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Analysing the antecedents to digital platform implementation for resilient and sustainable manufacturing supply chains - An IDEF0 modelling approach

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ABSTRACT

Digital platforms offer opportunities to enhance the resilience of manufacturing supply chains facing complexity, data sharing challenges, external stressors (e.g., resource scarcity, geo-political factors), emerging risks and environmental sustainability. Despite the growing importance of digital platforms for industrial value creation, limited research has focused on their practical application in this context. Furthermore, a comprehensive understanding of the holistic factors crucial for successful implementation is lacking. Through a qualitative empirical research approach involving three case companies in a manufacturing value chain, this study examines the challenges, requirements, and opportunities associated with leveraging digital platforms for resilient supply chains. Additionally, the paper demonstrates the use of a structured modelling technique, IDEF0, to identify interconnected antecedents that support the use of digital platforms in building resilience within manufacturing supply chains. The findings contribute to advancing knowledge in resilience modelling and dynamic capabilities for resilience, along with providing valuable insights for practitioners seeking to harness the potential of digital platforms for improved supply chain resilience.

1. Introduction

Resilience is becoming increasingly relevant in today's manufacturing context where companies and their Supply Chains (SCs) face an array of challenges, e.g., increasing internal complexity, resource scarcity, regulatory pressures, geo-political stressors etc. Supply chains also face vulnerability challenges due to geographically dispersed suppliers; rapidly changing and differentiated requirements from customers and supply fluctuations (Chen et al., 2020). Consequences of disruptions due to these risks can have further implications on the SC which are known as 'ripple effects' (Kinra et al., 2020).

Digital platforms can enable industrial value creation, collaboration and data sharing within the Industry 4.0 (I4.0) paradigm (Kagermann, 2013; Marie-Christin et al., 2019) while addressing associated challenges described above, for both individual companies and entire SCs (Veile et al., 2022). Digital platforms are one of the four pillars of the European Commission's Digitizing European Industry (DEI) initiative (European Commission, 2019) to increase European digital technology competitiveness.

Data sharing and transparency in the SC has long since been emphasized for building top-performing resilient supply chains, i.e., making them agile, adaptable and recover quickly from disruptive events (Lenz et al., 2022), increasing transparency across SC stages (Gawer, 2009), improving stakeholder relationships through knowledge of customer demand (Chari et al., 2021) and enabling decarbonization efforts (World Economic Forum, 2022). In fact, decarbonizing manufacturing operations, enhancing supply chain resilience and adoption of novel technologies are stated as some of the industrial strategies in urgent need today (World Economic Forum, 2023a). Moreover, collaboration, transparency and trust between supply chain partners can contribute to their individual sustainable development goals (SDGS) (Khan et al., 2021a).

Despite these advantages, many individual manufacturing companies accumulate an abundance of data over time, without having a

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clear view of how to make it available and accessible for the purpose of value co-creation across the SC. In addition, there is a lack of data and information that is shared along supply networks both upstream and downstream. Challenges also exist in terms of how end-users use existing data, as well as what the requirements are for capturing value from data from other parts in the value chain (VC). The resilience of organizations can be improved if data is available across an entire VC, encompassing suppliers' suppliers and customers' customers (World Economic Forum, 2021).

To enable successful platform implementation for resilience, digital maturity and infrastructure (Marie-Christin et al., 2019) are required along with increased competence, knowledge (Veile et al., 2022) and capabilities to deal with unexpected events and risks. Capabilities are sources of a firm's competitive advantage (Teece et al., 1997) which can be developed as dynamic capabilities for the resilience of firms and their SCs (Chari et al., 2022; Raj et al., 2022; Teece et al., 2016). These capabilities are different from strategies (Teece, 2017) for resilience, as they can help deploy mitigation strategies to deal with unexpected events in dynamically changing environments.

There are other interrelated and interdependent factors that strengthen or weaken connections between the VC partners for successful platform implementation which need to be identified and visualised so that it can aid partners in value co-creation for resilience. To fulfil this outcome, we selected a resilience model (Chari, 2021) built on the industrially accepted Structured Analysis and Design Technique (SADT) modelling method (Ross, 1977) later presented as IDEF0 (Morgan and Stilwell, 1983) to investigate and visualise the different holistic factors at each stakeholder of the VC, as well as their impact on the overall VC resilience. These antecedents for digital platform implementation are thus derived using the IDEF0 modelling method, to give rise to the outcome which are resilient and sustainable VCs. Their relationships are conceptualised in Fig. 1.

The study thus addresses two main research questions:

RQ1. What are the challenges and opportunities for implementing digital platforms for building resilience from a manufacturing value chain perspective?

RQ2. How can the resilience of manufacturing value chains be modelled so that corresponding factors can be visualised and applied on multi-sided digital platforms?

The purpose of the paper is to showcase the use of the IDEF0 method for digital platform implementation where holistic resilience factors can be easily visualised by all VC partners, and with the aim to bridge a knowledge gap in both academic literature and industrial practice. The motivation of using such a robust and well-established modelling method was twofold: (i) the model's simplicity and ease of use in industrial use cases, and (ii) to unravel and graphically represent the interrelated factors that could impact the entire value chain's resilience and to input these parameters into a digital platform software infrastructure in the next phase of the present study. Subsequent instantiation of resilience factors on digital platforms has the potential to further

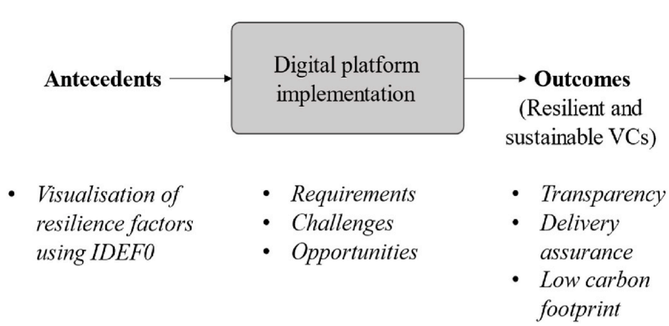

Fig. 1. Conceptual model of the study.

improve real-time availability of data for all partners in the VC and could enable the creation of more efficient strategies for building value-chain resilience on a completely new level.

The paper is organised as follows: the introduction is followed by a literature review in Section 2 where the theoretical background and different research gaps addressed in the study are described. Section 3 outlines the research method employed in the study, followed by the results in Section 4. This section presents the requirements, challenges and opportunities for implementing digital platforms for resilient and sustainable value chains along with the identification of the holistic factors (using IDEF0 functional modelling) required for digital platform implementation. Finally, discussions and conclusions are given in Sections 5 and 6.

2. Literature

2.1. *Digital platforms: typologies and abilities for building resilience*

Industrial digital platforms can transform Business Models and enhance inter-company relationships in the VC (Veile et al., 2022). Platforms connect VC partners, simplify communication and collaboration between them, and allow larger value network effects to be seen (Parker et al., 2016). There are several examples of information technology companies that have harnessed the value of data using digital platforms in I4.0– Siemens, through their cloud-based IoT system 'MindSphere' (Siemens, 2022) help enhance manufacturing companies' decision-making abilities in real time; SAP, through their 'Cloud Platform' (SAP, 2022), help their customers improve integration in their value chains and enhance their flexibility and agility; and GE through their IIoT cloud platform 'Predix' (GE, 2022) provide data solutions to improve efficiency of manufacturing operations.

Within the context of Industry 4.0 and building on existing manufacturing paradigms, Guo et al. (2021) proposed 'Synchroperation', "the ability of a manufacturing system to achieve synchronized operations" (pg.4). The new paradigm was built in the context of Industry 4.0 to upgrade production and operations to become resilient, agile and cost-efficient. To this end, the authors developed a data-driven 'Hyperconnected Physical Internet-enabled Smart Manufacturing Platform' (HPISMP), consisting of digital twins and blockchain technologies to showcase the potential of manufacturing synchroperation and real-time information sharing. Several other approaches derived from the I4.0 revolution such as the honeynet approach explored by Tan et al. (2022) helped address network security issues which resulted in a more resilient 'Artificial Intelligence of Things (AIoT)' platform. The use of honeypots to detect cyber threats and the importance of sharing real-time data to improve resilience of a SCADA/ICS system was also showcased in the work by Simoes et al. (2013).

Several categories and typologies of digital platforms have been defined in literature based on number of actors (Asadullah et al., 2018; Derave et al., 2021; Hagiu and Wright, 2015) boundaries (Gawer, 2021), etc, however two main types are distinguished for the purpose of this study: two-sided and multi-sided platforms or MSPs (Hagiu and Wright, 2015; Otto and Jarke, 2019; Trabucchi and Buganza, 2019). Two-sided platforms allow interactions between two groups of users from specific domains whereas MSPs are characterised by interactions that take place between actors along two or more sides of the platform and every side is somehow affiliated to the platform (Evans, 2003; Hagiu and Wright, 2015; Helfat and Raubitschek, 2018, p. 1392) describe digital MSPs as "*providing interfaces with and among two or more groups of economic actors on different 'sides' of the platform, including providers of complementary assets*", a description we use in the present study. Literature also describes digital platforms in terms of product architectures and components in the field of engineering design (Teece, 2016). However, this will not be the focus of the present work.

MSPs are widely considered as socio-technical constructs containing both technical platforms (modules and components that communicate with each other) and an ecosystem architecture (the various user groups or sides that engage on the platform) (Tiwana et al., 2010). The process of value co-creation – where firms and their customers collaborate and co-create to produce new value, both in terms of materials and services – can hence be realised in MSPs (de Oliveira and Cortimiglia, 2017). Previous studies have focused on the use of digital MSPs in different domains such as retail, food, entertainment, travel etc (Diane et al., 2020; Hänninen et al., 2017; Trabucchi and Buganza, 2019), but the focus on manufacturing supply chains have been too few and far between.

Thus, the primary motivation of conducting this study was to explore the potential of digital MSPs in facilitating value co-creation and enhancing resilience in manufacturing VCs. To effectively address this need in the digital era, it is crucial to identify and transparently communicate the corresponding resilience factors. This requires the utilization of robust modelling methods to ensure accurate representation and future analysis of resilience. We will discuss this in the following sections.

