Digital Technologies as Enablers of Organizational Resilience in SMEs

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Abstract

Small and medium-sized enterprises (SMEs) are particularly vulnerable to disruptions in supply chains because their limited financial, human, and organizational buffers make it difficult for them to absorb and offset shocks (Amin & Jolevski, 2023; Eggers, 2020; OECD, 2024). At the same time, digital technologies are increasingly being discussed as levers for strengthening organizational and supply chain resilience; however, the mechanisms of action often remain unclear and SME-specific conditions are under-examined (OECD, 2021). This paper therefore develops a mechanism-based conceptual model that explains how key technology classes, such as monitoring/IoT, data integration/platforms, analytics/AI, and digital collaboration, operate through three resilience mechanisms: (1) visibility and sensemaking, (2) decision quality and response speed, and (3) organizational learning and adaptation (Awad & Martín-Rojas, 2024; Duchek, 2020). Building on conceptualizations of resilience and current evidence regarding the role of information processing, transparency, and innovation capacity, measurable dimensions and indicator logics are proposed that account for SME realities such as data heterogeneity, skills shortages, and overcomplexity (Chen et al., 2021; OECD, 2021). The discussion derives testable proposals and demonstrates how digital twin and simulation approaches, as well as AI-supported decision aids, can enhance resilience in SME contexts not only through better decisions but also through structured learning loops (Pan et al., 2025; Roman et al., 2025; Weigert & Behrendt, 2022).

1. Introduction

1.1. Background and Problem Definition

Supply chains are characterized by tighter interconnections, faster rhythms, and greater interdependencies, which means that disruptions spread more quickly and local bottlenecks can have systemic consequences. This dynamic is particularly critical for SMEs, as they often have fewer redundancies, smaller liquidity buffers, and more limited options for offsetting shocks through alternative supply sources, reserve capacities, or financing. This structural vulnerability is described in SME research as the “liability of smallness,” which is exacerbated in times of crisis by additional resource and coordination challenges (Eggers, 2020). Empirically, this asymmetry is evident, for example, in the fact that SMEs experienced, on average, steeper declines in revenue than large firms during the COVID-19 pandemic (Amin & Jolevski, 2023). Furthermore, the OECD emphasizes that since 2020, a series of external shocks has placed a particular strain on SMEs and that SMEs are often less able to pass on rising input costs, which closely links resilience to survival (OECD, 2024).

A key reason why disruptions in supply chains have such severe effects is the so-called ripple effect. The ripple effect describes the propagation of a disruption through the network. Capacity shortfalls, delivery delays, or quality issues at a single node lead to knock-on effects along material flows, inventories, production schedules, and service levels, often across multiple stages and with a time lag. The literature emphasizes that the ripple effect should not be equated with the bullwhip effect. While the bullwhip effect typically amplifies demand fluctuations through information and ordering processes, the ripple effect describes the structural and operational propagation of real disruption events and their consequences for performance and recovery (Dolgui et al., 2018). The literature on disruption management highlights that ripple effects are a central stressor for supply chain resilience and that the management of propagation and recovery, such as through redundancy, flexibility, and resilience-oriented

planning, has become a distinct field of research and practice (Dolgui et al., 2021). This perspective is particularly relevant for SMEs because the propagation of disruptions often leads more quickly to uncompensable service interruptions when alternative options are lacking and responsiveness is limited by scarce resources.

In addition to structural propagation, a second, often underestimated set of effects plays a central role: the behavioral effect in disruption situations. Supply chain reactions are not exclusively the result of rational optimization but are significantly shaped in crises by human decision-making under uncertainty. This includes limited information processing, errors in risk perception and assessment, delays in escalation and coordination processes, as well as tendencies toward overreaction or hesitant action. Recent studies from a behavioral perspective argue that disruption management must go beyond purely rational decision-making models because behavior and cognitive biases can significantly influence the effectiveness of measures (Smith & Fatorachian, 2025). Behavioral effects occur not only at the operational decision-making level but also on the market and demand side, for example through panic buying and hoarding, which distort demand in the short term and thereby generate additional instability; relevant syntheses discuss this as a key dynamic in disruption contexts (Zheng et al., 2025). For the resilience of SMEs, this means that disruptions are not merely "technical" or "logistical," but result from a coupling of network propagation (ripple effect) and human or market-side behavioral dynamics. Against this backdrop, the question of how SMEs can systematically strengthen resilience in supply chains gains significance. Digital technologies are frequently cited as key levers in this regard. In practice, however, it often remains unclear why identical technologies improve resilience outcomes in some cases, while in others they have little effect or even create new vulnerabilities. It is precisely this ambivalence that necessitates a precise logic of impact, one that views technologies not as an end in themselves, but as enablers of concrete organizational mechanisms.

