

Enabling Technologies as a Support to Achieve Resilience in Supply Chain Operations

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Abstract—In response to the dynamic and ever-changing landscape of supply chains, which are continually challenged by internal and external factors, there is a critical need for continuous adaptation, learning, and improvement. Historically, scholars have argued that traditional information systems lack the capacity to effectively support resilience strategies within supply chains. However, advancements in Industry 4.0 technologies may have shifted this paradigm. This article explores how enabling technologies (ET) can support the development of resilient operations at the supply chain level. To that end, a systematic literature review is combined with a multiple case study to understand how these technologies can support the development of elements of resilience. Three distinct sectors from different geographical locations were chosen for this study: an agri-food company in Brazil, a manufacturing firm in the food industry in Canada, and a logistics service provider in Italy. Integrating both theoretical insights and empirical findings leads to the formulation of a research framework, the primary contribution of this study, which serves as a resource for scholars and practitioners aiming to leverage ET to increase supply chain resilience. The article concludes with key findings and suggests avenues for future research.

Index Terms—Disruptions, enabling technologies (ET), Industry 4.0, operations and supply chain management, resilience.

I. INTRODUCTION

COVID-19 has been a tipping point for recent discussions on disruptions around the world, as it has adversely affected global supply chains through all their stages, with major impacts on manufacturing, processing, and logistics, as well as significant shifts in demand [1], [2]. More recently, geopolitical tensions such as the Russia–Ukraine conflict, environmental catastrophes such as wildfires in Canada and Australia, and the Suez Canal blockage by the Ever Given have also caused significant

disruptions. These events have led to delays, increased costs, and re-evaluations of supply chain strategies globally. Thus, to survive in an increasingly turbulent environment, organizations need to develop capacities for purposefully adapting, integrating, and reconfiguring internal and external organizational processes, resources, and functional competencies [3], [4].

These capacities are closely linked to the concept of resilience, which has been at the forefront of discussions among practitioners, academics, and the government. Resilience is commonly known as a dynamic set of conditions that help organizations better cope with unpredictable disruptions, both reactively and proactively. Therefore, the ability of an organization (in conjunction with its supply chain partners) to effectively develop capabilities in anticipating, adapting, responding, recovering, and learning from any disruptive event by means of resource management [5]. Achieving resilient capability requires a set of enablers or elements, such as a flexible and collaborative ecosystem of suppliers and partners that can handle sudden shortfalls or even produce new products. This means setting up alternative manufacturing sites or assembly nodes and making the most technological tools to optimize costs, improving visibility across the network and accelerating response [6].

Digital transformation is often invoked as an alternative to overcome the crisis in many spheres of society, such as markets [7], education [8], healthcare [9], urban services [10], and clearly, manufacturing [2]. Companies adopt sets of enabling technologies (ET) to maintain business models, operational processes, and customer requirements [11]. On the basis of current facts, we have witnessed a continuous evolution of technology enabling organizations in their decision-making processes, both reactively and proactively. For example, they can support businesses in understanding alternative sources of supply, enhancing inbound material visibility, focusing on production scheduling agility, evaluating alternative outbound logistics options and secure capacity, opening channels of communication with key customers, and conducting global scenario planning [12].

Despite the increasing interest in academia in exploring the gains in resilience achieved through ET, studies are still only nudging forward while exploring different particularities on this key topic (e.g., [2], [13], [14], [15], [16], [17], and [18]). Therefore, the aim of this article is to explore how ET can support the development of resilient operations at the supply chain level. To achieve this aim, this study starts with a systematic literature review (SLR) to understand the current knowledge of how ET can support the development of elements of resilience (EoR). As a second step, a multiple case study was conducted within three

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different businesses and in three different geographical locations (an agri-food company in Brazil, a manufacturing company in the food industry in Canada, and a logistics service in Italy). Both theoretical and empirical data inform the research framework proposed by this study as a tool for scholars and practitioners to reflect on the use of ET to develop resilient operations at the supply chain level. This is, therefore, the main contribution of this study.