2.2. Modelling resilience of supply chains

Generating a comprehensive understanding of process flows and dependencies is crucial in correctly modelling an organization's business processes (Aguilar-Savén, 2004). This emphasizes the increased significance of selecting the appropriate technique, particularly when it comes to visualizing and comprehending processes within an end-to-end supply chain. Several authors (Aguilar-Savén, 2004; Durugbo et al., 2010; Recker et al., 2009) have put forth classifications of business process modelling techniques by assessing their effectiveness and efficiency. These classifications can assist in selecting the most appropriate technique for a given purpose and are described in Fig. 2.

Some of the techniques described in the above studies were simple flowcharts, data flow diagrams, Gantt charts, IDEF, role activity diagrams, role interaction diagrams, coloured Petri nets, object orientation language (e.g., UML), workflows, rich pictures, business process model and notation, etc. Given the impossibility of conducting a comprehensive evaluation of all available methods for modelling every potential variable in a full-scale industrial value chain spanning from 1977 to the present, this study employs the IDEF0 business process modelling technique (IEEE, 1998; Morgan and Stilwell, 1983) to leverage its functionalities for utilizing digital platforms for resilience.

The IDEF0 standard showcases an interesting way to model large and complex systems with complex interaction and integration patterns and was described in the 1970's as a part of US defence research and the Air Force's Integrated Computer Aided Manufacturing (ICAM) program. The Structured Analysis and Design Technique (SADT) modelling method (Ross, 1977) has historically been applied across numerous technical, social, and biological fields due to its ability to handle internal as well as external multi-level complexity. It was subsequently renamed IDEF0 (Morgan and Stilwell, 1983), a method that has been widely accepted and used for business process modelling in various applications (Collier et al., 2022; Tserng et al., 2021), and specifically for risk management and resilience (Tah and Carr, 2001; Tanuputri and Bai, 2023; Tserng et al., 2021).

A review of existing literature for previously developed models/methods for resilience (Table 1) showed that although several of these models were developed and utilised for building resilient value chains, few exist in the manufacturing domain and even fewer showcase the potential of digital technologies for resilience. It is to be noted that the reviewed list is not exhaustive but gives an overview of the different models available and why the IDEF0 approach was chosen.

The purpose of choosing the IDEF0 modelling approach for building resilience in manufacturing value chains is that it allowed: (i) rapid process mapping, (ii) the depiction of end-to-end supply chain processes through graphical representation, (iii) ease of comprehension for all stakeholders while maintaining control over the level of detail, and (iv) visualise risk-related hot-spots to avoid a domino effect in the SC. While other mathematical models and quantitative methods (Alexopoulos et al., 2022; Hu, 2013; Jin and Gu, 2016; Morari, 1983) also study the resilience of manufacturing firms, the models depicted in these studies were used to 'analyse' and later 'simulate' system response to disruptions. However, these were not the objectives of the present study and the IDEF0 was deemed to be the most suited to 'capture' and 'understand' (highlighted boxes in Fig. 2) the risks, disruptions and capabilities that could impact the resilience of the value chain.

Five elements constitute basic functions in a generic IDEF0 model (Fig. 3): The central functionality is the "activity". The activity is fed by an "input", resulting in an "output". The "activity" is enabled by "mechanisms" and steered by "control" functions. The IDEF0 functional modelling method allows the creation of a structured blueprint allowing dependencies and interfaces to be captured thus providing visibility to an organization and their value chain partners. The IDEF0 diagram allows for recursion, where the parent diagram serves as the top-level context diagram. It can be decomposed or zoomed in/out to create child diagrams, enabling the examination of varying levels of granularity as required.

The components of the IDEF0 model are aligned with Tamberg et al. (2020)'s checklist where they describe two important aspects that should be addressed while modelling systems for resilience. First, the definition of resilience must be precisely communicated. Second, a compatible model must be chosen that can precisely answer the research question(s) of the study. To this effect, the authors propose a checklist with four structural components or aspects of resilience that need to be incorporated in a resilience model: system (resilience of what), sustainant (resilience regarding what), adverse influence (resilience against what) and response options (how to achieve resilience). In their work on the resilience ontology for food systems, van Wassenaer et al. (2021) described resilience features and relationships that need to be

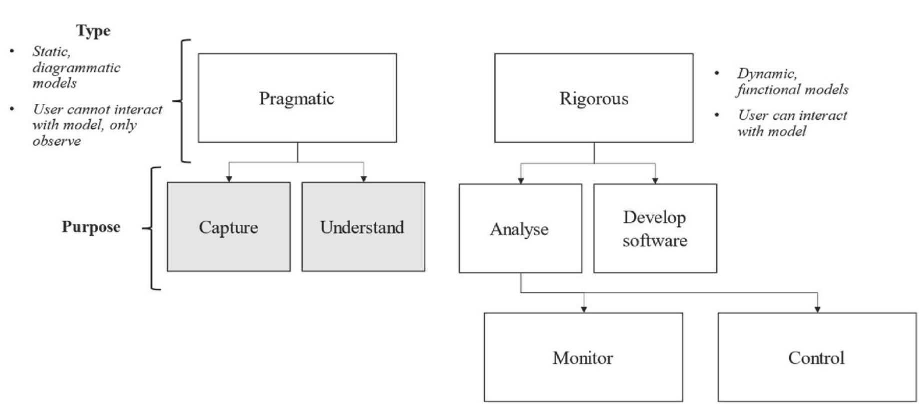

Fig. 2. Classification of business process models based on purpose (based on (Aguilar-Savén, 2004)).

Table 1
Previous work on different models/methods for resilience.

Reference	Model/method used	Domain	Objective of using model	Primary outcomes achieved
Tanuputri and Bai (2023)	IDEF0	Tea supply chain	Business process analysis (interrelated stakeholder evaluation for risk analysis and vulnerability assessment)	Resilient supply chains
Collier et al. (2022)	IDEF0	Semiconductor production	Business process modelling	Risk identification and management
Liu et al. (2022)	Model based on semi-Markov process	Multi-state networks (road network)	Probability distribution transition of components in multi-state networks	Process model for reliability and resilience evaluation
Tserng et al. (2021)	IDEF0	Construction	Logical analysis for data flow on risk items	Risk management for infrastructure projects
Melanson and Nadeau (2019)	Comparison of FMECA & FRAM	Manufacturing	Occupational health and safety (OHS)	Risk analysis
Nyambayar and Koshijima (2017)	IDEF0 based on IEC 62443 standard and OSHMS	Chemical manufacturing	Safety and security framework	Resilience against cyber security attacks
Moreno et al. (2017)	IDEF0	Consumer goods industry	Visualise barriers for technology readiness and circular economy business model development	Implementation of redistributed manufacturing to handle environmental risks
Vimal et al. (2015)	Best Worst Method (BWM) and fuzzy technique	Medical oxygen supply chain	Modelling strategies for improving maturity and resilience through digital technologies	Efficient and resilient supply chains, help prioritise mitigation solutions
Tah and Carr (2001)	IDEF0	Construction supply chain	In-depth understanding of elements for project risk assessments	Risk management process model
This work	IDEF0	Manufacturing supply chain in the steel industry	Visualization of antecedents for digital platform implementation	Resilient supply chains where risks, disruptions and dynamic capabilities were identified and visualised for the value chain

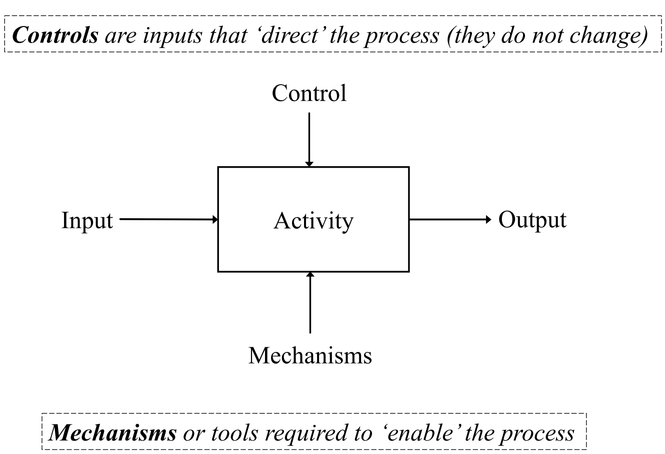

Fig. 3. Top-level context diagram of an IDEF0 functional model.

considered when conceptualising and measuring resilience. For instance, aspects such as 'resilience of what', 'measuring resilience', 'managing resilience', 'resilience to what', 'properties of resilience', 'resilience for what purpose' could also be applied in the present manufacturing context.

It is highly interesting to note that while modelling techniques such as SADT and IDEF0 adapted for extremely complex systems were present already in the 1970's, contemporary computer power as well as software and networking capabilities were nowhere near realisation for the instantiation and data analyses of e.g., manufacturing value chains. One cannot help but wonder what authors like Ross (1977) and (Morgan and Stilwell, 1983) would have been able to do with today's available computing power.

2.3. Supply chain risk management and how it relates to resilience

SC resilience can be described as an organisational capacity to deal with unintended events and disruptions (prepare, respond and recover) that could change the system to original or better operating states (Duchek, 2019; Martin and Peck, 2004; Ponomarov and Holcomb, 2009; Rice and Caniato, 2003). Every SC is inherently susceptible to various risks, rendering them vulnerable to disruptions. Risks can be defined in terms of SC vulnerability (Martin and Peck, 2004) as the likelihood of an adverse and unexpected occurrence of events that may either directly or indirectly result in SC disruption, thus making it vulnerable. The risks considered in this study are those related to production 'loss' rather than 'fate' (for instance climate disruptions, pandemic etc), with the goal of providing strategic decision-support tools to top-level management (Emblemsvåg, 2011). Disruptions are events that alter normal operations, creating disorder and discontinuity in the form of operational contingencies, production stoppages or financial instability (Madni and Jackson, 2009).

Risk management should not be confined to individual companies, as products and information flow through intricate networks like SCs that connect industries to society. The strength of an organization or network of organizations is determined by its weakest link. Consequently, the magnitude of risks is often greater within the broader supply chain networks rather than originating solely within individual businesses. Risks can also be interdependent, which could compromise the functioning of the entire VC and requires the use of suitable modelling methods (Settanni et al., 2019). This highlights the significance of adopting expansive perspectives in contingency planning to account for threats to business continuity that may arise beyond the focal firm (Colicchia et al., 2012; Martin and Peck, 2004).