1.2. State of Research

Organizational resilience is increasingly described as a meta-capability that cannot be reduced to short-term "recovery" performance, but rather encompasses anticipation, coping, and adaptation or learning (Duchek, 2020). This process-oriented view is particularly well-suited to supply chain contexts because disruptions often do not occur in isolation but require recurring adjustments and learning. At the same time, there is a line of research that aims to make resilience measurable by empirically deriving dimensions and translating them into scales. Chen et al. (2021) demonstrate how organizational resilience can be structured from case studies and operationalized as a multidimensional measurement object, thereby bridging the gap between theoretical definition and practical manageability (Chen et al., 2021). In the supply chain context, resilience is additionally discussed as a network phenomenon. Ivanov and Dolgui (2020) argue that, in the face of extraordinary disruptions, resilience should be expanded to include a "viability" perspective that emphasizes the long-term functionality and survivability of interconnected networks (Ivanov & Dolgui, 2020). Within this framework, it becomes clear that resilience is not merely "speed of recovery," but also the ability to further develop structures, decision-making routines, and coordination patterns in such a way that the supply chain remains functional under changed conditions.

1.3. Research gaps and questions

While the role of digital technologies is acknowledged in the resilience discourse, the pathways through which they exert their effects in SME contexts are often formulated too broadly. Two shortcomings are particularly relevant. First, many studies fail to clarify the mechanisms through which technologies actually influence resilience and how these mechanisms can be empirically tested. Second, SME-specific constraints, such as skills shortages, data heterogeneity, integration costs, and cyber and governance resources, are not sufficiently accounted for as moderators in impact models (OECD, 2021). This creates a gap between technology-centered promises and design and measurement logics suitable for SMEs. Two research questions are derived from this gap. First, the question is how key classes of digital technologies contribute to the resilience of SME supply chains through specific mechanisms, so that impact pathways become explainable and testable. Second, we ask how these mechanisms can be translated into measurable dimensions of resilience and indicator frameworks that account for SME realities without losing scientific validity (Chen et al., 2021; Duchek, 2020).

2. Methodology

This paper follows a conceptual-analytical approach that can be described as a mechanism-based synthesis. The starting point is the clarification of key constructs: resilience as a process and a meta-capability (Duchek, 2020), resilience as a multidimensionally measurable construct (Chen et al., 2021), and SME-specific implementation conditions (OECD, 2021). Building on this, digital technologies are grouped into classes to map different levels of maturity and make impact pathways comparable. Subsequently, a mechanism logic is developed that explains how these technology classes can contribute to resilience outcomes. The mechanism logic is linked to empirically supported pathways, particularly to

findings that digital transformation influences resilience through organizational learning and innovation (Awad & Martín-Rojas, 2024). Finally, the mechanism logic is translated into measurable dimensions and indicator logics to make conceptual statements empirically testable.

