Digital Resilience in Flux: A Comparative Analysis in Manufacturing Pre- and Post-Crisis

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Abstract

Major disruptions or crises such as COVID-19 or the war in Ukraine impact various industries such as manufacturing. These crises triggered declines in production due to lockdowns, problems in supply chains, and unavailability of production material. To cope with disruptions and crises, manufacturing companies need to be or become resilient. This work presents how major disruptions impact the digital resilience capabilities of manufacturing companies. By comparing the results of two surveys on digital resilience in manufacturing - one conducted in 2019 (pre-crisis), one replicated and conducted in 2023 (post-crisis) - it was found that major disruptions strengthened the capabilities of absorbing disruptions and adapting to disruptions in manufacturing companies.

Keywords: Digital Resilience Capabilities, Manufacturing Companies, Pre- and Post-Crisis Analysis

1. Introduction

The manufacturing industry represents one of the most important economic sectors, employing 12.8% of the world's total workforce in 2018 (Gitnux, 2023). During the COVID-19 pandemic, manufacturing faced massive declines in production and revenues due to problems in supply chains or lockdowns (Ardolino et al., 2022). Not only major shocks and disruptions, such as COVID-19 or the Tsunami in 2011, leading to a production slump of 30 percent for Toyota, require resilience. Shortage of skilled workers, power failures, materials of insufficient quality, or damage to machines and tools represent shocks or disruptions leading to high costs and production slumps in manufacturing.

Coping with the pandemic meant to be or become resilient for companies. Here, resilience can be defined as a company's ability to permanently adapt to external and internal changes and disruptions in complex, rapidly changing production networks (Hamel and Välikangas, 2003). Using digital technologies such as AI to foster resilience relates to the term "digital resilience", referring to capabilities developed based on digital technologies to absorb shocks, adapt to disruptions, and transform to new stable states (Boh et al., 2023). In manufacturing, several approaches are deployed to deal with disruptions, e.g., manufacturing execution systems for monitoring and controlling systems (Darmoul et al., 2013), rescheduling approaches (Wang et al., 2020) or optimization methods and analytic tools (Choi et al., 2022). Also, approaches for digital resilience such as digital twins and the industry 4.0 framework are applied (Dohale et al., 2022; van der Aalst et al., 2021). How digital resilience capabilities developed during and after major shocks still represents an open research topic.

The research objective of this paper is to *understand the impact of major disruptions on digital resilience capabilities in manufacturing.* Therefore we acquired the estimation of digital resilience capabilities by manufacturers pre- and post-crisis and analyzed which implications can be drawn on digital technology characteristics and conditions for digital resilience. We mainly focused on the capabilities of absorbing disruptions and adapting to disruptions. To gather the required knowledge, we conducted a questionnaire-based survey with manufacturing companies in 2019 and replicated the survey in 2023.

In the theoretical background, we elaborate on the typology of crisis and disruptions, the terminology used in this paper, digital resilience in industry, and the theoretical framework applied. Then, we describe our methodology and present the results. The latter are clustered after the theoretical framework for digital resilience research by Boh et al. (2023). Afterward, we discuss the results and conclude the paper.

2. Theoretical Background

2.1. Typology of Crises and Disruptions

A crisis is defined as the "perception of an unpredictable event that threatens important expectancies of stakeholders and can seriously impact an organization's performance and generate negative outcomes" (Coombs, 2014, p. 2). In response to a crisis, organizations often do not choose the optimal strategy. Mostly, they prefer strategies that avoid short-term losses to those that offer long-term gains and protect the organization's reputation (Claeys and Coombs, 2020). In the face of uncertainty, conflicting objectives, dynamic circumstances, and time constraints, decision makers are often confronted with challenging conditions and pressures (Klein et al., 2010). Behavioral economics elucidate how intuitive decision-making processes can be influenced by cognitive shortcuts, i.e., heuristics, leading to suboptimal decisions made under time pressure or in high-pressure situations (Claeys and Coombs, 2020). Cognitive overload is accompanied by the fact that information stems from heterogeneous sources and stakeholders and is characterized by uncertainty if it is available at all. Further, time and capacity to gain information and make decisions are limited and decision makers do not always possess the expertise and background knowledge to make it (Klein et al., 2010).

