labour by 92%. In addition, they have saved up to \$1.6 million in annual energy costs. The entire factory's energy consumption is monitored by an advanced Factory Management Control System (FMCS) based on IoT sensors (Lee et al., 2022, p. 27). An automated and technological environment is a concrete example of how digitalisation enables resilience and efficiency in production. It also shows that real-time energy consumption monitoring and data-based decisions can reduce costs and improve resource efficiency. The need for manual labour is also reduced, allowing human resources to be redirected elsewhere. The systems enable automated maintenance, optimisation and quality control. This case shows how digital solutions can be beneficial economically and operationally, especially in unpredictable environments.

### **3.3.6 Summary of literature review**

According to Malburg et al. (2023, p. 1), previous studies (Lasi et al., 2014; Bübmann et al., 2015; Cheng et al., 2017; Bergweiler, 2016) highlight that intelligent manufacturing systems that are easy to configure and enable high flexibility during production are

essential in modern industry. Malburg et al. (2023, p. 1) also note that the use of artificial intelligence methods in cyber-physical production systems (CPPS) is essential to achieve this goal. In summary, the literature indicates that digitalisation, automation and flexibility tend to strengthen each other and together then improve the production planning resilience.

## 4 Findings

### 4.1 Common supply chain disruptions

The effects of the COVID-19 pandemic were strongly felt in the manufacturing industry, in the United Kingdom, as many as 80% of manufacturing companies reported a decline in orders and sales volumes. In addition, production in both the service and manufacturing sectors contracted significantly, by 19% and 24.3% respectively (Shi et al., 2025, p. 1, citing Make UK, 2021 and UK ONS). COVID-19 led to a significant drop in demand and a decline in production which particularly affected industry. This was a global disruption with far-reaching effects, impacting both supply and demand. This is one of the most common effects of supply chain disruptions.

Kudakwashe and Poe (2024, p. 2) point out that recent major supply chain disruptions such as the 224,000-ton ship stuck in the Suez Canal, the COVID-19 pandemic, and border crossing delays have exposed the vulnerability of fast-moving consumer goods (FMCG) and retail supply chains in an unprecedented way. Disruptions in supply chains can occur in a variety of situations, caused by factors such as natural disasters, pandemics and geopolitics. The causes of supply chain disruptions are not always straightforward; they can be caused by a combination of different types of disruptions.

Nel (2024, p. 3, referring to Habermann et al., 2015) divides supply chain disruptions into three main categories: disruptions related to supply sources, internal process disruptions (which Parast and Subramanian [2021] have addressed in their own studies), and customer-side disruptions. What these have in common is that disruptions can occur anywhere in the supply chain, upstream, internally, or downstream. Organising disruptions in this way helps to understand where in the chain the disruption occurs and what its effects are. This allows us to examine different examples.

The COVID-19 pandemic caused a chain reaction in the supply chains of many companies. Disruptions in one area affected other areas and increased uncertainty throughout the supply chain. Companies had to adapt to changing competitive environments, as the entire supply chain had to adjust at the same time (Nel, 2024, p. 2; referring to Magableh, 2021; Modgil, Singh & Hannibal, 2021). COVID-19 is an example of how the impact of a disruption can be felt throughout the entire chain. For example, problems with deliveries affect production and thus deliveries to customers. The impact of disruptions can therefore increase significantly without management.

## **4.2 Strategies to improve production planning flexibility**

The flexibility of production systems refers to the ability to respond to changes in production volumes and product ranges with relatively little time and effort, for example by changing manufacturing processes, material flows, and logistics operations. Although flexibility can increase costs and its added value is minimal in stable conditions, growing uncertainty can significantly increase its value (Kuhn et al., 2024, p. 1404). Flexibility is a significant investment in a company's strategy, the value of which increases especially in uncertain situations. The costs are substantial and guarantee value if the uncertainty of the company's operations is sufficiently high.

Adjustable production speeds offer production planners flexibility in managing inventory growth and reduction as well as controlling costs. In practice, production speed can be changed in many ways, such as by adding workers to the production line, utilizing overtime, organising training, modernizing or adding machines, or even increasing the clock speed of the machine, if technically possible (Glock & Grosse, 2020, p. 703). Adjusting production speed is a rapid and effective way to respond to changes in demand. It allows for more flexible inventory and cost management.