To organize the breadth of digital technologies, the paper uses four technology classes that recur in the literature on supply chain digitization and resilience and can simultaneously be implemented with varying degrees of "lightweight" effort in SME contexts. Monitoring/IoT aims to capture states and events along critical process and partner points. Data integration/platforms address data quality, consistency, and accessibility as prerequisites for actionable information. Analytics/AI encompasses both classical analytics and AI-supported forecasting and risk sensing, which can support information processing and prioritization. Digital collaboration and workflows address the standardization of coordination and action processes across organizational boundaries. This classification is intentionally product-agnostic to increase scientific generalizability and avoid being tied to proprietary implementations. Systematic reviews and conceptual overviews of Industry 4.0-based supply chain digitization identify, in particular, IoT/connectivity, cloud and platform infrastructure, as well as big data analytics and AI as key enablers that are regularly considered together (Atieh et al., 2025; Chauhan et al., 2023; Zhang, 2024). The collaboration and workflow domain is further supported by research on digital platforms in supply chain and logistics, which explicitly describe platforms as coordination and orchestration infrastructure for interorganizational processes (Kam, 2026). To precisely discuss the impact of digital technologies on resilience in SMEs, four technology classes are distinguished, which are repeatedly described in the digital supply chain literature as key enablers. Monitoring/IoT encompasses technologies for capturing and transmitting status and event data across production, warehousing, and transportation, such as sensors, RFID/barcodes, telematics and tracking systems, as well as cyber-physical systems; these technologies are frequently discussed as the foundation for visibility because they provide early signals of deviations (Chauhan et al., 2023; Haman et al., 2025). Data integration/platforms bundle technologies that consolidate heterogeneous data sources and make them actionable, particularly cloud-based ERP/SCM applications, APIs and middleware, ETL/ELT pipelines, as well as data quality and master data mechanisms; platform approaches are also described as coordination and orchestration infrastructure across organizational boundaries (Kam, 2026; OECD, 2021). Analytics/AI encompasses descriptive, diagnostic, predictive, and prescriptive methods, including forecasting, anomaly detection, risk scoring, and scenario comparisons, which can enhance decision quality and response speed when embedded in routines (Pan et al., 2025; Roman et al., 2025). Finally, digital collaboration/workflows encompass technologies for structuring coordination, escalation, and action tracking, such as collaborative planning, workflow management, digital ticketing systems, and supplier portals; their impact on resilience stems primarily from the coordinated implementation of decisions and the closing of learning loops (Kam, 2026).

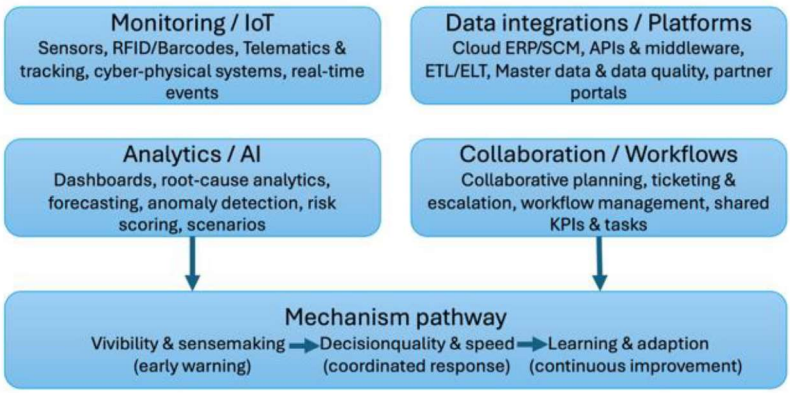

Figure 1: Technology classes and typical components for SME resilience

3. Results and Discussion

3.1. Mechanism Model

The first result is a mechanism model that treats digital technologies not as direct drivers of resilience, but as enablers of three mechanisms. The first mechanism is visibility and sensemaking. It describes how the supply chain becomes observable through event and status data, allowing deviations to be detected earlier and interpreted. Monitoring/IoT and data integration are central prerequisites for this because they not only generate data but also make data available in a form suitable for decision-making. This mechanism is particularly relevant in the supply chain context because early detection of disruptions can limit escalation and thus enable more cost-effective adjustments.

The second mechanism is decision quality and response speed. It describes how better information processing, scenario assessment, and prioritization can lead to faster and more consistent actions. Here, analytics and AI come to the fore. Mechanistically, this path aligns with research that views AI as a means to improve information processing, collaboration, and proactive risk management. Pan et al. (2025), for example, examine mechanisms through which AI can promote supply chain resilience and attribute this effect to improved information and coordination processes (Pan et al., 2025). For SMEs, it is crucial that decision-making aids are effective only when embedded in clear decision-making routines, because otherwise data may exist, but no action is taken.