Viewing the industrial sector for the VC of this paper, the complexity is extensive in terms of unique material specifications and dependencies of specific suppliers, implying that several risk sources exist and could emerge unexpectedly in the future. Thus, it is important to identify and manage those risks (Collier et al., 2022) by addressing aspects of risk management such as 'sources of risks' that need to be managed, 'frequency of occurrence', 'consequences of the risk' on operations and the 'risk management activities' that need to be coordinated across all partners in a VC. Sodhi et al. (2012) categorize key elements for SC Risk Management (SCRM) such as (1) risk identification (2) risk assessment (3) risk mitigation and (4) response to risk incidents. Jüttner et al. (2010) proposed four strategies to mitigate risks within a SC context such as (1) avoidance (2) control (3) co-operation and (4) flexibility. However, traditional SCRM strategies are insufficient, and proactive and adaptive resilience strategies may be necessary to deal with disruptions (Madni and Jackson, 2009; Um and Han, 2020).

Hence, resilience goes beyond just mitigating risks - it helps organizations learn to deal with disruptions effectively, make trade-offs between required safety and economic levels (Madni and Jackson, 2009), and go to newer and better operational states (Fiskel et al., 2015). Risk management strategies impact SC resilience in that they either reduce the probability or the consequence of a negative event occurring (Um and Han, 2020). By augmenting traditional SCRM with resilience thinking, organizations can outweigh their competitors as they can better prepare for, respond to and recover from disruptions (Fiskel et al., 2015). In addition, due to the different interacting components in manufacturing SCs, improving the resilience of one part may have adverse effects on other parts of the SC. Resilience of the total system should prevail at the end (Amadi-Echendu and Thopil, 2020). Resilience thus has wider implications than conventional risk management methods for SCs (Brusset and Teller, 2017) since they are getting longer, are more complex and are more prone to disruptions.

Risk-related hot spots can be improved or eliminated through data collaboration activities across digital platforms (Helfat and Raubitschek, 2018), which in turn could improve the resilience of SCs. Risk preparedness, and qualitative risk assessment in terms of severity and consequences (disruptions) have also been identified as some of the important components of understanding global risks today (World Economic Forum, 2023b). Therefore, risks and corresponding disruptions need to be holistically identified to avoid a domino or ripple effect as described earlier. These act as ‘controls’ in the IDEF0 modelling approach which is described in detail in Section 4.3.

2.4. Dynamic capabilities for resilient manufacturing

Dynamic capabilities are organisational capabilities characterised by the ability to scan environments for threats and vulnerabilities, adjust quickly to changing environments by creating appropriate mitigation strategies and recover to normal or better operational states (Barreto, 2010; Di Stefano et al., 2010) with a focus on creating value (Katkalo et al., 2010). Since the context of the present study deals with co-creating value in relation to unexpected events, the dynamic capabilities theory was an appropriate theoretical lens to understand what different mitigation strategies or ‘mechanisms’ for building resilience of the SC can be deployed.

Supply chain resilience is thus based on capabilities that can help firms maintain and enhance their operational performance and competitiveness (Birkie and Trucco, 2020; Han et al., 2020). Several facets and pathways for resilience exist in literature: from avoiding, absorbing, adapting to and recovering from disruptions (Madni and Jackson, 2009), absorptive and adaptive paths for resilience (Conz and Magnani, 2020); readiness, response and recovery (Han et al., 2020); proactive, absorptive, adaptive, reactive (Dabhilkar et al., 2016) and transformative phases for resilience (Chari et al., 2021) to supply-side, logistics/storage and demand-side capabilities (Raj et al., 2022) to name just a few. Furthermore, Duchek (2019) categorised resilience capabilities according to three main stages: anticipation, coping and adaptation, a categorisation we believe is congruous to the dynamic capability microlevels of sense, seize and transform.

Based on these, several resilience practices have been identified from previous work. Some examples include creation of redundancy, forming collaborative relationships with suppliers (Tukamuhabwa et al., 2015), flexible sourcing (Pettit et al., 2013; Sabahi and Parast, 2019) and transportation (Bag et al., 2019), flexibility (Borella and Borella, 2021; Santos Bernardes and Hanna, 2009), robustness (Amadi-Echendu and Thopil, 2020), agility (Martin and Peck, 2004; Santos Bernardes and Hanna, 2009) and collaboration (Martin and Peck, 2004) among others. Other examples are optimization of the production line by implementing Industry 4.0 technologies, dual and back-up sourcing (Gatenholm et al., 2021), and risk avoidance and risk sharing strategies (Tarei et al., 2020).

Specifically, several authors have described the development of dynamic capabilities to support a firm’s response to disruptions or the SC’s resilience. Golgeci and Y. Ponomarov (2013) and Sabahi and Parast (2019) showcased the importance of firm innovativeness as an important dynamic capability, while others described technological capabilities (Bustinza et al., 2016; Rajesh, 2017) in giving rise to manufacturing resilience. Applying digital technologies has also been shown to enhance the development of dynamic capabilities for supply chain resilience (Bag et al., 2021; Dubey et al., 2021; Scholz, 2021; Sgobbi and Codara, 2022). Teece (2017) analyzed the requirements in digital platform lifecycle stages from a dynamic capability perspective, and the necessary strategies to deploy those capabilities. With regards to digital platform implementation, Helfat and Raubitschek (2018) explored the development of integrative capabilities that can help in value capture, i.e., it can impact the costs of carrying out transactions in platforms.

From a theoretical perspective, there seems to be various definitions and classifications related to capabilities for resilience, making it challenging to assess the resilience of a system in terms of a ‘single measurable quantity’ (Tamberg et al., 2020). In addition, analysing resilience of SCs from a holistic perspective using empirical data (Shen and Sun, 2021) and modelling it in real-world scenarios (Tamberg et al., 2020) still remain a challenge. This is another research gap that the paper will address: to empirically understand the capabilities that can help deploy appropriate mitigation strategies for building resilient VCs, using the dynamic capabilities theory (further explained in Section 4.3).

2.5. Research gaps addressed in the paper

To summarise, the following research gaps are addressed in the present study:

- The challenges, requirements, and opportunities of digital MSP implementation for manufacturing VC resilience.
- The application of the IDEF0 modelling method to describe and interpret the utilization of antecedents for implementing digital MSPs, ultimately leading to the emergence of resilient manufacturing value chains. Specifically, it helped to holistically:
  - o Gain an understanding of the different risks and disruptions (the ‘controls’) that could cause ripple effects in the VC.
  - o Identify dynamic capabilities that can help deploy appropriate mitigation strategies (the ‘mechanisms’) for building resilient manufacturing VCs.

3. Method

The study follows a deductive case study approach (Yin, 2014) using three use cases from a manufacturing VC in the Swedish research and innovation project “Digitala Stambanan” (Digitala Stambanan, 2021). The project’s background stems from the growing urgency to establish digital infrastructure for industries and value chains in Sweden, particularly for communication and data sharing purposes. The increased adoption of digital platforms aims to foster resilient, flexible, and efficient manufacturing value chains. The “Digitala Stambanan” project name refers to the expansive building of standardised iron railroads across Sweden during the 1860s. This enormous, governmental infrastructure effort forced 19th century companies to radically upgrade their communication and logistics for export, enabling Sweden to become a European industrial superpower in the early 1900s, creating immense prosperity. The project aims to present arguments for the requirements of new (this time digital) infrastructure investments by companies and policy makers. Expected impacts of increased digitalisation of the manufacturing industry’s VCs are e.g., increased competitiveness; high resilience against disruptions and unexpected events; and higher efficiency and adaptability in complex and dynamically changing environments.

As shown in Fig. 4, the manufacturing VC used in the present work consists of three main companies: Company A which processes and subassembles products for the automotive industry; Company B which handles smaller products such as screws and nuts; Company C which is a

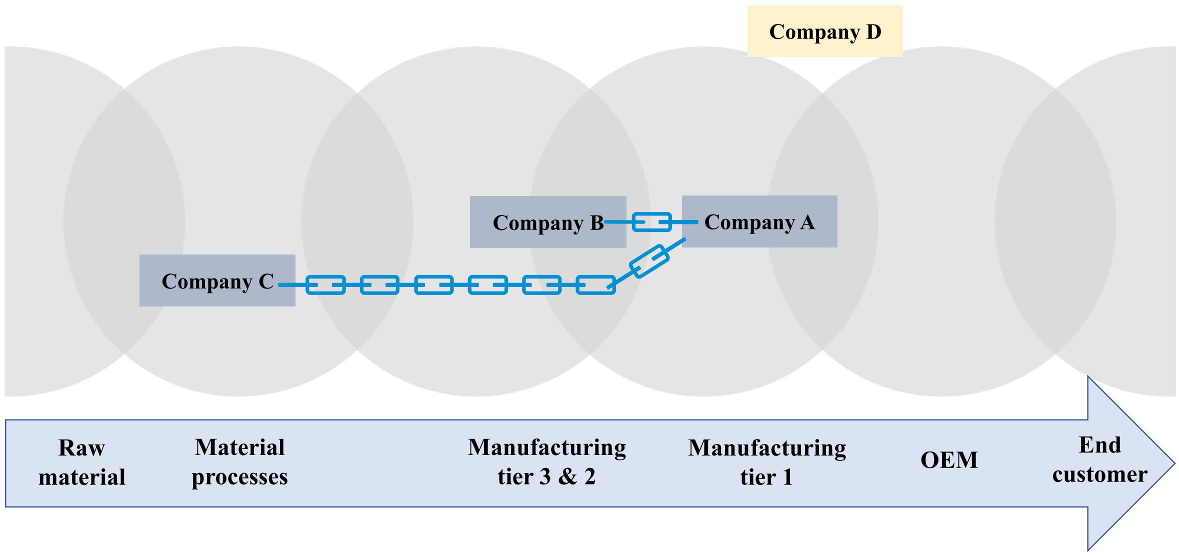

Fig. 4. Manufacturing value chain used in the present work.

raw material supplier to company A; and Company D which is a technology company with a digital platform solution for digitized product certificates and CO2 visualization.

Company A incorporates lean principles and a strong leadership (how to lead, prioritise team efforts, avoid blame and shame etc). They believe that a top-down approach will help them grow bottom-up. Cost and quality are important drivers, but their core company value is that if an effective team is present to affect change, then it can impact the resilience and sustainability of the organization as well as that of the VC. Company B focuses on letting their customers focus on their core business by taking a big part in operations that carries low cost but high maintenance. They want to do this together with their customers through collaboration and digitalisation. Company C has a strong sales focus with a core belief that what they provide to their customers has a strong impact on the value created not only for their company but for the entire VC.