As crises take many forms, several crisis taxonomies were proposed in literature. According to (Gundel, 2005), crises are considered as predictable but hardly influenceable, e.g., the energy crisis or the war in Ukraine. Furthermore, they can be categorized as industrial accidents (cf. Seeger, 2006) and accidental crises respective technical error accidents (cf. Coombs, 2004). Different types of disruptions can have an enormous impact on the performance of systems, e.g., manufacturers. **Regular, irregular**, and **unexampled threats** can be distinguished with respect to the unexpectedness of their occurrences (Hollnagel et al., 2006; Wied et al., 2020. Regular threats are common for systems. Due to their frequency, standardized countermeasures are available, e.g., new market demands indicating changes in product portfolio. Irregular threats do not occur regularly and have different forms, i.e., representing individual cases. Due to their complexity, no standardized responses are available; e.g., poor quality of input material, accidents, delays in timely material delivery. Unexampled threats are not expected at all. Such threats are new to a system and beyond experiences. Those black swan events are high-impact events that can have significant consequences and disrupt the status quo (Taleb, 2007a), e.g., the 9/11 terrorist attacks, the global financial crisis of 2008, and COVID-19. Those threats are characterized by their extreme rarity, their unexpectedness, and their out-sized impact on financial markets, economies, and whole societies (Taleb, 2007b). Up til now, it is impossible to predict black swan events with certainty due to their rarity as well as their uniqueness (MAI, 2020). In this paper, we will use the term **disruption** as a synonym for crises, threats, and shocks.

2.2. Resilience in Industry

The term resilience stems from "resilíre", meaning "to leap back" or "to bounce back". In Engineering, resilience is adopted describing a system as resilient if it is able to adjust its functioning prior to, during, or with respect to following events, i.e., disruptions, and thereby sustain required operations under both expected and unexpected conditions (Hollnagel, 2013). Resilience capacity can be characterized by three parameters: **absorptive capacity (robustness), adaptive capacity (redundancy)**, and **restorative capacity (resourcefulness and rapidity)** (Francis and Bekera, 2014; Tierney and Bruneau, 2007). Considering reactions of resilient systems towards disruptions, we can further distinguish **"bounce back"** from worse-than-expected conditions and **"bounce forward"** under better-than-expected conditions (Meerow and Stults, 2016; Wied et al., 2020). In addition, bounce forward can be regarded as an opportunity for enhancement; extensive consideration must be given to how an affected system will recover, adapt, and "bounce forward" toward a better system state rather than a simple return to the status quo before crisis (Hynes et al., 2020; Manyena et al., 2011). The system performance bounces back from worse-than-expected conditions, generating a "resilience triangle" of deviation from and return to its equilibrium (Florin and Linkov, 2016). An equivalent "inverse resilience triangle" is created when the system performance bounces forward under better-than-expected conditions.

Disruptions in production companies concern the supply of materials of insufficient quality, leakage of lubricant lines, damage to machines or tools, power failures or overload, and illness of employees (Selcuk, 2017). In this context, disruptions can be predictable and unpredictable (Madni and Jackson, 2009). Often, disruptions affect a company from external sources, such as systematic market changes in the form of innovative technologies (e.g., shared production lines or 3D printing), changes in demand patterns and supply chains, or abrupt changes in political or financial systems (Kusiak, 2017). In addition, changes can also come from within, i.e., the products and production themselves, such as their quality, branding, and manufacturing (in)efficiency. In addition, there are changes in political regulation, the labor market, and the environment (Yeung and Coe, 2015). The ability of a company to permanently adapt to major, internal, and external changes and disruptions in complex, rapidly changing production networks is called the "quest for resilience" (Hamel and Välikangas, 2003). In order to increase the resilience of individual production companies or entire production systems, disruptive potentials and trends in the market, network, and company must be identified at an early stage, acute disruptions must be responded to optimally and lessons learned from them. Thus, resilience is directly decisive for the competitiveness of a company. Companies that lack sufficient resilience suffer considerable competitive disadvantages. The smaller the effects of disruptions on production, the higher the resilience of a company (Fraccascia et al., 2017). Due to a considerable increase in complexity in production as a result of Industry 4.0, resilience optimization and resilience management are becoming indispensable success factors in production companies. Resilience considers all processes within a production system (Chukwuekwe et al., 2016).