The rest of this article is organized as follows. It begins with a concise literature review in Section II that provides the basis for our decision on the EoR and the associated ET. The research method given in Section III includes the steps of SLR followed by multiple case studies, each with its own distinct characteristics. Section IV gives a discussion of the findings, which commences with the identification of key ET supported by empirical data, whereas theoretical insights from the SLR are used to underpin the analysis and develop the research framework given in Section V. Finally, Section VI concludes this article.

II. LITERATURE REVIEW

Internal and external factors constantly challenge the stream of operations at the supply chain level. Therefore, supply chains must adapt continuously, learn from their failures, and seek opportunities for ongoing improvement. While some experts argue that information systems were previously too weak to support supply chain resilience strategies effectively [19], recent technological advancements in Industry 4.0 may have changed this outlook [2], [20].

Pereira et al. [5] defined supply chain resilience as an organization's ability, along with its supply chain, to effectively build capabilities for anticipating, adapting, responding, recovering, and learning from disruptive events through resource management. To address these disruptions, organizations must develop capabilities, which can be achieved by focusing on EoR. Although authors may differ in defining these elements, the majority of them (including well-cited papers such as [21], [22], [23], [24], [25], and [26]) agree on the 13 following EoR: agility, collaboration, financial strength, flexibility, information sharing, knowledge management, redundancy, risk management, robustness, security, supply chain design, trust, and visibility. These are the elements of EoR addressed in this study.

Zhang et al. [27] highlight ET as vital tools for mitigating risks and managing disruptions. Aheleroff et al. [28] suggested that Industry 4.0 (I4.0) technologies, such as the use of augmented reality in manufacturing, increase agility and reproducibility. Bécue et al. [29] even noted challenges in human-machine collaboration despite benefits such as safety and effectiveness from digital twins. Thus, the debate on digital I4.0 technologies may include a variety of existing technologies that are currently applied to businesses. This article adopts the categorization of ET presented by Rüßmann et al. [30] and Danjou et al. [31], defining 12 groups of technologies used in I4.0: Internet of Things (IoT), cyber-physical systems, artificial intelligence (AI), cloud computing (CC), Big Data (BD), augmented reality, cybersecurity, systems integration, simulation, autonomous

TABLE I
GROUPS OF ET AND POTENTIALLY RELATED TECHNOLOGIES

Groups of ET	Potentially related technologies
Additive Manufacturing	3-D printing
Artificial Intelligence	Machine Learning, Neural networks, Bayesian networks
Augmented Reality	Hardware
Big Data	HPCC, Hadoop-yarn, HPC,
Cloud Computing	Infrastructure as a Service (IaaS)
CPS	Sensors, Actuators
Cybersecurity	Blockchain, VPN, DNSSEC, TLS, PIR, P2P,
Internet of Things	RFID, QR code, Network, WSN, RSN,
Machine Autonomy	Robots
Machine-to-Machine Communication	DLNA, UPnP, IGRS, TCP/IP
Simulation	Digital twins
System Integration	Electronic Data Interchange (EDI)

machines, machine-to-machine communication (M2MC), and additive manufacturing.

This categorization includes some well-known technologies. Table I lists some of these technologies without intending to be complete and exhaustive.

III. RESEARCH METHOD

This research is classified as exploratory and seeks to investigate an underexplored topic within the literature [32].

The research question addresses “how ET can support the development of resilient operations at the supply chain level.” For this purpose, this study integrates two main research methods: an SLR and a multiple case study. Fig. 1 shows the main steps conducted in this study.

A. Systematic Literature Review

According to Tranfield et al. [33], an SLR allows the researcher to portray and explore the existing intellectual field on a given topic. The results can help researchers deepen their knowledge of a specific topic, considering that this method's process is composed of structured phases to ensure consistent, robust, and replicable results.

1) *Planning the Review*: This stage includes the definition of the review question and the protocol to be executed to address the research problem. The SLR protocol (see Table II) synthesizes the phases and steps adopted by this study, which followed guidance provided by Tranfield et al. [33] and Denyer and Tranfield [34]. The sole review question (How do companies use ET to build resilience?) aims to investigate what is known in the literature about the relationship between the use of ET as a factor in building resilience in business operations and their supply chains.