The third mechanism is organizational learning and adaptation. It describes how disruptions must give rise not only to short-term reactions but also to lasting improvements and reconfigurations if resilience is to increase over the long term. Digital systems contribute to this by making events, measures, and outcomes documentable, thereby supporting learning loops. This pathway is particularly well supported by empirical evidence, as digital transformation can influence resilience especially through organizational learning and innovation (Awad & Martín-Rojas, 2024). In SME contexts, this mechanism is also challenging because learning routines are often informal and documentation can be perceived as an additional burden. Consequently, the design of "simpler" learning loops and clear responsibilities is significant. Figure 2 visualizes the mechanism model by linking the four technology classes with three resilience mechanisms as well as with outcome-based resilience metrics. The central matrix illustrates the strength of the respective technology-mechanism relationships (low, medium, high), thereby highlighting that technologies typically do not influence resilience through a single pathway, but rather through multiple, differently pronounced contributions. Monitoring/IoT and data integration/platforms have a particular impact on visibility and sensemaking, as they generate or consolidate event and status information. Accordingly, their dominant impact pathways primarily lead to improvements in time-to-detect. Analytics/AI makes the strongest contribution to decision quality & speed, as predictive and diagnostic analyses, anomaly detection, risk scoring, and scenario comparisons support the prioritization and coordination of responses, resulting in a dominant pathway to time-to-respond. Digital collaboration/workflows show the strongest connection to learning & adaptation, thereby emphasizing that coordinated implementation, escalation discipline, and closing feedback loops are central to sustainable improvement and resilience; consequently, the dominant pathway points to time-to-recover and service stability. At the same time, it becomes clear that Learning & Adaptation not only influences recovery outcomes but can also reinforce upstream mechanisms, because organizational learning stabilizes routines and improves future sensing and responding. The moderator band in the figure also explicitly shows that the effect sizes depend on SME-specific contextual conditions, particularly digital maturity and competencies, data quality and governance, partner dependencies, as well as risk exposure and flexibility options. Finally, the measurement note indicates that an empirical assessment should combine both outcome KPIs and capability indicators (e.g., decision-making routines, learning loops, and collaboration discipline) to consistently capture short-term performance under disruption and long-term adaptability.