2.3. Theoretical Framework: Digital Resilience

For this work, we capitalize on the theoretical framework for digital resilience proposed by Boh et al. (2023). The framework supports the understanding of how entities build digital resilience by developing the capabilities of absorbing disruptions, adapting to disruptions, and transforming to new stable states. For each digital resilience capability, they provide digital technology characteristics to be leveraged and organizational conditions for building digital resilience (Boh et al., 2023). This framework builds the theoretical foundation for analyzing the survey results in section four and enables the comparison of the impact of major disruptions on digital resilience companies.

Absorbing a major disruption involves withstanding shocks while preserving an entity's original structure and operations. Companies can minimize initial losses and ensure survival by loosening the coupling between the entity and the changed environment. It comprises the digital technology characteristics of **redundancy** and **intelligent sensing**, as well as **coordination** and **data governance** as the conditions for building resilience (Boh et al., 2023). **Adapting** to disruptions involves the capability to function in a significantly different environment and adjust established operations, processes, models, or assumptions. The capability involves **ubiquity and accessibility**, as well as **experimentation** as digital technology characteristics. **Organizational restructuring** and **adaptive culture and mindset** represent conditions for building resilience (Boh et al., 2023). **Transforming** to a new stable state involves deep and revolutionary changes that require fundamental transformations. Short-term adjustments and quick fixes may not be sufficient to bring about lasting change. The transform capability involves **reconfigurability** and **scalability** (digital technology characteristics) and **business model innovations** and **ecosystem strategies** as conditions for building resilience. Digital technologies have played a significant role in transforming industries by enabling new capabilities, changing organizational structures, and developing new business models (Boh et al., 2023).

This theoretical framework highlights the interplay between digital technologies, organizational conditions, and resilience capabilities to help entities build resilience and mitigate major disruptions. The framework is supported by empirical evidence from the special issue papers and examples of how entities have responded to major disruptions (Boh et al., 2023).

3. Methodology

In order to understand the impact of major disruptions on digital resilience capabilities in manufacturing, a survey was conducted in two different years. The first one was conducted in 2019 (pre-crisis) and the second one replicated in 2023 (post-crisis).

3.1. Survey Structure

The survey was divided into three question blocks - resilience management within companies, status quo on resilience management, and general questions. The survey consists of 21 questions of which six questions were answered on a five-point Likert scale; five were multiple response questions, where the participants were able to choose a maximum of three answers. Four of the questions were simple yes/no decision questions and five were demographic questions. One of the questions was open-ended. The survey used skip patterning to ask different questions, depending on answers to previous questions. For example, the participants were asked if a resilience management system is in use and if yes which one. This was also used to ask specific questions on why they wish to deal with disruptions in the future in the same way as before or different than before.

In the survey, respondents were first asked about the importance of digital technologies in their companies. We then inquired about their opinion on the increasing digitization and the support potential of AI-based resilience systems. Next, they stated the frequency of disruptions in their company and in which business sector they mainly occur. The second part focused on the presence of an available resilience management approach and if yes which one. The participants were asked about how they dealt with disruptions in the past, their response time, and how they wish to respond to disruptions in the future. Furthermore, they should give insights on the risks and potentials of AI-based systems in resilience management. The last section consisted of demographics and questions about the business sector, location, company size, gender, and job position.