The main objective of this value chain is to integrate digital platforms with the following aims: (i) facilitate efficient logistics flows through enhanced data sharing to meet customer deadlines (delivery assurance) and (ii) visualise CO2 emissions to enhance transparency and support decarbonization initiatives (green conversion).

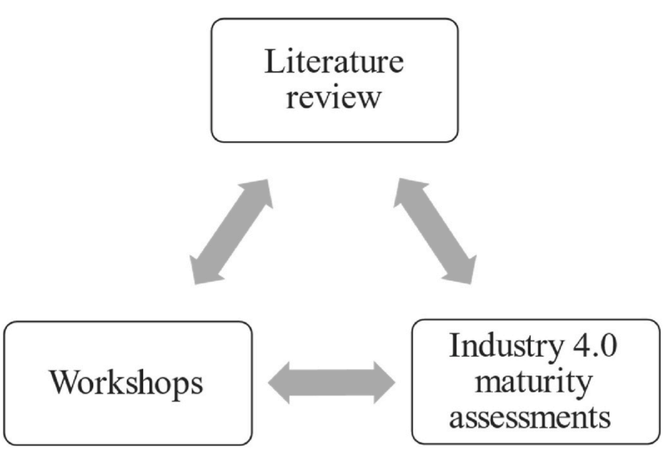

Fig. 5. Data collection sources.

3.1. *Data collection*

Data was triangulated from different sources: literature, workshops and Industry 4.0 maturity assessments as shown in Fig. 5. Company details and profiles of the interviewees who took part in the workshops and Industry 4.0 maturity assessments are described in Table 2.

The literature review provided a better understanding of the characteristics and classifications of digital platforms for resilience, the different antecedents for digital platform implementation for resilience and the corresponding modelling approach undertaken. Details on how the Industry 4.0 maturity assessments and workshops were conducted are outlined in the sections below.

3.1.1. *Industry 4.0 maturity assessment*

The Industrie 4.0 Maturity Index (Schuh et al., 2020), an Industry 4.0 maturity assessment method, was used to assess the digital maturity of the three companies A, B and C as part of their current state analysis (digital maturity) for digital platform implementation. The Industrie 4.0 Maturity Index was chosen as it is widely used and accepted by manufacturing industries (Li et al., 2019; Schuh et al., 2020) as a holistic tool to support their digital transformation in Industry 4.0. Conducting an Industry 4.0 maturity assessment in this study was essential to demonstrate how various facets of digital maturity contribute to the efficient sharing of data across digital platforms and build the necessary capabilities. This, in turn, enables data-driven value creation and enhances the resilience of the entire value chain.

The maturity assessments were carried out between August–November 2022 at the three companies and took 3 days each to complete, with over 30 people interviewed in total (Table 2). The methodology of the assessments can be found in previous work (Li, 2021). Apart from talking to different stakeholders at the companies during the Gemba walk, several 1-h interviews were also conducted in a one-one semi--structured manner. Specific operational details were asked to the personnel who carried out the different processes as well as strategic questions to management level stakeholders. The questionnaire covered four structural areas of the maturity index (Information systems, resources, organization and culture).

3.1.2. *Workshops*

A total of four workshops were carried out and divided into two stages in the present study. In the first stage, three workshops were carried out between July 2021 and March 2022 to identify the sub-areas of the VC's focus [product data used by the customer, understand

Table 2
Description of companies in the value chain and interviewee profiles.

Company	Description	Number of employees at the main site	Number of interviewees	Domain expertise of the interviewees
A	Processes and sub-assembles products for the automotive industry	150	1	COO
			1	Business manager
			1	Production manager
			3	Production leaders
			1	Technical manager
			4	Operators
			1	IT systems engineer
B	Handles c-parts such as screws and nuts	200	1	CEO
			1	Business & HR manager
			2	Production leaders
			1	Quality manager
			5	Operators
			1	Global projects and supply chain development
			1	IT- leader
			1	Export & administration manager
C	A raw material supplier to A	1700	1	External sales
			1	Internal sales
			1	Technical development manager
			2	Digital application managers
			1	Global IT Architect
D	Technology company with a digital platform solution for digitized product certificates and CO2 visualization	9	Not part of the maturity index assessment and interviews	Not part of the maturity index assessment and interviews

customer requirements, data for prediction and security of delivery (delivery assurance), and visualization of carbon footprint of the VC (green conversion)], to identify expectations and get a common understanding for digital platform implementation at the VC level and to understand how raw material data can be used more efficiently and contribute positively to sustainability.

In the second stage, a workshop was conducted at Company A in January 2023 where data was collected from the VC partners using an online collaborative whiteboard (Mural, 2022). The workshop was divided into three parts to understand: (i) the partners' key take-aways/reflections, strategies to be applied after the Industry 4.0 maturity assessment and digital maturity needed for digital platform implementation (ii) the requirements, challenges and opportunities of digital platforms to enable resilience in the four focus areas of the value chain and (iii) the dependencies between risks/disruptions and capabilities for resilient VCs using IDEF0.

In addition, process maps describing the production process flows for each company's end-end functions were created using Microsoft Visio, after which they were translated into IDEF0 diagrams. The creation of these diagrams helped in visualizing the risk/disruption hotspots as well as highlight the capabilities and strategies that act as mechanisms for data-driven value creation for resilience and sustainability of the VC.

4. Results

4.1. Demonstrator based on digital Multi-Sided Platforms (MSPs)

A digital platform offered by Company D was utilised to create a demonstrator aimed at visualizing the carbon footprint of scopes 1, 2, and 3 for the entire VC. Information regarding emission sources, CO2eq footprint, as well as mechanical and chemical properties of the material was collected for each actor within the VC. This demonstrator served as an initial step to showcase the benefits that could be derived from MSPs for resilience, particularly focusing on the 'green conversion' focus area of the VC.

The significance of developing such a demonstrator is that the final product carried a traceability stamp representing the entire manufacturing VC. This closed-loop concept was of great importance to VC partners who sought information on steel that could be environmentally friendly (with a low CO2 footprint), recycled, or efficiently managed to reduce waste. The platform's "traceback view" depicted a tree structure (Fig. 6) containing comprehensive details of the final product, including data on all components and the overall CO2 footprint.

Data collected from the three companies helped to understand which product data had the most impact on VC emissions, ensure individual deliveries, and increase traceability in CO2 data. By linking emission data from each actor in the VC, the traceback tree could be generated showcasing the source and size of the carbon emissions. The data was then used to identify the hotspots in the VC and to simulate the effect that various actions would have on the total emissions. Detailed data could also be accessed by clicking each node in the traceback tree function.

4.2. Challenges, requirements, and opportunities of digital platform implementation

During the workshop involving the partners of the VC, valuable data was gathered to comprehend the requirements, challenges, and opportunities associated with the implementation of digital platforms. The aim was to explore how value could be collaboratively generated to enhance resilience in four key areas of focus within the VC: delivery assurance, product data, customer requirements, and green conversion.

4.2.1. Delivery assurance

Requirements: Implementing QR codes on materials can provide a convenient and efficient way to track and identify specific components, enabling improved traceability and management within the value chain. Having a mechanism in place to receive confirmation that all deliveries are made on time ensures that the value chain operates smoothly and minimizes disruptions due to delays. Timely communication of deviations from expected schedules or specifications could allow for proactive rescheduling and adjustment of operations, preventing emergency situations and maintaining continuity in the value chain. Gaining a clear understanding of critical time schedules from various suppliers, including forwarders and shippers, enables effective coordination and planning, ensuring timely delivery and minimizing delays.

Challenges: The presence of different labelling schemes at the customer and supplier levels, coupled with a wide range of suppliers, creates difficulties in finding generic solutions for effective data sharing and standardization across the value chain. The absence of a transparent system that can identify and flag deficiencies, along with a lack of dialogue and cooperation among all parties involved, hampers the efficient flow of data and information throughout the value chain. Obtaining timely updates from land transportation companies poses a challenge, as the availability and accuracy of such updates can impact the overall visibility and responsiveness of the value chain. Dealing with varying

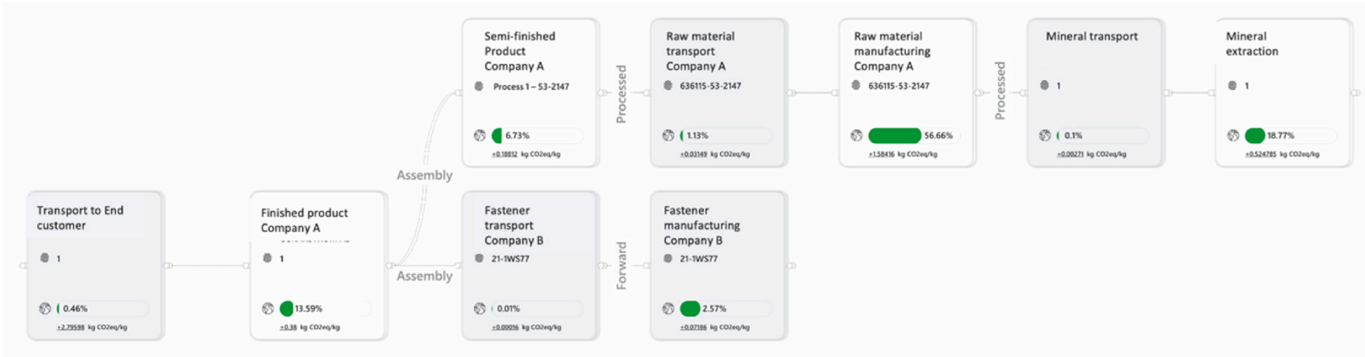

Fig. 6. Traceback tree generated from the data collected from each actor in the VC. The green bars represent the contribution to the total carbon footprint (image from Company D). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

schedules within different regions, such as Sweden, the UK, and other European countries, adds complexity to logistics coordination and poses challenges for ensuring timely deliveries.

From the viewpoint of a platform provider, various demands for internal platforms and standards, as well as those from customers and suppliers, can present challenges in effectively utilizing the platform for delivery assurance. Obtaining support from IT departments and consultants to facilitate integrations may also prove to be a complex task. Furthermore, there is often a prevailing focus on current requirements, neglecting the anticipation of future requirements, which can significantly impact the resilience of the value chain. Addressing these challenges requires collaborative efforts, standardization initiatives, improved communication, and forward-thinking strategies to ensure the effective utilization of platforms for enhancing delivery assurance and overall value chain resilience.