Multiskilling refers to an employee's ability to expand their expertise beyond their actual role and respond to other needs within the organisation. This requires effective planning,

scheduling, and allocation of multi-skilled resources so that their flexibility in performing tasks can be utilized in the best possible way (Afshar-Nadjafi, 2021, p. 1–2). A multi-skilled workforce enables rapid increases in production flexibility without a significant increase in resources. At the same time, it can also improve continuity in production planning in unexpected situations.

According to Shi et al. (2025, p. 1) operational flexibility refers to the ability of a company's systems, its processes and personnel to cope with uncertainty without using additional resources or costs. Their study found that during the significant supply chain disruptions caused by the COVID-19 pandemic, companies with higher operational flexibility were better at managing inventory growth, avoided larger staff reductions, and maintained higher operational efficiency. This indicated that high operational flexibility improves companies' ability to maintain efficiency and workforce during crises. This shows that flexibility has a positive impact not only on production but also on the workforce.

According to Nel (2024, p. 1) results show clear differences in how companies use agility, flexibility, collaboration and redundancy as supply chain risk management strategies to manage upstream, internal and downstream disruptions. Nel discovered that flexibility, cooperation and redundancy strengthen one another on supporting production planning and together these strategies work effectively against disruptions.

### **4.3 Role of digitalisation in risk management**

According to Caon et al. (2024, p. 216), digitalisation uses advanced technologies to transform an organisation's practices, business models and offerings. Automation and real-time data collection can improve performance by streamlining processes, reducing errors and improving productivity. The study also highlights targeted policy measures specifically to improve access to digital infrastructure and to strengthen the resilience of businesses to future crises. Digitalisation is not just about investing in technology, but also a strategic component that increases flexibility and resilience within an organisation.

Alshawabkeh et al. (2024, p. 1) state that analytical capabilities significantly improve the visibility of supply chain resilience and digital collaboration on the other hand has a positive impact on supply chain speed and flexibility. According to the study, both of these are important when using resilience to improve organisation's performance. They also point out that digital collaboration and data analytics improve supply chain visibility and responsiveness. This is important for resilience, as visibility and responsiveness reduce the impact of disruptions.

Zaid et al. (2024, p. 1) point out those disruptive technologies, like IoT, artificial intelligence, blockchain, and big data can help organisations to achieve sustainable supply chain performance. They also point out that Digitalisation improves collaboration, real-time visibility and more efficient information exchange. In addition, digital technologies improve information flow and real-time response to events which strengthens supply chain risk management and improves operational efficiency. This helps to respond proactively and rapidly to disruptions.

Shahab et al. (2025, p.1) describe cloud-based manufacturing as combining distributed resources and collaborative processes which provides production solutions. According to them it can streamline resource allocation and strengthen system resilience, which improves the adaptability and continuity of cloud-based manufacturing systems. Because of cloud-based manufacturing decentralized resources can be used efficiently and quickly reorganised in crisis situations. This strengthens the ability of production to continue operating during disruptions.

Feddoul et al. (2025, p. 1) suggest that digital twins reduce the gap between reality and virtual models and improve the system's ability to adapt to changing conditions. The AP approach highlighted in the study reduces the impact of disturbances and restores performance to near normal, which makes it important for systems that require flexibility. They also introduce the Digital Twin, which helps manage disruptions before they affect production. It enables rapid recovery from disruptions and continuity in production.

Malburg et al. (2023, p. 1) state that automated planning enables flexible production processes and continuous redesign and rescheduling, which can be used to optimise production and adapt to dynamic changes in the environment. Artificial intelligence-based automatic redesign enables rapid reorganisation of production in the event of disruptions.

Ranaboldo et al. (2024, p. 1) emphasize that technologies related to digitalisation, such as digital twins, cyber-physical systems, IoT sensors, robots, edge computing, artificial intelligence, and big data, offer promising opportunities to improve services in the manufacturing industry. Industrial risk management is enhanced when various digital technologies are used in a versatile way, helping to create effective monitoring and responsiveness.