3.2. Study Execution and Analysis

The studies were conducted among trade show exhibitors and visitors from different companies. The first study was conducted in June 2019 at a leading congress of measurement and automation technology in manufacturing, the second one in April 2023 at one of the world's leading trade fairs for industry and manufacturing. Both took place in Germany. On average, respondents took 5.8 minutes to complete the survey in 2019 and 4.4 minutes in 2023. The sample of respondents was discovered through random sampling. This method gathered 60 ($N_1 = 60$) participants in 2019 and 63 ($N_2 = 63$) participants in 2023. Demographics of the participants are displayed in Table 1.

Table 1. Participant demographics.

Type of Text	Study 2019	Study 2023
N	60	63
Leading Position	56%	50%
Employee	44%	50%
Male	96%	86%
Large enterprise	82%	16%
SME	18%	83%

Table 2 shows the business areas the manufacturing companies work in. Participants who selected "Other" work in business areas like the automation industry, the steel industry, and industrial research institutions.

The six five-point Likert questions were grouped into two constructs and then analyzed for normal distribution using the Kolmogorov-Smirnov-Test (Pratt and Gibbons, 1981). The first construct includes questions regarding digitization and opinion towards AI and is named "Digitization", while the second construct "Disruptions" contains questions about disruptions in the company. The results show that none of the results are normal distributed both in 2019 and 2023. With this information, the Mann-Whitney-U test for non-normal distributed data (Pratt and Gibbons, 1981) was performed on the same questions to see if there has developed a significant change in enterprises regarding the view on digitization and AI between the years 2019 and 2023. The five multiple response questions were analyzed using Pearson's chi-squared test (Cox, 2002). In both cases, a null hypothesis was made, claiming that the responses were dependent on the year of the study and therefore equally distributed. For all results with a significance below 0.05, the null hypothesis was rejected. Results show, that the following five questions were answered approximately in the same way: Digital technologies currently play a role in my company's business model (Digitization); I rate the support potential of AI-supported systems in the event of disruptions and turbulence as high (Digitization); If you noticed disruptions in your business unit or company, were you or the management able to respond in a timely manner? (Disruptions); In the future, I would like to approach disruptions differently, because…; In the future, I would like to approach disruptions in the same way, because…

Table 2. Business areas

	Study 2019	Study 2023
IT Sector	15%	3.2%
Finances & Insurances	0%	0%
Aerospace technology	1.6%	3.2%
Automotive industry	1.6%	14.3%
Construction industry	1.6%	11.1%
Service industry	1.6%	4.7%
Chemical & Pharmaceutical	23.3%	0%
Electronics industry	28.3%	23.8%
Wholesome & Retail	0%	4.7%
Forestry & Agriculture	0%	0%
Other	26.6%	33.3%

However, there are still trends visible that will be further analyzed in section four. The test also revealed, that for the following six questions, the null hypothesis had to be rejected, meaning the answers were significantly different in 2019 and in 2023: I assess the increasing digitization of the economy as a threat for my company (Digitization); I assess the increasing digitization of the economy as an opportunity for my company (Digitization); How often do unforeseen disruptions and turbulence occur in your business (Disruptions); In which business area do they occur?; What are the biggest drivers for AI-supported resilience systems?; What are the biggest risks for AI-supported resilience systems?

4. Results

We first give an insight on the status quo of digital resilience and dealing with disruptions in manufacturing companies that took part in the survey in 2019 and 2023. The results show a reduction in the frequency of entering disruptions from 2019 to 2023. While 2019 disruptions occasionally occurred (mean = 2.92, standard deviation (SD) = 0.56), disruptions occur rather rarely to occasionally in 2023 (mean = 2.44, SD = 0.69) (Q5). Next, the potential of AI technologies to support dealing with disruptions stagnated: in 2019 (mean = 2.05, SD = 1.06) and 2023 (mean = 2.25, SD = 0.96), the potential was rated as rather high (Q6). The main results are presented following the theoretical framework for digital resilience research, described in related work. We thereby focus on the three resilience capabilities absorb, adapt, and transform.