Opportunities: By securing confirmed deliveries from suppliers, the value chain can gain better control over production processes, ensuring timely and reliable supply of materials and components. Providing data to customers before delivery enables them to have a comprehensive understanding of the product, leading to smoother transactions and increased customer satisfaction. Additionally, gathering customer feedback beforehand allows for proactive improvements and customization. Achieving traceability down to a detailed level provides a holistic perspective of the value chain. This comprehensive view enables better decision-making, identification of bottlenecks, and optimization of processes. Transparency within the value chain fosters trust and collaboration among stakeholders. It allows for better visibility of operations, accountability, and the identification of areas for improvement. Ensuring 100% security of supply mitigates the risk of disruptions or shortages in the value chain. It involves effective inventory management, supplier relationship management, and contingency planning. Understanding which segments of the supply chain have the most significant impact allows for targeted interventions, such as sustainability initiatives or risk mitigation strategies, to enhance overall performance. Enhanced traceability regarding changes in specifications and previous orders enables better management of product variations, reduces errors, and facilitates efficient order fulfilment. Furthermore, gaining a better understanding of feasible and unfeasible processes throughout the value chain supports informed decision-making and resource allocation.

By capitalizing on these platform opportunities, organizations can strengthen their production systems, increase customer satisfaction, optimize operations, and build resilience within their value chains.

4.2.2. Product data

The following description outlines the discussed requirements, current challenges, and potential opportunities regarding the utilization of platforms to comprehend customer-related data associated with products, materials, and components.

Requirements: VC partners emphasized the importance of traceability throughout the value chain, requiring the availability of product data digitally. This digital product data serves as input for various processes and enables analysis. It facilitates tracking and monitoring of batches, ensuring quality control and compliance. Company A specifically highlighted the need for information regarding the "outer tolerance range" of incoming materials. This information is crucial for their production processes to ensure accurate and consistent output. Partners also recognized the significance of meeting future customer requirements. By having digital data delivery capabilities, they can proactively adapt to evolving customer needs, enhance customer satisfaction, and maintain competitiveness. There was a requirement for automatic data transfer linked to deliveries. Partners expressed the need for seamless integration with existing software systems to enable efficient data exchange and eliminate manual data entry. In addition, partners emphasized the importance of a standardized application or system for sharing product data and certificates. This standardization facilitates seamless communication and collaboration among partners, streamlining processes and ensuring data consistency. The use of platforms for product data management was seen as a means to minimize administrative tasks and reduce the need for multiple data entry. By centralizing data and automating processes, partners can save time, reduce errors, and improve overall efficiency.

Challenges: The process of comprehending product data for customer utilization faces multiple obstacles. This necessitates the adoption of new work methodologies and a revised planning philosophy. It is crucial to establish robust systems and structures for comprehensive data management and ensure ongoing data integrity maintenance. Additionally, finding a shared approach to multi-party and multi-industry management and meeting customer demands for integration and platform utilization are essential components of addressing these challenges.

Opportunities: By harnessing platforms, there are various potential opportunities to enhance resilience in this specific area of focus. These opportunities include: Efficiently addressing all components contributing to a defective product, avoiding wasted efforts on non-critical components; ensuring customers receive the desired quality by selecting the optimal lot of products, minimizing rejection rates for end customers; enabling partners to effectively manage and control faulty goods in case of quality problems, reducing the impact on the value chain; identifying the most suitable lot for demanding applications, ensuring optimal performance and customer satisfaction; facilitating fast and accurate recall processes for incoming and outgoing materials and products, improving response times and minimizing disruptions; streamlining administrative tasks and maximizing data collection through simplified processes, reducing complexity and improving efficiency; leveraging data analysis to optimize processes by understanding the correlation between input and output, leading to improved efficiency and effectiveness.

4.2.3. Customer requirements

Comprehending customer requirements is an outcome derived from the focus areas of delivery assurance and product data. In particular, the requirements, challenges and opportunities related to the utilization of platforms and the attainment of favourable resilience outcomes in this specific focus area are delineated below.

Requirements: Customer A expressed the need for additional information regarding material specifications, including critical dimensions presented as 3D models. This would provide valuable insights into customer requirements and contribute to accelerated delivery times. Gaining deeper insight into the item's environment, mechanical properties, dimensional tolerances, assembly and processing methods, and usage conditions is crucial to grasp the customer's specific requirements. Determining which aspects carry more significance than others aid in prioritizing the fulfilment of concrete customer demands. A concise overview of comprehensive requirements expressed through specific product and end-use specifications is necessary. This clarity ensures a thorough understanding of customer needs and facilitates effective communication throughout the value chain. Alongside material specifications, it is essential to consider downstream processes. Identifying the material properties that hold relevance in subsequent manufacturing stages allows suppliers to offer the most suitable materials for optimal performance. Expanding the understanding of requirements beyond material properties to encompass transportation, packaging, environmental considerations, and original equipment manufacturer (OEM) requirements provides a comprehensive perspective across the entire value chain.

If digital platforms can meet these requirements, they can empower organizations to align their processes and offerings more effectively with customer expectations, fostering stronger partnerships and enhancing resilience within this focus area.

Challenges: The absence of automated systems for data collection and calculations poses a significant challenge, as manual processes can be time-consuming, error-prone, and inefficient. There are also challenges related to determining the extent of data sharing, the type of data available, and deciding what specific data should be shared. These issues can hinder the collection of accurate end-user requirements throughout the value chain. Addressing these challenges is crucial to enhance data collection processes, improve transparency, and foster effective communication within the value chain. Implementing automated systems for data collection and establishing clear guidelines for data sharing can mitigate these challenges and enable more efficient and transparent practices.

Opportunities: Opportunities in this focus area include: improved communication and dialogue among actors within the value chain, fostering better collaboration and alignment; facilitating a shared vision between VC partners and customers enables collective improvement efforts, driving mutual growth and development; leveraging 3D models and product specifications establishes a clear link between product attributes and related processes, facilitating verification and ensuring alignment with customer requirements; digitizing the periodic follow-up of product specifications enables more efficient monitoring and ensures adherence to customer requirements; automating the management of changing customer requirements throughout the value chain, streamlining the process and reducing errors; enabling a better understanding of customer's critical requirements, giving rise to proactive action and focused attention on key areas; facilitating the receipt of accurate requirement specifications from customers through methods such as Electronic Data Interchange (EDI), reducing misunderstandings and ensuring alignment; supporting the creation of clear requirement specifications based on customer needs, ensuring clarity and reducing ambiguity; enabling faster and more efficient flow when updating and implementing new specifications, minimizing delays and improving agility.

Leveraging these opportunities can drive positive outcomes in this focus area, leading to improved resilience and performance within the value chain.

4.2.4. Green conversion

In order to leverage platforms efficiently for sustainability purposes, specifically for visualizing carbon footprint, a thorough discussion took place to address the various requirements, challenges, and opportunities. These are outlined below to highlight the key considerations in utilizing platforms effectively for resilience in this focus area.

Requirements: There is a need for increased transparency throughout the value chain to access relevant data and information regarding carbon emissions. Integration of LCA analysis calculations is crucial to comprehensively evaluate the environmental impact of products and processes. Access to accurate and comprehensive product and production data from suppliers is essential to accurately assess carbon footprints. Inclusion of transport data is necessary to account for emissions generated during transportation activities within the value chain. Consideration of supplier selection plays a pivotal role in managing scope 3 emissions, as different suppliers may have varying environmental impacts. Engaging customers in the carbon footprint visualization process enables a collaborative approach to sustainability and promotes awareness among stakeholders. A unified platform that facilitates the visualization of CO_2 emissions enables effective communication and understanding of carbon footprints across the value chains.

By addressing these requirements, organizations can better visualise and manage carbon footprints, leading to improved sustainability practices within the value chains.

Challenges: Quantifying environmental impacts is a challenge as the availability of necessary data and expertise for conducting environmental impact calculations is often inadequate, making it difficult to accurately quantify these impacts. Different industries have unique requirements when it comes to environmental impact assessment, necessitating tailored approaches and methodologies for each sector. Acquiring accurate and comprehensive data at the product level from suppliers can be challenging, hindering the ability to accurately assess environmental impacts across the value chain. Ensuring the accuracy of data generated from an organization's own operations is crucial but can be a complex task due to various factors and limitations. Effectively disseminating and managing product data, including information on environmental impacts, throughout the value chain presents a significant challenge, requiring efficient communication and collaboration among stakeholders.

Opportunities: Platforms provide opportunities to screen and influence suppliers based on their environmental performance, enabling proactive sustainability measures within the value chain; they offer the capability to select suppliers based on both their environmental impact and competitive pricing, fostering sustainable supplier relationships; facilitate collaboration among stakeholders, enabling joint initiatives to address environmental challenges and drive collective improvement projects; enable new perspectives in customer dialogue, such as highlighting the carbon footprint implications of different delivery methods (e.g., air versus other modes), promoting environmentally conscious decision-making. Utilizing platforms and CO_2 visualizations for marketing purposes can showcase a competitive edge in terms of sustainability, enhancing brand reputation and attracting environmentally conscious customers. And finally, digital platforms provide opportunities to reshape markets by promoting sustainability practices and encouraging market players to adopt environmentally responsible approaches.

Table 3 summarises the different requirements, challenges and opportunities of digital platform implementation to derive resilience outcomes in the four focus areas.

4.3. Antecedents for successful digital platform implementation through IDEF0 modelling

The IDEF0 modelling approach used in this paper builds on previous

Table 3
Summary of requirements, challenges and opportunities of digital platform implementation for resilience.