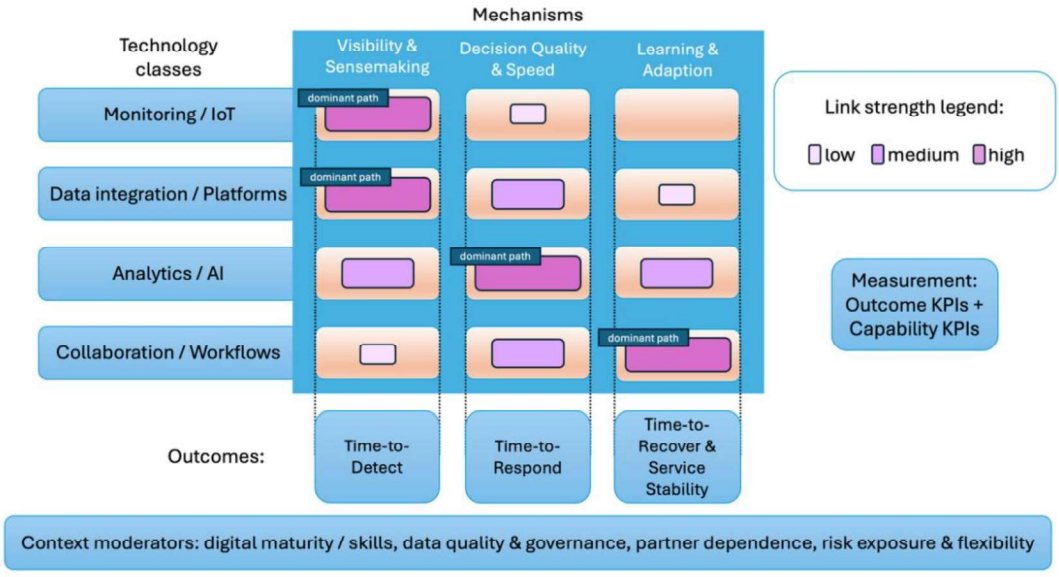

Figure 2: Technology - Mechanism Mapping

3.2. Measurement Dimensions and Indicator Logic

The second result is an operationalization that integrates outcome and capability dimensions. Outcome dimensions capture observable supply chain behavior during disruptions, such as time to detection, time to effective response, time to restore defined performance levels, and stability of service levels. Capability dimensions capture capabilities that sustainably enable these outcomes, such as the stability of data-driven decision-making routines, the quality of interorganizational coordination, and the institutionalization of learning loops. This dual logic is central for two reasons. First, resilience cannot be validly represented as a single metric because it is multidimensional (Chen et al., 2021). Second, particularly in SME contexts, there is a high risk that short-term successes result from improvised "firefighting" reactions without an increase in the ability to replicate and scale these efforts. Capability indicators make this distinction visible. Another factor relevant to context dependency is that risk exposure and flexibility options moderate resilience outcomes. Piprani et al. (2022) demonstrate that multidimensional supply chain flexibility supports resilience and that risk exposure plays a significant role (Piprani et al., 2022). It follows that measurement models require context indicators to avoid overestimating or misinterpreting effects. Table 1 shows how the technology classes primarily contribute to the mechanisms and which measurement dimensions can be derived from them in SME contexts

Table 1: Technology categories and mechanisms contributing to resilience in SME supply chains

Technology Class	Primary mechanism pathway	Typical effect of resilience	Measurement dimension
Monitoring/IoT	Visibility & Sensemaking	Earlier detection, less escalation	Time to detection, data latency
Data Integration/Platforms	Visibility → Decision	Consistent situational awareness, less decision-making bias	Data completeness, error rate
Analytics/AI	Decision Quality & Speed	Faster and prioritized responses, proactive risk detection	Time to action, achievement of goals
Collaboration/Workflows	Decision → Learning	Better coordination, more consistent implementation, greater transfer of learning	Escalation time, completion of action
…	…	…	…

3.3. Impact of the technologies

For SMEs, it is particularly helpful not to list the technology categories, but to explain their specific contributions through mechanisms. Monitoring/IoT primarily contributes to visibility by making events and conditions at critical nodes measurable. In SME supply chains, the most effective contribution is often not "comprehensive tracking," but rather the targeted instrumentation of critical bottlenecks and interfaces, because otherwise the benefits get lost in a flood of data and the risks of overcomplexity increase. Data integration/platforms help ensure that visibility translates into actionable insights. Without consistent data objects, clear definitions, and up-to-date information, visibility remains fragmented, and decisions continue to be based on assumptions or incomplete information.
Analytics and AI primarily influence decision-making quality and speed by identifying patterns, providing forecasts, or comparing alternative measures. In this context, Pan et al. (2025) emphasize mechanisms that rely on information processing and coordination, rather than interpreting AI as automatic "resilience generation" (Pan et al., 2025). Furthermore, studies show that digital supply chain digitization and resilience mechanisms often operate through visibility, collaboration, and information quality, which supports the focus on these mechanisms (Hu et al., 2026). Digital collaboration acts as a bridge between decision-making and implementation. If responses are not coordinated, responsibilities are not clarified, and actions are not tracked, even good analyses remain ineffective. A complementary, increasingly discussed technology path is the use of digital twins for monitoring and decision support in supply chains. Roman et al. (2025) demonstrate that digital twin applications can particularly improve visibility, agility, and decision-making capability, which directly ties into the mechanisms of visibility and decision-making (Roman et al., 2025). However, the digital twin path is ambivalent for SMEs. It can enhance transparency and scenario evaluation, but it is data- and integration-intensive. Precisely for this reason, a version suitable for SMEs, a "lightweight twin", that works with a few, highly relevant data objects is plausible.