4.1. Absorbing Disruptions

The digital technology characteristics for absorbing disruptions include redundancy, i.e., creating a diversity of options for continuity, and intelligent sensing, i.e., gathering and analyzing data to anticipate and withstand a shock (Boh et al., 2023). Concerning redundancy, we investigated the largest risks in adding AI-supported digital resilience to the current resilience approach in companies. We found that the risk of potential problems in IT rose from 30% in 2019 to 38% in 2023 (Q13). In addition, the potential of reducing the impacts of disruptions using AI decreased from 48% in 2019 to 35% in 2023 (Q12). This shows that participants see higher risks and reduced positive outcomes by diversifying their technological options for digital resilience, leading to reducing redundancy. With respect to intelligent sensing, we found that more companies systematically record disruptions in the company or on their machines entirely or at least partially: 85% in 2019 vs. 92% in 2023. This shows a trend to use smart sensors to monitor disruptions, following the guidelines of the Industry 4.0 framework, i.e., increasing intelligent sensing.

The conditions for building resilience to absorb disruptions are composed of coordination to facilitate internal operations, identify redundant or slack resources, and to support swift utilization across a company's entities, as well as data governance, which shall pose organizing structures to ensure trust with respect to the use of data between collaborating entities (Boh et al., 2023). After the major disruptions in 2020 (COVID-19) and 2022 (Ukraine war), 20% eliminated their disruptions more efficiently. In general, shocks were better absorbed: an increase of 15% in companies wishing to stick with their current approaches to deal with disruptions was recorded. The results show a trend towards deploying recent approaches to reach digital resilience. 48% of the companies that indicated to be willing to change their approach to deal with disruptions stated in 2023 that their current approach would be outdated, aiming for a more swift utilization of new technologies and resources across their companies. Data governance aspects became more critical. Data protection, e.g., unintentional GDPR violations, and data security represent the highest risks towards using AI to increase digital resilience. We see an increase in significance of 24% for data protection and of 14% for data security between 2019 and 2023 from the companies' perspective (Q13). In general, coordination and data governance within the absorb capability improved after major disruptions.

4.2. Adapting to Disruptions

Adapting to disruptions entails the digital technology characteristics of ubiquity and accessibility, i.e., responding quickly to disruptions, as well as experimentation, referring to engagement in rapid learning, development, and implementation (Boh et al., 2023). In terms of ubiquity and accessibility, our results were ambivalent. On one hand, 25% companies in 2023 stated to notice disruptions early before they could cause great damage, reflecting an increase of 10% since 2019 (Q9). On the other hand, we see a reduction of 15% in companies that noticed disruptions in good time but faced minor damages since 2019 (Q9). In addition, the companies noticing disruption a little too late but faced manageable damage increased by 10% (Q9). Despite several companies being relatively early in 2023 compared to 2019 in anticipating disruptions, we also see a shift towards being more reactive, i.e., when disruptions already occurred. Concerning experimentation, our results indicate an increase of 20% in efficient solving of disruptions, indicating learning processes (Q10). Furthermore, the willingness to change outdated approaches thereby increased compared to 2019, supporting the engagement in rapid learning and improvement.

The conditions for building resilience include organizational restructuring, i.e., enacting organizational routines to leverage available technologies, and adaptive culture and positive mindset, meaning to be open and flexible to experimenting (Boh et al., 2023). From the perspective of organizational restructuring, we found that slightly more companies have a digital resilience management approach in place. Still, the increase only equals 6% from 2019 to 2023 (Q8). In addition, the increasing digitization of the economy is seen as an opportunity in 2023 (mean = 1.63, SD = 0.73) (Q3). But the consent is reduced compared to 2019 (mean = 1.2, SD = 0.47). This goes hand in hand with observation in the context of adaptive culture and digital mindset. While companies in 2019 did not regard the increasing digitization as a threat for their company (mean = 4.6, SD = 0.69), the results in 2023 draw a different picture. Companies see digitization only as rather not being a threat (mean = 3.48, SD = 1.44) (Q2). Nevertheless, the timidity about necessary changes to develop digital resilience capabilities is reduced by 11% to one quarter of the participants compared to 2019 (Q13).