Focus area	Requirements	Challenges	Opportunities
Delivery assurance	• QR codes on materials • On-time delivery confirmation • Timely deviation information • Understanding critical time schedules from different suppliers	• Diverse labelling schemes and suppliers • Lack of transparent system and collaboration • Updates from land transportation companies • Varying schedules • Diverse demands for internal platforms and standards • IT support and integration • Focus on current requirements vs future needs	• Enhanced production control • Pre-delivery data provision • Holistic perspective and traceability • Increased transparency • Security of supply • Identifying high-impact supply chain segments • Improved traceability and understanding
Product data	• Traceability and digital product data • Outer tolerance range • Meeting future customer requirements • Automatic data transfer • Standardised application for data sharing • Minimised administration	• Adoption of new methodologies and planning • Establishing comprehensive data management systems • Meeting customer demands	• Comprehensive component tracking • Optimal quality assurance • Proactive quality management • Suitability for demanding applications • Streamlined recall processes • Simplified administration and data collection • Optimization through analysis
Customer requirements	• Detailed material specifications • Comprehensive understanding of materials • Clear expression of requirements • Material properties • End-end visibility	• Lack of automated systems • Transparency and communication issues	• Enhanced dialogue • Shared vision and continuous improvement • Integration of specifications • Digitized periodic follow-up • Automation of changing customer requirements • Improved understanding of critical requirements • Clear and needs-based requirement specifications • Streamlined flow for updating specifications
Green conversion	• Transparency in the VC • LCA calculations • Product and production data from suppliers • Transport data • Supplier selection • Customer involvement • Common platform for CO2 visualisations	• Limited data and skills • Industry-specific requirements • Obtaining product-level data from suppliers • Generating internal data from internal operations • Distributing product data	• Supplier environmental screening and influence • Supplier selection based on environmental impact and price differentiation • Collaboration in projects • Alternative angles in customer dialogue • Marketing advantages • Market redefinition

work by Chari (2021) focusing specifically on resilience modelling and facilitates the identification of resilience factors at different levels of abstraction.

The work of Chari (2021) is presented in Fig. 7, where an IDEF0 diagram has been adapted to fit factors and functionalities relevant to resilience modelling. In this paper we will further apply this methodology to a manufacturing value chain. We derive the top-level context diagram (A-0 or parent diagram) of the resilience model that we use in the present study. The activity (or function) represented in the box is 'building long-term resilience'. Several factors 'control' this function, for instance threats/risks as well as corresponding disruptions. The mechanisms that enable this function are the dynamic capabilities that can help deploy long-term strategies that need to be in place before disruptions take place as well as the operational tactics that need to be deployed during or after a disruption. Since the 'activity' in our model is to build resilience of the VC, we do not delve into specific manufacturing processes in each company but consider overall risks and corresponding

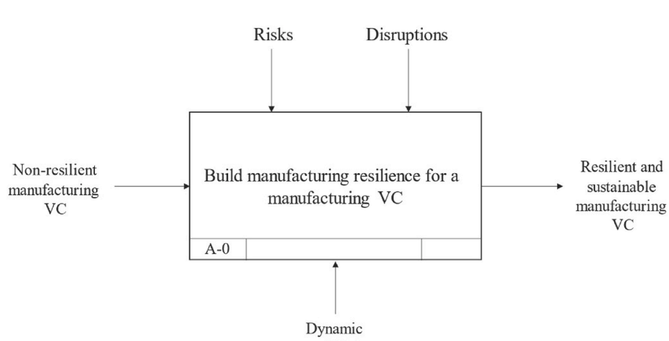

Fig. 7. Top-level context diagram of the resilience model for the manufacturing value chain. Adapted and modified from (Chari, 2021).

disruptions as controls that would impact the resilience of the entire VC and the mechanisms that would help mitigate or deal with the risks/disruptions.

According to Tamberg et al. (2020)'s checklist for resilience modelling as described earlier, the 'system' in our case is a socio-technical manufacturing VC, the 'sustainant' describes the features of the system that are supposed to be maintained for it to be resilient and in our study it is building the long-term resilience of the VC, the 'adverse influence' depicts the factors influencing the sustainant which are the risks/threats and disruptions in our model, and the 'response options' are the dynamic capabilities that can help manufacturing value chains deploy short-term tactics and long-term strategies to mitigate or deal with the risks and disruptions. In addition, we used van Wassenaer et al. (2021)'s resilience ontology to cross-check and ensure that the different features of resilient systems were included in our model namely, 'resilience of what' (manufacturing VC), 'measuring resilience' (through dynamic capabilities), 'managing resilience' (strategies), 'resilience to what' (risks and disruptions), 'properties of resilience' (anticipation, coping, adaptation) and 'resilience for what purpose' (sustainability, data sharing, delivery assurance).

4.3.1. Risks and disruptions-the 'controls' of the IDEF0 model

Risk analysis is an important element of building resilience (Chopra and Sodhi, 2004; Fiskel et al., 2015) and the IDEF0 was utilised to holistically understand risks/disruptions that occur in the individual case companies and their collective impacts as they propagate along the VC. Risks that cannot be contained within an organization (i.e., if the company cannot mitigate the corresponding disruptions due to the lack of long-term strategies or short-term tactics), become risks/disruptions for the next company(ies) in the VC. This domino effect due to hotspots in the VC are better visualised using a holistic model such as the IDEF0.

During the workshop held in January 2023, the partners of the VC engaged in detailed discussions about their production processes, examining their individual business process maps. They were then prompted with questions to explore their perspectives, including: defining resilience ('What does resilience mean to you, and how significant is it in your operations?'), identifying hot spots ('Can you identify areas of vulnerability or risks within the value chain that have the potential to disrupt manufacturing operations?'), examining disruptions ('What types of disruptions are associated with these identified hot spots?'), assessing frequency and severity ('How often do these disruptions occur, and how severe are their impacts on the value chain?'). By delving into these topics, the workshop aimed to gather insights from the VC partners, facilitating a deeper understanding of their production processes and the importance of resilience within their operations. A total of 21 risks and corresponding disruptions were identified for the manufacturing VC case in the present study, and a few have been highlighted in Table 4.

4.3.2. Dynamic capabilities for resilient strategies – the 'mechanisms' of the IDEF0 model

As described before, building SC resilience requires organizations to develop capabilities (Pettit et al., 2013), specifically dynamic capabilities (Teece et al., 1997) so that they can respond effectively to uncertainties in dynamically changing environments (Conz and Magnani, 2020). Ordinary capabilities enable firms to execute their daily production plans, while dynamic capabilities are future-oriented, helping firms tackle challenges and seize opportunities, while also positioning themselves for competitiveness (Teece, 2017). Further, if organizations need to measure their level of resilience (how they assess and react to disruptions), there needs to be certain performance metrics or best practices in place (Han et al., 2020). The authors of the present study are currently conducting parallel research to investigate the detailed connection between resilience capabilities and practices. However, the idea of building supply chain resilience dynamic capabilities to deploy suitable strategies to effectively respond to disruptions will be considered in the present work.

Table 4 presents some of the risks and disruptions observed within the value chain, which have the potential to impact multiple companies. Accordingly, the dynamic capabilities required to deploy the required long-term strategies and short-term tactics for risk mitigation are also described. The classification of risk management (seen in the first three columns of the table header) was conducted based on the works of (Collier et al., 2022; Madni and Jackson, 2009; Sodhi et al., 2012). The dynamic capabilities (the last column in Table 4) were categorised according to the micro-levels of sense, seize and transform according to (Teece, 2017), i.e., the capabilities required in the anticipation, coping and adaptation resilience stages (Duchek, 2019).

We provide an illustration of a High Impact, High Probability (HIHP) risk using the IDEF0 model, which demonstrates the organization's resilience and its ability, in turn, to enhance the resilience of the entire value chain by mitigating the identified risk through the development of dynamic capabilities. Due to limited space, not all identified risks in the study could be included in the IDEF0 model.

A significant risk was observed in Company A, which has a direct impact on the company and its OEM supplier. The risk concerns the possibility of receiving materials from the supplier (Company C) that fall outside the specified tolerance range in terms of flatness, hardness, and material surface defects, among others (risk 2 in Table 4). This risk leads to various disruptions in Company A's operations. Production is halted until new material is received, rendering it unusable for assembly. The material cannot be returned or repaired and ultimately needs to be scrapped. Moreover, the risk can result in machine breakdowns, leading to costly machine replacements. Additionally, the high residual stresses

Table 4
Risks, disruptions and dynamic capabilities identified for the manufacturing value chain.

	Risk identification		Risk assessment		Risk mitigation		Dynamic capabilities required
	Risk	Disruption	Severity	Frequency	Long-term strategy	Short-term tactics	
1	Data is missing	Order is late	High	High	Understand the end-end process in the VC and how the end-product will be used makes it easier to suggest alternatives	Reminder/call suppliers for information, product certificates	• Visibility (sense) • Stakeholder involvement (sense, seize) • Data sharing (seize) • Dynamic collaboration (seize) • Information management systems (sense, transform)
2	Deviations in material characteristics are unknown	Delay in supplying product to customer	High	High	Suggestions for other dimensions or alternative products during feasibility check at the beginning of the project	• NA (company A) • Visually check material (Company C)	• Situation awareness (sense) • Visibility (sense) • Stakeholder involvement (sense, seize) • Communication and data sharing (seize) • Dynamic collaboration (seize)
3	Cyber-security issues	Critical data is not shared with stakeholders	High	Low	Avoid cloud-based solutions for critical processes	Continuous monitoring from IT	• Culture (sense, seize) • Technology and information system management (sense, transform)
4	Issues with machines/ furnaces	Production is blocked	High	Low	Transparent dialogue and good relationship with suppliers	Backup supply available	• Resource utilization (sense, seize) • Dynamic collaboration (seize)
5	Dependency on supplier	Lack of redundancy leads to disruption in operations	High	Low	Alternative suppliers in place for non-unique materials	Alternative materials in stock	• Resource utilization (sense, seize) • Redundancy (sense) • Flexibility (seize) • Technological innovation (e.g., for automated reporting) (seize, transform)
6	Different data formats	Production is blocked	Low	High	Build systems and structures to manage data	NA	• Technology and information system management (seize, transform)

in the material cause warping during cutting, preventing Company A from starting the laser cutting process and halting subsequent processes. Consequently, this has a negative impact on lead time to the OEM customer.

Company A develops long-term strategies to address this issue. They conduct risk assessments and feasibility checks at the beginning of projects to categorize risks based on their probability of occurrence. They have also established alternative flows to the customer that are pre-approved. Additionally, from an operational perspective, Company A closely monitors each item to ensure it meets the required quality standards. Unfortunately, due to strong dependencies on material quality from specific steel mills, finding an immediate and perfect solution to address the disruption is challenging. Consequently, the disruption cannot be contained within Company A, posing a potential risk or disruption to the OEM customer and, subsequently, their customers.