## 5 Summary and Conclusions

### 5.1 Key findings

This literature review revealed several common disruptions that have emerged in the manufacturing industry in recent years in particular COVID-19 was the most common and widespread disruption. During the COVID-19 pandemic, approximately 80% of manufacturing companies reported a decline in sales and orders (Shi et al., 2025, p. 1). The pandemic affected at the same time to demand and production, showing how linked global supply chains are. Examples of recent significant supply chain disruptions include the shipwreck of a 224,000-tonne ship in the Suez Canal, the COVID-19 pandemic, and border crossing delays (Kudakwashe & Pooe, 2024, p. 2). Understanding the diversity of disruptions can help companies to classify them into different types. Nel (2024, p. 3) divides supply chain disruptions into three main categories: disruptions related to supply sources, internal process disruptions, and customer-side disruptions. This classification helps to manage disruptions comprehensively

The finding show that flexibility is especially important in uncertain conditions. Investments may seem expensive in difficult circumstances, but they play a critical role in crisis situations. As the uncertainty of future situations increases, the value of production flexibility may rise significantly (Kuhn et al., 2024, p. 1404). Flexible adjustment of the production rate is one of the most effective ways to counteract the effect of changes in demand. Adjustable production rates give production planners more flexibility in managing inventory growth and reduction, as well as in controlling costs (Glock & Grosse, 2020, p. 703). When a workforce has multi-skilling, it reduces the risk of production downtime. Multi-skilling can improve flexibility, productivity, quality, continuity of work, and job satisfaction (Afshar-Nadjafi, 2021, p. 2). However, this requires systematic planning in training and resources. During times of crisis, operational flexibility also helps to retain workforce. Companies with higher operational flexibility were able to manage inventory growth, avoid staff reductions and maintain operational efficiency during major global supply chain disruptions (Shi et al., 2025, p. 1). According

to research, the most effective approach to deal with disruptions is to use different strategies together. Nel (2024, p. 1) also states that agile and flexible companies that collaborate and utilize redundancy strategies are better prepared to manage disruptions.

In practice digitalisation gives concrete tools for improving supply chains and industrial resilience, increasing visibility, cooperation and flexibility. Analytics capabilities have a significant positive impact on digital collaboration and supply chain resilience visibility (Alshawabkeh et al., 2024, p. 1). Visibility helps to detect disruptions at an earlier stage, and digital collaboration helps to respond more effectively in a crisis situation. Digitalisation also affects practical operations in technology solutions, which in themselves already affect resilience. Disruptive technologies such as IoT, artificial intelligence, blockchain, and big data can, as part of the digitalisation of supply chains, help organisations achieve sustainable performance (Zaid et al., 2024, p. 1). Real-time data and intelligent systems reduce the impact of disruptions and improve production operations. Digitalisation does not only mean impacts on information systems or process visibility, but also on physical production. Jay Lee et al. (2022, p. 27) describe the Lights-out factory as a system that utilizes machine learning and artificial intelligence devices to support automated optimisation, implementing intelligent self-maintenance and automated production and quality control through the predictive management of networked robots, machines, and production systems. Solutions such as these reduce dependence on labour and ensure continuity of production even in crisis situations.

## **5.2 Practical recommendations**

I will now outline the practical recommendations in order: (i) managing disruptions, (ii) improving the flexibility of production planning and (iii) applying digitalisation to risk management.

The major disruptions of recent years have highlighted the need for proactive and responsive measures. Recent and ongoing major supply chain disruptions, such as the 224,000-ton ship stuck in the Suez Canal, the COVID-19 pandemic, and border crossing delays, have exposed vulnerabilities in supply chains (Kudakwashe & Pooe, 2024, p. 2).

Similar chain reactions occur in industrial supply chains. For example, production stoppages caused by delays increase customer delays. Concrete actions are needed to minimize such situations. Classifying disruptions into supplier, process, and customer levels helps to target actions at the right point in the chain. Nel (2024, pp. 3–4) emphasizes that the interconnection between upstream, internal and downstream disruptions should be considered, as a disruption in one part can also affect other parts of the supply chain. It is important to consider each level in order to minimize the impact of disruptions in a comprehensive manner. This should be linked to the SCRM process to ensure efficiency.

First, practical measures are based on a step-by-step SCRM process. According to Nel (2024, p. 1), previous research (as cited in El Baz & Ruel, 2021; Nel & Simon, 2020) defines the SCRM process as consisting of four stages: risk identification, risk assessment, risk mitigation and risk control. This model is applied to the recommendations I present. First, risks are identified and assessed, then mitigation measures are selected and finally activities are controlled and improved.