4.3. Transforming to New Stable States

In the context of transforming to new stable states, we neglected the digital technology characteristics of reconfigurability and scalability, and ecosystem strategies in conditions for building resilience, as our survey did not cover these aspects. We thereby focus on the condition of business model innovations; the aspect refers to assessing the impacts of reconfigured technologies on existing and new business opportunities (Boh et al., 2023). In this context, we see a drop of 10% to overall 84% of companies in 2023, saying that digital technologies currently play a role in their business model (Q1). Next, the biggest drivers for using AI to foster digital resilience remained smooth production flow, cost savings, and time savings in dealing with disruptions. Cost and time savings grew in importance by 7% and 4%, while smooth production flow was reduced by 13% (Q12). 2019, one further main reason for using AI for digital resilience was to reduce the impact of disruptions. This driver dropped by 13%, solely being mentioned by 35% of the participants in 2023. For comparison: cost savings were mentioned by 62% of the participants (Q12).

5. Discussion

Building on our results, we provide an overview of the change in the expression of digital resilience capabilities in manufacturing companies in comparison from 2019 (pre-crisis) and 2023 (post-crisis). We analyzed our results to the effect that how digital technology characteristics and the conditions for building resilience influenced the development of digital resilience capabilities positively or negatively. Figure 1 provides an overview as well as an overall result of how the digital resilience capabilities of manufacturing companies changed through major disruptions.

Despite the decline in redundancy, intelligent sensing, coordination, and data governance improved post-crisis. This means the absorb capability was strengthened altogether after major disruptions. With respect to the adapt capability, both ubiquity and accessibility as well as adaptive culture and a positive mindset are ambivalent. I.e., parts of these characteristics and conditions showed an improvement post-crisis, while other aspects of our results showed a deterioration. Experimentation was amended and organizational restructuring stagnated. We notice a slight improvement in the adapt capability in manufacturing companies post-crisis. The transform capability might have stagnated: due to our survey design we were only able to analyze the business model innovation aspect as a condition for building digital resilience; that one stagnated and decreased in parts. Based on our results, we suggest a stagnation of the transform capability. This corresponds with related works that mainly focus on the capabilities of absorbing and adapting currently (e.g., Malgonde et al., 2023; Park et al., 2023). The transform capability is a more advanced one that will develop over time in the sense of a long-term achievement (Boh et al., 2023). We now discuss our results on the changes in digital resilience capabilities, related digital technology characteristics, and conditions for building resilience in detail.

Absorbing Disruptions. Within redundancy, we saw that companies in 2023 see higher risks of potential problems in IT when aiming to use AI to support digital resilience. This aspect might fall back to a lack of knowledge on the technology, and the war for talents, meaning the need for data scientists and AI experts. Large parts of the manufacturing domain, especially SMEs cannot afford data scientists or find potential skilled workers at all. The introduction and implementation of AI by relying solely on AutoML techniques or 'just giving it a try', with personnel trained purely in IT might either fail, lead to tensions in IT department, workforce dissatisfaction, or faulty results (Malik et al., 2021). Next, in the context of redundancy, the potential of reducing the impacts of disruptions using AI was estimated to be lower in 2023 than in 2019. After the disruptions of COVID-19, energy crises, and Ukraine war, the representatives of manufacturing companies seem to be disillusioned in parts concerning the capabilities of AI to really protect them against