The VC partners highlighted the importance of digital maturity in implementing digital platforms for resilience, during the I4.0 maturity assessments that were carried out. The digital maturity mapping exercise provided a clearer understanding of digitization, including the associated opportunities and risks. The interconnectedness and significance of dynamic capabilities that can be derived within the structural areas of the I4.0 Maturity Index were also seen. Varying digital maturity levels among stakeholders can impact data sharing in the VC, but understanding the content of each maturity stage to enable individual and VC-related digitalisation strategies was more important than simply moving between maturity levels. The varying digital maturities were due to different goals of the individual companies as well as due to the difference in boundaries that were assessed. That is, the main production line was assessed in Company A versus only the sales division in Company C.

Overall, dynamic collaboration within value networks was identified as a crucial capability in the VC, with varying maturity levels potentially leading to significant negative consequences. Cooperation and willingness among stakeholders were also highlighted as essential, aligning with previous research findings (Chari et al., 2022). The implementation of digital platforms was seen as a collective effort requiring support from all VC stakeholders. They acknowledged that data sharing across the VC relies on the active involvement of all stakeholders. The foundational role of receiving material data from suppliers was consistently highlighted across the four focus areas of the VC. Customer-specific requirements were considered vital for streamlining and digitizing processes, emphasizing the importance of fulfilling these data requirements. Participants expressed a need for automated reporting with more reporting points.

Company C expressed that although it has several digital systems and tools aimed at reducing staff dependency and increasing efficiency, there was a recognition that the available resources are not always fully utilised and variations in working methods exist. Competitive capabilities such as skills, particularly for traceability, and corresponding technology and information management systems were acknowledged as crucial factors for mitigating risks. In addition, fostering an inclusive and democratic leadership style enables employees to have the autonomy to take ownership and make independent decisions, thereby enhancing their maturity within the 'culture' and 'leadership style' capabilities.

Hence, to deploy mitigation strategies (for risk 2 in Table 4) at the VC level, partners will need to have situation awareness, visibility of customer specific requirements, develop data sharing capabilities, involve stakeholders and have a dynamic collaboration with them and understand how different underlying company cultures can impact building resilience.

The parent diagram A-0 (Fig. 7) of the IDEF0 was elaborated into a child diagram A1 (Fig. 8) to further illustrate resilience antecedents for platform implementation using IDEF0 principles. The purpose of this breakdown is to highlight the specific risks and disruptions that give rise to hotspots or bottlenecks in the subsequent levels of the value chain. Additionally, it outlines the long-term strategies, short-term operational tactics, and potential dynamic capabilities that can be employed to address these risks. Here, the dynamic capabilities can support the development of both, the short-term tactics and the long-term strategies. Although the OEM (the customer of Company A) shown in the model was not explicitly described in Table 2, it was important to show how the risks/disruptions seen in the upstream VC processes could impact their operations. Another observation in the model was how the disruptions seen in the OEM and Company A had an impact of creating more disruptions in the upstream activities due to a feedback mechanism (Fan et al., 2023), further intensifying the urgency to fix the disruption.

When examining a specific risk (risk 1 in Table 3) in relation to the digital maturity level within the information processing capability, it was observed that operators and systems within the companies processed information in slightly different ways. All companies had the

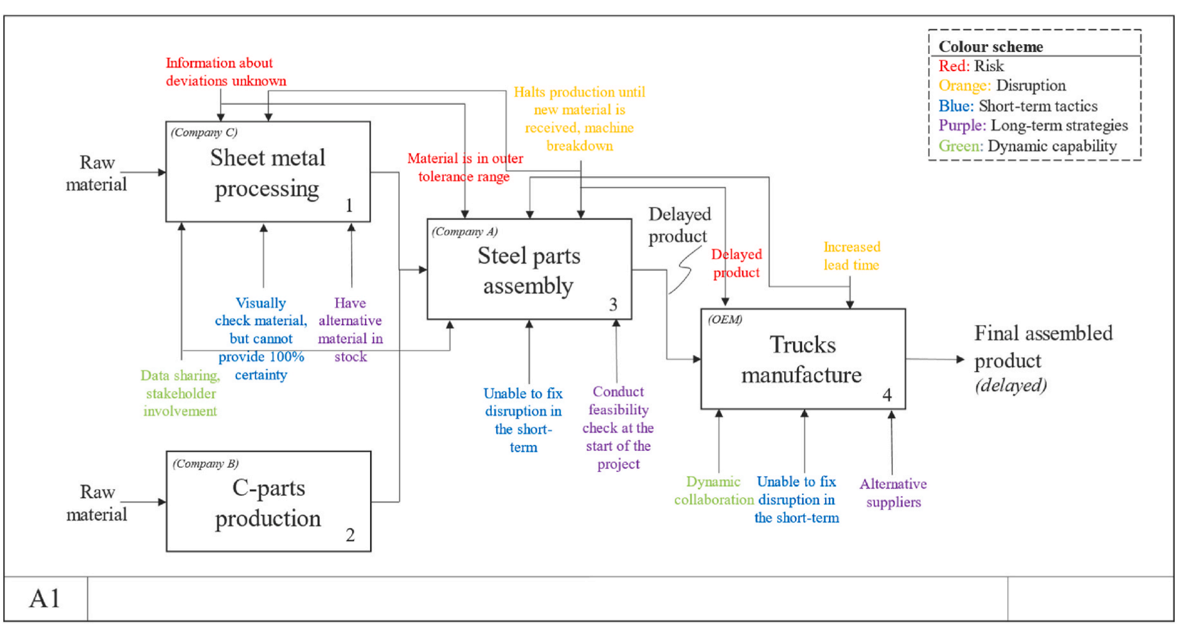

Fig. 8. The child diagram A1, showcasing the inter-related risks, disruptions and capabilities that impact the resilience of the value chain.

same level of maturity in the 'provision of information' sub-area, where operators manually retrieved order numbers using IT systems. However, differences arose in the 'information offering' aspect, with Company C possessing information on sales processes in various systems, which could only be shared with customers upon request. This lack of visibility in delivery delays to customers could negatively impact the downstream resilience of the value chain, as Company C served as a raw material supplier to Company A. Another distinguishing factor was the availability and redundancy of systems across organizations. Companies A and B did not have backup systems in place for instances of system downtime caused by internet connectivity issues or power outages. On the other hand, Company C's server facilities were equipped with diesel plants for backup power supply, with dedicated IT departments responsible for server and application operation and monitoring. Any failure in these systems would pose a risk, disrupting both the company's internal operations and the overall value chain.

4.3.3. Impact of resilience on the environmental sustainability of the value chain

The VC partners were also asked about their vision for integrating environmental sustainability aspects in their organizations and how their resilience strategies had an impact on sustainability. Due to regulations (locally and with EU's Green Deal), partners mentioned that it is better to be prepared proactively; that there was considerable value in offering greener alternatives to customers; that the companies had their own goals and targets for impacting the environment in addition to customer requirements. This had a large role to play in the type of products produced, as 'green steel' is becoming more important from a stakeholder perspective (who takes responsibility for the investment).

Some of the effects of building resilience in the VC also had sustainability implications. For instance, a lack of redundancy in suppliers (since the VC has unique material specifications and steel coming from specific mills) could lead to an increase in scope 3 emissions and transportation-based emissions due to the geographical location of the suppliers. Using digital platforms allowed the opportunity to clearly visualise this and plan for corrective strategies, for instance, planning for alternative products or checking material quality before processing them, thus reducing scrap. Visualizing the carbon footprint also helps in understanding the critical hotspots in the VC and thus create alternate suppliers, processes and materials that could reduce emissions and waste. Having redundant materials on the other hand could affect lean management and may not be cost effective and this needs to be kept in mind when creating strategies for resilience which have positive sustainability implications.

5. Discussion

When organizations prepare for propagating risks and corresponding disruptions, they are in effect, building the resilience of their organization as well as impacting the resilience of their entire VC. Risks that have smaller impacts at one level or company in the VC should be recognized fast enough and mitigated so that they do not become risks in the next levels of the VC. The level with which risks/disruptions can be contained within a certain level/company shows how resilient the VC is.

In line with platform implementation challenges seen in (Marie-Christin et al., 2019), the present study identified collaborative challenges in terms of participation of stakeholders and their varying digital maturity levels; internal challenges in terms of new ways of working that would be required, knowledge required and change of mindset; and technological challenges in terms of data security, exchange and software requirements.

Furthermore, in order to effectively utilize digital platforms for resilience, companies need to possess a certain level of digital maturity. This level of maturity enables them to cultivate dynamic capabilities that help harness the full potential of digital platforms. Presently, many companies still rely on manual order handling, resulting in a misalignment between their current practices and the desired processes. Prior to adopting digital platforms and reaping the benefits of digital and automated order handling, companies must first achieve the necessary level of digital maturity and capabilities. The integration of IT systems and the establishment of a well-structured organization play crucial roles in facilitating investments in and the implementation of digital platforms. However, to fully leverage the functionalities provided by the platform, a higher level of resource maturity and organizational culture is essential. Engaging individuals within the organization and fostering their willingness to effectively utilize the platform functionalities are key considerations. Insufficient resource maturity encompassing competence, skills, and technologies, can hinder the optimal utilization of resources and disrupt the flow of information.

The IDEF0 model is not a static organisational model but is a strategic tool that can be used in real-world applications to showcase the dynamic interactions between the processes across the VC. The VC is as strong as its weakest link, and visualizing this dynamic nature of interrelated risks, disruptions and capabilities could help manage the resilience of the entire VC. The model portrays a multi-influence based on the different risks specified, along with their inter-relatedness. These help to reduce the trade-offs that could occur if some were not included in the model (Tamberg et al., 2020).

The paper has the following outcomes:

- Identified the challenges and opportunities of digital MSPs for building resilience in a manufacturing VC.
- Enabled a case-based translation of IDEF0 resilience modelling into an empirically based manufacturing analysis.
- Analyzed the antecedents for digital MSP implementation for resilient and sustainable manufacturing VCs.

5.1. Contribution to theory

The I4.0 digital maturity assessments provided an opportunity for VC partners to understand their individual digital transformation journeys as well as reflect on how their practices and digital maturity levels could impact the flow of data and the mitigation of risks across the VC. The first contribution of the study is to change management literature (Hiatt and Creasey, 2012) which describes the dimensions and influence of process or technology changes on VCs. The implementation of digital platforms for resilience and some of the corresponding dynamic capabilities required (in brackets below) could be attributed to the five steps in change management where 'change' takes place in the business process of the organizations. For instance, awareness of the need to implement platforms (stakeholder involvement, culture, collaboration), the willingness to embrace and participate in the implementation (culture, skills), knowledge on how to implement platforms (skills, data sharing), the technical ability to carry out the implementation (collaboration, technology and information management system), and the strategies to maintain changes for the future (the long-term strategies and short-term tactics that could be deployed due to the development of dynamic capabilities).