Second, operational flexibility i.e., the coordination of processes and people, reduces the impact of major disruptions on warehouses, employment, and efficiency. U.S. manufacturing companies with higher operational flexibility experienced greater abnormal inventory growth, fewer staff reductions, and better operational efficiency during the COVID-19 pandemic (Shi et al., 2025, p. 1). Responding to crises emphasizes building flexibility, as it has been shown to create efficiency and retain labour during crises. Companies with flexible resources can easily shift their production from products with high component supply risk to products with lower supply risk and growing demand (Shi et al., 2025, p. 5). This is a concrete example of how flexibility helps companies operate in changing situations.

Third, improved visibility and information flow facilitate the detection of disruptions and response to them, and technology helps in this regard. The adoption of blockchain

technology can strengthen the supply chain resilience in situations where risks and uncertainty are high (Kudakwashe & Pooe, 2024, p. 2). In practice blockchain helps increase traceability and transparency, which will help to track and manage disruptions.

Fourth, according to Lou et al. (2024, p. 2) there are two important aspects to managing supplier disruptions, which are investing in supplier stability and dual sourcing and combining these. They also highlight how manufacturers can invest in suppliers of critical components to improve supply stability and increase supply chain redundancy through dual sourcing. Combining these two strategies can further enhance disruption risk management (Lou et al., 2024, p. 2). Manufacturers that emphasize delivery reliability often adopt a hybrid strategy to maximize expected sales volume, while in other cases they choose dual sourcing to pursue higher profits (Lou et al., 2024, p. 16).

A single measure to minimize the effects of disruptions is usually not enough. Nel (2024, p. 1) states that agile and flexible companies that collaborate and utilize redundancy strategies are better prepared to respond to disruptions. Nel provides a recommendation that combines operational flexibility, visibility in collaboration and selective redundancy targeting at upstream, internal and downstream segments. In summary, these recommendations implement the disruption models identified in section 4.1 (RQ1) and address production planning flexibility (RQ2) and risk management enabled by digitalisation (RQ3).

This thesis is on academic literature, but its findings can also be implemented in industrial management. Combining flexibility strategies and digitalisation improves production planning flexibility. However, to use these methods it requires significant commitment and investment. Future research could use empirical data to prove the connection between flexibility, resilience and performance.

### **5.3 Limitations**

This thesis is a literature review, which means that its conclusions are not based on original findings. Recommended databases such as ABI/ProQuest, Business Source and ScienceDirect were used in this thesis. This may have influenced my choice of sources. The latest studies from 2020–2025 were prioritized in the selection of sources, which may have resulted in some classics being left out. Certain terms, such as resilience or flexibility, can be defined differently across studies, which can make comparison difficult. In addition, technological development is still in its early stages, so the information may be partial or incomplete.

These limitations provide an opportunity to explore the topic in new ways. Empirical studies can be used to further strengthen the theory. In the future, research will deepen our understanding of how digitalisation and flexibility support resilience in different environments.

### **5.4 Future research**

Many technologies are still under development, so research need to be conducted, particularly into the implementation of AI and CPPS. The services available on the industrial demand response market are currently fragmented, and there are no standardised solutions for interfaces, protocols, data models or communication processes (Ranaboldo et al., 2024, p. 2). The full potential of digitalisation has not yet been realized, as there are no common standards in the market. In the future, development should focus on standardization and interoperability so that solutions can be widely applied in production. In the future, implementation and investments must be extensive in order to achieve results in large-scale production.

In the future, case studies and surveys will be needed in the manufacturing industry to determine whether flexibility actually improves resilience during disruptions. Studies are also needed to monitor changes in inventory, employment and efficiency before, during

and after a disruption. This will provide concrete evidence of the situations in which flexibility actually improves resilience. Research in the future could confirm how these methods support the resilience of production planning.