	Digital resilience capabilities and change in their expression in comparison from 2019 to 2023					
	Absorb	**Change**	**Adapt**	**Change**	**Transform**	**Change**
Digital technology characteristics	Redundancy (Q13, Q12)	↓	Ubiquity and accessibility (Q9)	↓ ↑	Reconfigurability	N/A
	Intelligent sensing (Q4)	↑	Experimentation (Q10)	↑	Scalability	N/A
Conditions for building resilience	Coordination (Q11, Q12)	↑	Organizational restructuring (Q8, Q3)	—	Business model innovations (Q1, Q12)	— ↓
	Data governance (Q13)	↑	Adaptive culture and positive mindset (Q2, Q13)	↓ ↑	Ecosystem strategies	N/A
Overall change of capability	↑		↗		—	

Figure 1. Overview on the change in the expression of digital resilience capabilities in manufacturing companies in comparison from 2019 to 2023. Representation of framework adopted from Boh et al. (2023)

major disruptions. In psychology, the disillusionment phase occurs months after a disruption and is concerned with individual and community capacities reaching a minimum (Dückers et al., 2017; Raphael, 1984). Converted to manufacturing companies, this relates to the impression of not being resilient enough to deal with major disruptions. Still, we expect the capacities and confidence to deal with disruptions to grow gradually, relying on related work from psychology (Dückers et al., 2017). Nevertheless, as manufacturing companies expect cost and time savings as well as smooth production flow from using AI to foster digital resilience, they recognize current AI trends that show what the technology could achieve in the future. This could resemble either an ambivalence towards the use of innovative technologies (Malik et al., 2021) or concerning the general ability to actually handle major disruptions. I.e., they could believe that minor or medium disruptions could be handled efficiently and effectively, but several types of disruptions cannot be handled at all as they will produce negative consequences anyway (cf. Dückers et al., 2017). Furthermore, the increased criticality of data protection and data security might have increased due to several reasons. The survey participants, despite partially operating worldwide, are mainly settled in Europe, especially Germany. Data protection and data security were pressing topics for years now in general and in manufacturing (Corallo et al., 2020; de Azambuja et al., 2023; Kerber, 2023; Koops, 2014); reaching a peak with the General Data Protection Rules (GDPR) in 2016, as well as in 2022 and 2023 with the development of the European Data Act and Data Governance Act (Comission, 2022; Kerber, 2023). In addition, cyber attacks massively increased since COVID-19. For example, companies experienced 50% more cyber attacks per week in 2021 compared to the beginning of the pandemic in 2020; trend rising (Zerlang, 2022). Therefore, to further develop digital resilience, adopting cyber security measures is critical. In spite of the regressions in redundancy, we observe a general improvement for manufacturing companies in the digital resilience capability of ”absorbing disruptions” post-crisis, fostered through major disruptions.

Adapting to Disruptions. For ubiquity and accessibility, we recognized a growing span concerning timeliness in dealing with disruptions. Partially there is a growth in companies recognizing and dealing with disruptions very early; nevertheless, more companies are also facing damages due to later noticing and reacting to disruptions. We suggest explaining this gap due to changes in the type of disruptions occurring. For example, while disruptions on the machine itself (i.e., internal disruptions) can be dealt with relatively easy, external disruptions such as supply chain disruptions or energy failures are harder to anticipate and to cope with (Gundel, 2005). In the context of organizational restructuring, we found that while companies in 2023 see digitization of the economy as an opportunity for their companies, at the same time they rather see it as a threat to their company compared to 2019. This ambivalence is anchored in frustration after the introduction of digital technologies in their companies (Malik et al., 2021), AI advances and resulting fear for the job (Malik et al., 2021), cyber attacks (Zerlang, 2022), and regulation (Picht, 2023). The ambivalence relates to prospect theory: risks and potential gains are valued differently (Kahneman and Tversky, 2013). I.e., while digitization could lead to gains in efficiency, cost, and time savings, the risks are more heavily weighted (Kahneman and Tversky, 2013). Despite ambivalences, we recognize a slight improvement in the digital resilience capability to adapt to disruptions post-crisis, fostered through major disruptions.