3.4. SME-specific moderators

The mechanisms discussed cannot be automatically activated in SMEs. The OECD (2021) emphasizes that SMEs often lag behind in terms of advanced digitalization and digital capabilities, and that barriers exist in financing, skills, implementation, and cybersecurity capacity (OECD, 2021). These

factors moderate the impact: visibility fails due to poor data quality or the absence of a data governance model, decision support fails without established decision-making processes, and learning fails without institutionalized reflection and action management. A key risk is technological overcomplexity. "Overcomplexity" describes the state in which tool diversity, integration efforts, and data management and security requirements grow faster than the organization's capacity to absorb them. In SMEs, this can lead to increased fragility because more systems create more points of failure and dependence on external service providers rises. In practice, this means that technologies must be designed to activate mechanisms without overburdening the organization; "more digital" does not automatically mean "more resilient." The logical consequence is to design resilience technologies as "minimum viable systems" that generate high impact at critical points and are then expanded iteratively.

3.5. Simulation and AI-powered decision-making tools

One aspect that is often underestimated is that resilience does not stem solely from the use of technology, but from the ability to act consistently and from learning. Here, simulations, business games, and AI-supported learning and decision-making tools can make a twofold contribution. On the one hand, they can make mechanisms visible by clarifying the dependencies and consequences of decisions, and on the other hand, they can structure learning loops by enabling reflection, feedback, and repeated training. Weigert and Behrendt (2022) describe how simulation technologies and AI can be integrated into a learning experience platform, for example through AI-based bots and supporting widgets that guide learning paths and provide didactic support in decision-making situations (Weigert & Behrendt, 2022). Although this paper does not primarily measure resilience, it is relevant to resilience logic because it demonstrates how AI and simulation can be designed as a socio-technical infrastructure for learning and competency development, precisely the mechanism that emerges as a central pathway of impact in the digital resilience evidence (Awad & Martín-Rojas, 2024).

4. Limitations and Conclusion

4.1. Limitations

The limitation of this paper lies in its conceptual nature. It develops a framework for mechanisms and measurement, but does not present new primary data on the impact of individual technologies. Furthermore, the effects of digitalization and resilience are highly context-dependent. Industry dynamics, supply chain structures, and power asymmetries can modify the pathways of impact. Another limitation lies in operationalization. Indicator frameworks suitable for SMEs must deal with heterogeneous data sets, which can limit the precision and robustness of individual metrics. Finally, the boundary between helpful data integration and overcomplexity is not universal but context dependent. Thresholds must be determined empirically.

4.2. Conclusion

The paper demonstrates how digital technologies contribute to the resilience of SME supply chains when viewed as enablers of defined mechanisms. Monitoring/IoT and data integration primarily enhance visibility and sense-making. Analytics/AI improve decision quality and response speed, and digital collaboration ensures that decisions are translated into coordinated implementation. Overall, it becomes clear that the most important long-term path lies through learning and adaptation, which is consistent with empirical evidence that digital transformation can influence resilience particularly through learning and innovation (Awad & Martín-Rojas, 2024, 2024). The proposed operationalization integrates outcome and capability indicators to make resilience manageable and empirically testable (Chen et al., 2021; Duchek, 2020). For SMEs, it is crucial to avoid overcomplexity and to design technologies as iteratively expandable, lightweight resilience systems (OECD, 2021). Table 2 structures the measurement logic into outcome, capability, and context dimensions and illustrates how the indicators are interpreted.

Table 2: Outcome and Capability Dimensions of Resilience

Dimension type	Dimension	Interpretive logic	Literary Anchor
Outcome	Response and recovery capabilities	Shows immediate behavior when disturbed	Chen et al. (2021); Ivanov and Dolgui (2020)
Capability	Decision-making and learning skills	Demonstrates long-term adaptability	Duchek (2020); Awad & Martín-Rojas (2024)
Context	Risk Exposure and Flexibility	Explains variance and moderation of effects	Piprani et al. (2022); OECD (2021)

4.3. Outlook

Follow-up studies should empirically test the derived recommendations, for example through case studies in SME supply chains or survey studies that jointly model mechanisms and contextual moderators. In addition, the effectiveness of digital twin approaches in SME contexts should be systematically investigated, particularly in "lightweight" versions that generate significant impact with limited data resources (Roman et al., 2025).

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