## Appendix

### List of reviewed articles

Afshar-Nadjafi, B.	2020	Multi-skilling in scheduling problems: A review on models, methods and applications	RQ2 – planning flexibility	ScienceDirect
Alshawabkeh, R. O., Rumman, A. R. A., & Al-Abbadi, L. H.	2024	The nexus between digital collaboration, analytics capability and supply chain resilience of the food processing industry in Jordan	RQ3 – Digital enablers	Taylor & Francis
Caon, M., Panetti, E., Meier, E., & Baldegger, R. J.	2024	The dual effect of COVID-19: Diverse digitalisation approaches in micro- and small businesses	RQ3 – Digital enablers	Taylor & Francis
Feddoul, Y., Ragot, N., Duval, F., Havard, V., & Baudry, D.	2025	The Augmented Perception: An emerging approach towards resilient manufacturing systems involving robotic agents and digital twin	RQ3 – Digital enablers	ScienceDirect
Elyasi, M., Altan, B., Ekici, A., Özener, O. Ö., Yanıkoğlu, İ., & Dolgui, A.	2023	Production planning with flexible manufacturing systems under demand uncertainty	RQ2 – Planning flexibility	Taylor & Francis

Etemadi, N., Borbon-Galvez, Y., Strozzi, F., & Etemadi, T.	2021	Supply Chain Disruption Risk Management with Blockchain: A Dynamic Literature Review.	RQ3 – Digital enablers	MDPI
Geurtsen, M., Adan, I., & Atan, Z.	2023	Deep reinforcement learning for optimal planning of assembly line maintenance	RQ3 – Digital enablers	ScienceDirect
Glock, C. H., & Grosse, E. H.	2020	The impact of controllable production rates on the performance of inventory systems: A systematic review of the literature	RQ2 – Planning flexibility	ScienceDirect
Guzman, E., Andres, B., & Poler, R.	2021	Models and algorithms for production planning, scheduling and sequencing problems: A holistic framework and a systematic review	RQ2 – Planning flexibility	ScienceDirect
Kudakwashe, T., & Poee, D.	2024	Supply chain disruptions in the fast-moving consumer goods industry	RQ1 – Disruptions	EBSCO
Kuhn, C., Riesener, M., Schmitz, S., & Fulterer, J.	2024	Economic flexibility design in strategic production planning using real options valuation	RQ2 – Planning flexibility	ScienceDirect

Lee, J., Davari, H., Singh, J., & Pandhare, V.	2022	Industrial Artificial Intelligence for industry 4.0-based manufacturing systems	RQ3 – Digital enablers	ScienceDirect
Lou, G., Guo, Y., Lai, Z., Ma, H., & Tu, X.	2024	Optimal resilience strategy for manufacturers to deal with supply disruptions: Investment in supply stability versus dual sourcing	RQ1 – Disruptions	ScienceDirect
Lim, K. Y. H., Liu, Y., Chen, C., & Gu, X.	2024	Manufacturing resilience through disruption mitigation using attention-based consistently-attributed graph embedded decision support system	RQ3 – Digital enablers	ScienceDirect
Ma, Y., Luo, K., Chou, M. C., & Sun, J.	2025	Balancing optimality and efficiency in solving flexible process planning: A parameter-free two-stage algorithm	RQ2 – Planning flexibility	Taylor & Francis

Malburg, L., Klein, P., & Bergmann, R.	2023	Converting semantic web services into formal planning domain descriptions to enable manufacturing process planning and scheduling in industry 4.0	RQ3 – Digital enablers	ScienceDirect
Mraihi, T., Driss, O. B., & El-Haouzi, H. B.	2023	Distributed Permutation Flow Shop Scheduling Problem with Worker flexibility: Review, trends and model proposition	RQ2 – Planning flexibility	ScienceDirect
Nel, J. D.	2024	The role of supply chain risk mitigation strategies to manage supply chain disruptions.	RQ2 – Planning flexibility	ProQuest
Peukert, S., Lohmann, J., Haefner, B., & Lanza, G.	2020	Towards increasing robustness in global production networks by means of an integrated disruption management	RQ1 – Disruptions	ScienceDirect