Transforming to New Stable States. In the study 2023, 84% of the participants indicate that digital technologies currently play a role in their company's business model, representing a reduction of 10% from 2019. Business models grounded on digital technologies indicate opportunities to create competitive advantages and increase flexibility (Niewiadomski, 2020). While digital technologies and AI have a positive impact on resilience for manufacturing companies (Ardolino et al., 2022), the majority focused on improving their processes and expanding their core competency of producing goods post-covid, e.g., through repurposing (Ivanov, 2021); instead of driving digitization. In research, there is a lack of studies with respect to technologies to support manufacturers (Ardolino et al., 2022). Furthermore, Boh et al. (2023) state that digital technologies represent no panacea in order to build resilience. With respect to the digital resilience capability of transforming to new stable states, our data do not provide evidence of the influence of major disruptions on this capability. This relates back to the study design, enabling us to only make a statement on the business model innovation condition; we only found hints that the business model innovation condition is slightly decreasing. Still, the transform capability represents the most challenging one and needs to be further researched in manufacturing and other domains.

6. Conclusion

Our work is subject to limitations which need to be taken into account. **First**, despite being quite equal, our sample sizes are rather small which might reduce the expressiveness of our results. Still, as mentioned in section 3.2, the results show trends on the impact of major disruptions (e.g., COVID-19 and Ukraine war) on the digital resilience capabilities of manufacturing companies. **Second**, the high share of large companies in 2019 (82%) and high share of SMEs in 2023 (83%) raises the question of a potential bias or that the results would not be comparable. The Kolmogorov-Smirnov-Test showed that in both 2019 and 2023 neither the data for SMEs nor for large enterprises are normal distributed. To see whether the answer of a random participant is dependent on the company size, we performed a Mann-Whitney-U test for non-normal distributed data on all Likert-response questions and the Pearson's chi-squared test for all multiple response questions. In all cases the results showed, that the participants' answers were independent of company size in 2019 and 2023. This means that both SMEs and large enterprises answered the questions approximately the same way, independent of company size. Only for one question the tests showed, that there is a dependence on company size. In both 2019 and 2023, participants from SMEs and large enterprises answered differently on the question in which business sector disruptions occur. As this aspect is not central to the digital resilience capability of companies, our results provide a justifiable basis for analyzing the impact of major disruptions on digital resilience. Nevertheless, future work could perform an additional replication of the study with a more similar sample to the one of 2019 to further support the statistical evidence. **Third**, due to high standard deviations, e.g., in the question on how often disruptions occurred, we had to analyze whether differences exist between the answers in 2019 and 2023. We therefore applied Mann-Whitney-U and Pearson's chi-squared test. The tests showed, that the participants answered significantly differently in 2019 and 2023. Also, large companies are often pioneers: they adopt digital technologies, and new concepts earlier, while SMEs are often more versatile and need to catch up on large companies (Kumar et al., 2012). Our findings show a positive development in 2023 where primarily SMEs participated in the survey. They caught up and are partially more mature with respect to digital resilience, especially in the absorbing capability.

Our work presents a first study on how major disruptions such as COVID-19 and the Ukraine war occurring in 2020 and 2022 influence the digital resilience capabilities of manufacturing companies. We performed a study on digital resilience in 2019 (pre-crisis) and replicated it in 2023 (post-crisis). We analyzed the results with respect to changes in the digital resilience capabilities through major disruptions based on the digital resilience research framework (Boh et al., 2023). Our findings show a strong strengthening of the capability "absorbing disruptions" post-crisis and a slight strengthening of the capability "adapting to disruptions", i.e., the companies are "bouncing forward". Concerning the digital resilience capability "transform to new stable states", we found a stagnation post-crisis in business model innovations in manufacturing, one of the conditions for building resilience. This highlights the need for further research in this area, especially for further methodological support for manufacturing companies to develop their transform capability to increase digital resilience.

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