The second contribution is to dynamic capabilities literature (Teece et al., 1997, 2016), where different dynamic capabilities were identified (not a comprehensive list) for the different stages of building resilience. This also resonates with previous work (Conz and Magnani, 2020; Duchek, 2019; Han et al., 2020) where preparatory capabilities in the anticipation phase such as situation awareness, redundancy and visibility; coping capabilities such as flexibility, collaboration and leadership; and adaptation or learning stage capabilities such as knowledge management and planning can help build the resilience of the VC. However, it is important to note that the capabilities cannot be categorised and valid in only one specific stage of building resilience, but rather, many capabilities can be developed and utilised across multiple stages (Chari et al., 2022).

The third contribution is the evolution and utilization of a functional modelling tool such as IDEF0 for the visualization of risk management, especially in manufacturing VCs that are interested in building their resilience and sustainability. The utilization of such a holistic model for future digital platform implementation is a novel contribution of this work, where VCs have the potential to visualise not only risks and corresponding disruptions in real-time, but also their CO2 footprint which could impact their organization as well as the resilience of the entire VC. Madni and Jackson (2009) proposed endemic abilities of resilient systems such as the ability to anticipate, learn and adapt accordingly. The IDEF0 model showcased in this work allowed us to elaborate on such proactive principles for building the resilience of manufacturing systems.

The fourth contribution of the study is to SCRM literature where complexity of SC structures and inherent uncertainties could be modelled (Colicchia et al., 2012), providing a practical approach to guide risk assessments in supply networks and helping decision makers in the manufacturing industry to strategize and track for vulnerable hotspots in the VC (Jüttner et al., 2010).

5.2. Contribution to practice

An IDEF0 model can enable a holistic, systems-level perspective for a strategic and tactical handling of resilience, where time dependent mitigation of risks and corresponding disruptions could occur. The theoretical model was used in an implementation scenario where multiple companies across the value chain have the ability to access it and in real-time. By zooming in and decomposing the top-level IDEF0 diagram to child diagrams, practitioners can visualise the dependencies between risks, digital maturity, capabilities and strategies among the different processes in the VC, their impact on the implementation of digital platforms and the corresponding resilience and sustainability of the entire VC.

An analogy for the different processes and connections in a manufacturing VC are the neurons and synapses in the brain. Neurons communicate with each other through connections known as synapses. The more trained they are (in our case, higher the digital maturity and capabilities developed), thicker are the connections (in our case, higher resilience of the VC). We hence focus on antecedent factors, i.e., connections that are weak or strong to implement digital platforms, which can build the resilience and sustainability of the VC. The IDEF0 model helped us visualise these factors so that they could be further instantiated on digital platforms, thus allowing a free flow of information (transparency of data) in the VC. Having data present on such platforms can help VCs in real time follow the risks/threats and corresponding disruptions and take actions proactively. Risk analysis is quicker and more accurate if the platform is transparent. If not, it is an after-thought after the disruptions occur. Thus, one can enable non-resilient value chains to become resilient and sustainable by preparing for risks that can propagate and cause disruptions, which shows the level of resilience in the firm.

A demonstrator developed for the ‘green conversion’ focus area was a first step in showcasing the potential of digital MSPs for building resilience where the carbon footprint journey from the raw material to the final product to the customer could be transparently visualised. Although reliable and real data from VC partners can still be a challenge for environmental impact calculations (World Economic Forum, 2023a), industrial partners have the ability to focus on factors that can have a domino effect on the resilience of the VC and identify interventional strategies that can deliver the best value for the VC, especially with regards to environmental sustainability.

5.3. Limitations and future work

The IDEF0 model in the present study was developed for a manufacturing VC in Sweden. To test for generalisability, the model would need to be applied to other manufacturing industries globally and in different sectors. The utilization of the model as a resilience modelling tool did not demonstrate any significant limitations regarding its ability to handle internal and external complexities. However, its use may be constrained in terms of the level of granularity or abstraction at which it can be showcased, to ensure its relevance and practicality for modelling and for practitioners.

The IDEF0 model was selected among various other modelling languages such as Model-based Systems Engineering (MBSE) (Zhang et al., 2022), Unified Modelling Language (UML) (Selic et al., 2015), etc. The IDEF0 model was chosen (as also described in Section 2.2) because it enables the description and visualization of large and complex systems, specifically the manufacturing VC, using accurate and consistent representations (Ishizaka and Nishimura, 2021). Additionally, it was deemed suitable based on the guidelines provided by Tamberg et al. (2020) for enhancing the resilience of complex systems. However, alternative modelling methods could also be considered and tested. Other approaches for flexible and resilient production (Habib et al., 2022), and numerical models (Kar et al., 2023; Malik et al., 2023) to quantify and deal with risks and corresponding disruptions could also be explored.

Root Cause Analysis (RCA) is a method that is performed for eliminating causes that contribute to risks in an organization and is generally considered to be a part of an organization’s risk management process (Hughes et al., 2009). Combining RCA and the holistic resilience thinking from an IDEF0 description would allow complementarity between the methods and would have several advantages: it may help manage the resilience of not only the focal organization but also its entire VC, help define and quantify the risk, understand risk causation, identify necessary corrective actions (Hughes et al., 2009) and can help prioritise risks when the IDEF0 model is used in conjunction with RCA tools such as Failure Mode and Effect Analysis (FMEA) (Collier et al., 2022). The risks identified could also be quantified based on their frequency, severity and probability of occurrence using the functional resonance analysis method (FRAM) according to (Melanson and Nadeau, 2019).

A first version of the digital platform was developed in the form of a demonstrator to showcase resilience in the green conversion focus area at the process level of the product. Here, CO2 footprint was visualised and followed a specific process of the VC. In future work, the authors plan to use a differentiated product portfolio for the development and implementation of platforms for the VC. The authors also intend to integrate the antecedent factors identified in this study onto a digital platform, combined with a discrete event simulation model. This integration aims to demonstrate the real-time ability of mitigating risks and effectively manage resilience in a comprehensive and transparent manner, for the delivery assurance focus area of the VC.

The present work studied the implications of building resilience on the value chain’s sustainability. In addition, the sustainability of the value chain can also be assessed by the level of contribution of the individual companies to the United Nation’s sustainable development goals or SDGs (Khan et al., 2021b), and this can be evaluated with further empirical testing in future work.

6. Conclusions

Digital platforms have emerged as crucial drivers of innovation, growth, and competitiveness in various industries. However, specifying, implementing, and successfully launching a digital platform is a complex and challenging task. Using an empirical approach, this study provides a systematic and visual representation of the necessary antecedents for digital platform implementation using the Integrated Definition for Function Modelling (IDEF0) approach. The IDEF0 modelling technique introduced in the 1970s, was identified, revived and implemented for manufacturing organizations as well as for the VC level. The approach helped prove that a set of inter-dependent factors impact the resilience and sustainable competitiveness of a value chain. The selection and adaption of a well-established and robust modelling technique helped in putting the study's emphasis on the conceptual content for resilience management.

This paper offers stage-wise, practical recommendations for manufacturing value chain partners interested in building resilience as part of their digital transformation journeys. Firstly, it is important to understand that digital maturity and corresponding capabilities are important activity mechanisms to 'implement' digital platforms and for effective 'utilization' of them. Although digital maturity levels vary from company to company based on personal goals and VC objectives, the first step is to develop information systems where data is structured and connected in a good way. Only then can investments in platform implementations be recommended. However, one cannot make full use of platforms if the appropriate culture and resources capabilities are not present. Secondly, the next steps of a company's digital transformation should be focused on ERP/MES systems that could be integrated with both customers and suppliers, allowing maximum transparency in the flow of information, both horizontally along the VC and vertically inside each company.

Thirdly, it is imperative to collectively identify value co-creation opportunities for resilience stemming from digital platform implementation on a VC perspective. For the manufacturing VC, some of the most relevant and important opportunities were: (i) enabling 100% security, traceability, and transparency in the VC; (ii) ensuring that customers always receive the best and right quality of the product; and (iii) having better control over the final product due to visibility of critical delivery data.

Lastly, multiple resilience factors were identified for modelling interactions between companies on the digital MSP. The antecedent factors identified as relevant for building resilient manufacturing value chains were risk management (the 'controls') and dynamic capabilities (the 'mechanisms') for deploying strategies for sustainable competitive advantage. Although the companies would typically have long-term strategies to deal with risks and disruptions, this preparation might not be enough to maintain or control disruptions during day-day operations (using short-term tactics).

In order to facilitate proactive and corrective mitigation actions, it is essential to identify risks and associated disruptions within the VC. These risks should be described in terms of their frequency and severity, and transparently shared with the entire VC through digital MSPs. The study emphasized the importance of this process, as the resilience of the entire VC is ultimately determined by the ability of each organization within it to effectively address these risks and disruptions. It was highlighted that the strength of a VC is contingent upon its weakest link. Efficient modelling of the VC plays a crucial role in understanding and experimenting with various VC parameters. This is vital in striving for increased resilience and sustainability. We also identified several implications of building resilience on the sustainability of the value chain and these aspects should be kept in mind during the digital transformation process.

Therefore, the establishment of resilience within a VC necessitates the implementation of effective risk management practices and the development of time-sensitive risk mitigation strategies that are openly communicated to all VC partners. Without proper identification of risks and their corresponding disruptions, it becomes impossible to effectively manage them. The study recognized the importance of modelling challenges and risks arising from internal complexities, as well as external disruptions, within the VC. While the preparation for risks, disruptions, and the adoption of technology-driven improvements, as well as the transition to sustainable practices may sometimes not yield immediate outcomes, these investments have the potential to generate long-term benefits across production networks and beyond.

CRediT authorship contribution statement

Arpita Chari: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Johan Stahre:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Maja Bärring:** Resources, Project administration, Funding acquisition. **Mélanie Despeisse:** Supervision, Writing – review & editing. **Dan Li:** Methodology, Writing – review & editing. **Martin Friis:** Investigation, Project administration, Writing – review & editing. **Magnus Mörstram:** Investigation, Project administration, Writing – review & editing. **Björn Johansson:** Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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