Ranaboldo, M., Aragüés- Peñalba, M., Arica, E., Bade, A., Bullich- Massagué, E., Burgio, A., Caccamo, C., Caprara, A., Cimmino, D., Domenech, B., Donoso, I., Fragapane, G., González-Font- De-Rubinat, P., Jahnke, E., Juanpera, M., Manafi, E., Rövekamp, J., & Tani, R.	2024	A comprehensive overview of industrial demand response status in Europe	RQ1 Disruptions –	ScienceDirect
Shahab, E., Rabiee, M., Mobasseri, N., & Valilai, O. F.	2025	A robust service composition for a resilient cloud manufacturing service network	RQ3 – Digital enablers	Taylor & Francis
Shi, X., Prajogo, D., Fan, D., & Oke, A.	2025	Is operational flexibility a viable strategy during major supply chain disruptions? Evidence from the COVID-19 pandemic	RQ2 & RQ1 – Planning flexibility & disruptions	ScienceDirect
Solari, F., Lysova, N., Romagnoli, G., Montanari, R., & Bottani, E.	2024	Insights from 20 Years (2004–2023) of Supply Chain Disruption Research: Trends and Future Directions Based on a Bibliometric Analysis	RQ1 Disruptions	MDPI

Yang, Z., Wu, M., Sun, J., & Zhang, Y.	2024	Aligning redundancy and flexibility for supply chain resilience: a literature synthesis	RQ2 – planning flexibility	Taylor & Francis
Zaid, M., Farooqi, R., & Azmi, S. N.	2024	Driving sustainable supply chain performance through digital transformation: the role of information exchange and responsiveness	RQ3 – Digital enablers	Taylor & Francis

## References

- Afshar-Nadjafi, B. (2020). Multi-skilling in scheduling problems: A review on models, methods and applications. *Computers & Industrial Engineering*, *151*, 107004. <https://doi.org/10.1016/j.cie.2020.107004>
- Alshawabkeh, R. O., Rumman, A. R. A., & Al-Abbadi, L. H. (2024). The nexus between digital collaboration, analytics capability and supply chain resilience of the food processing industry in Jordan. *Cogent Business & Management*, *11*(1). <https://doi.org/10.1080/23311975.2023.2296608>
- Caon, M., Panetti, E., Meier, E., & Baldegger, R. J. (2024). The dual effect of COVID-19: Diverse digitalization approaches in micro- and small businesses. *Journal of the International Council for Small Business*, 1–13. <https://doi.org/10.1080/26437015.2024.2404184>
- Feddoul, Y., Ragot, N., Duval, F., Havard, V., & Baudry, D. (2025). The Augmented Perception: An emerging approach towards resilient manufacturing systems involving robotic agents and digital twin. *Advanced Engineering Informatics*, *66*, 103450. <https://doi.org/10.1016/j.aei.2025.103450>
- Elyasi, M., Altan, B., Ekici, A., Özener, O. Ö., Yanıkoğlu, İ., & Dolgui, A. (2023). Production planning with flexible manufacturing systems under demand uncertainty. *International Journal of Production Research*, *62*(1–2), 157–170. <https://doi.org/10.1080/00207543.2023.2288722>
- Etemadi, N., Borbon-Galvez, Y., Strozzi, F., & Etemadi, T. (2021). Supply Chain Disruption Risk Management with Blockchain: A Dynamic Literature Review. *Information*, *12*(2), 70. <https://doi.org/10.3390/info12020070>
- Geurtsen, M., Adan, I., & Atan, Z. (2023). Deep reinforcement learning for optimal planning of assembly line maintenance. *Journal of Manufacturing Systems*, *69*, 170–188. <https://doi.org/10.1016/j.jmsy.2023.05.011>
- Glock, C. H., & Grosse, E. H. (2020). The impact of controllable production rates on the performance of inventory systems: A systematic review of the literature. *European Journal of Operational Research*, *288*(3), 703–720. <https://doi.org/10.1016/j.ejor.2020.05.033>

- Guzman, E., Andres, B., & Poler, R. (2021). Models and algorithms for production planning, scheduling and sequencing problems: A holistic framework and a systematic review. *Journal of Industrial Information Integration*, 27, 100287. <https://doi.org/10.1016/j.jii.2021.100287>
- Kudakwashe, T., & Poe, D. (2024). Supply chain disruptions in the fast-moving consumer goods industry. *Journal of Transport and Supply Chain Management*, 18. <https://doi.org/10.4102/jtscm.v18i0.1071>
- Kuhn, C., Riesener, M., Schmitz, S., & Fulterer, J. (2024). Economic flexibility design in strategic production planning using real options valuation. *Procedia CIRP*, 130, 1403–1409. <https://doi.org/10.1016/j.procir.2024.10.258>
- Lee, J., Davari, H., Singh, J., & Pandhare, V. (2022). Industrial Artificial Intelligence for industry 4.0-based manufacturing systems. *Manufacturing Letters*, 18, 20–23. <https://doi.org/10.1016/j.mfglet.2018.09.002>
- Lou, G., Guo, Y., Lai, Z., Ma, H., & Tu, X. (2024). Optimal resilience strategy for manufacturers to deal with supply disruptions: Investment in supply stability versus dual sourcing. *Computers & Industrial Engineering*, 190, 110030. <https://doi.org/10.1016/j.cie.2024.110030>
- Lim, K. Y. H., Liu, Y., Chen, C., & Gu, X. (2024). Manufacturing resilience through disruption mitigation using attention-based consistently-attributed graph embedded decision support system. *Computers & Industrial Engineering*, 197, 110494. <https://doi.org/10.1016/j.cie.2024.110494>
- Ma, Y., Luo, K., Chou, M. C., & Sun, J. (2025). Balancing optimality and efficiency in solving flexible process planning: A parameter-free two-stage algorithm. *International Journal of Production Research*, 1–18. <https://doi.org/10.1080/00207543.2025.2490214>
- Malburg, L., Klein, P., & Bergmann, R. (2023). Converting semantic web services into formal planning domain descriptions to enable manufacturing process planning

and scheduling in industry 4.0. *Engineering Applications of Artificial Intelligence*, 126, 106727. <https://doi.org/10.1016/j.engappai.2023.106727>

- Mraihi, T., Driss, O. B., & El-Haouzi, H. B. (2023). Distributed Permutation Flow Shop Scheduling Problem with Worker flexibility: Review, trends and model proposition. *Expert Systems With Applications*, 238, 121947. <https://doi.org/10.1016/j.eswa.2023.121947>
- Nel, J. D. (2024). The role of supply chain risk mitigation strategies to manage supply chain disruptions. *Journal of Transport and Supply Chain Management*, 18. <https://doi.org/10.4102/jtscm.v18i0.1035>
- Peukert, S., Lohmann, J., Haefner, B., & Lanza, G. (2020). Towards increasing robustness in global production networks by means of an integrated disruption management. *Procedia CIRP*, 93, 706–711. <https://doi.org/10.1016/j.procir.2020.03.009>
- Ranaboldo, M., Aragüés-Peñalba, M., Arica, E., Bade, A., Bullich-Massagué, E., Burgio, A., Caccamo, C., Caprara, A., Cimmino, D., Domenech, B., Donoso, I., Fracapane, G., González-Font-De-Rubinat, P., Jahnke, E., Juanpera, M., Manafi, E., Rövekamp, J., & Tani, R. (2024). A comprehensive overview of industrial demand response status in Europe. *Renewable and Sustainable Energy Reviews*, 203, 114797. <https://doi.org/10.1016/j.rser.2024.114797>
- Shahab, E., Rabiee, M., Mobasser, N., & Valilai, O. F. (2025). A robust service composition for a resilient cloud manufacturing service network. *International Journal of Computer Integrated Manufacturing*, 1–17. <https://doi.org/10.1080/0951192x.2025.2504088>
- Shi, X., Prajogo, D., Fan, D., & Oke, A. (2025). Is operational flexibility a viable strategy during major supply chain disruptions? Evidence from the COVID-19 pandemic. *Transportation Research Part E: Logistics and Transportation Review*, 195, 103952. <https://doi.org/10.1016/j.tre.2024.103952>
- Solari, F., Lysova, N., Romagnoli, G., Montanari, R., & Bottani, E. (2024). Insights from 20 Years (2004–2023) of Supply Chain Disruption Research: Trends and Future

Directions Based on a Bibliometric Analysis. *Sustainability*, 16(17), 7530–7530.

<https://doi.org/10.3390/su16177530>

Yang, Z., Wu, M., Sun, J., & Zhang, Y. (2024). Aligning redundancy and flexibility for supply chain resilience: a literature synthesis. *Journal of Risk Research*, 27(2), 313–335. <https://doi.org/10.1080/13669877.2024.2328196>

Zaid, M., Farooqi, R., & Azmi, S. N. (2024). Driving sustainable supply chain performance through digital transformation: the role of information exchange and responsiveness. *Cogent Business & Management*, 12(1). <https://doi.org/10.1080/23311975.2024.2443047>