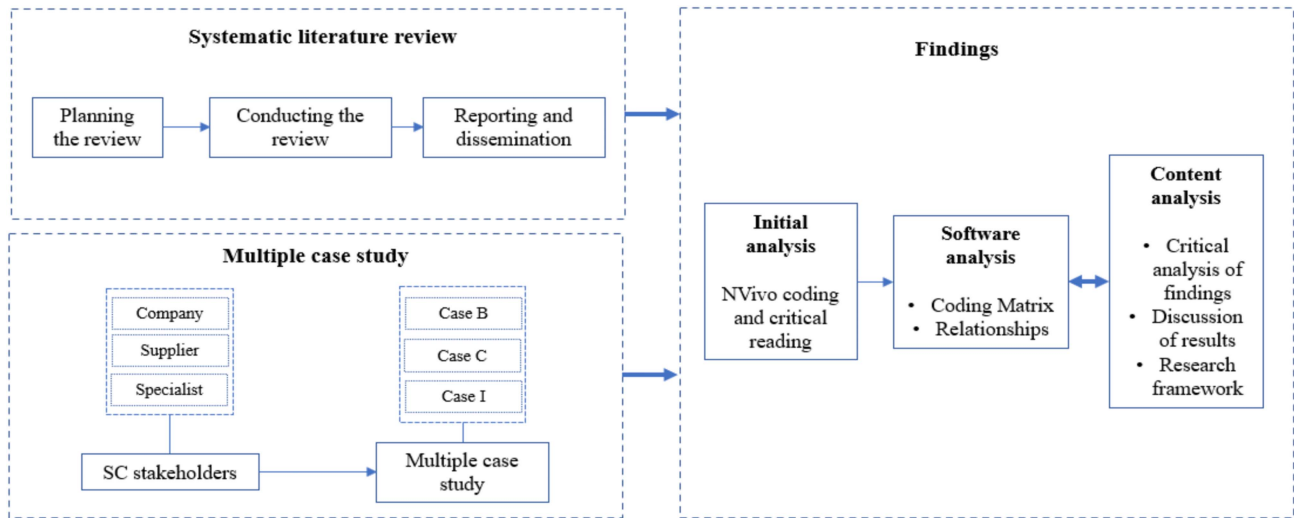


Fig. 1. Research design.

TABLE II
SLR PROTOCOL

STAGES	STEPS	DETAILS
Planning the review	Strategy to identify the studies	identification of constructs (see Table III) definition of keywords (see Table III) development of search strings (see Table III) search on two large databases on operations and supply chain management area: EBSCO and Scopus search period: 13 years (2011 – 2024)
Conducting the review	Selection of studies	First screening: Title, abstract and keywords Second screening: Introduction and conclusion reading Third screening: Fully read the selected articles and evaluate them against RQ1 Use of NVivo software to encode and organize content to answer RQ1 Critical analysis of the content of the selected articles through cross-referencing the codes (ET and EoR)
Reporting and dissemination	Analysis and synthesis Presentation of data	Answer review question based on what has been discussed and presented in the literature

For each construct, a list of keywords was created to address a wide range of concepts, especially those related to ET. This was done by checking the keywords of articles in the area of digital and Industry 4.0 technologies (e.g., [30] and [31]) and EoR (e.g., [23], [24], and [26]). Although it is important to consider the variety of terms associated with ET, we chose to search for the umbrella terms that encompass a more significant number of technologies, as presented by Rüßmann et al. [30] and Danjou et al. [31], as categorized in Table I. Following the creation of a comprehensive search string (see Table III) covering key concepts in this study, tests were conducted in both the EBSCO and Scopus databases prior to the initial screening. These databases were chosen because of their comprehensive coverage of scientific subjects and regular updates [35], [36] as well as their robust resources for conducting and refining search results [36], [37].

This study includes articles published over a 13-year period starting in 2011, recognizing that the term “Industry 4.0” was first mentioned at the Hannover Fair in 2011 [38]. The review prioritizes peer-reviewed articles to ensure credibility and robustness [34].

2) *Conducting the Review:* After the search strings were applied to each database, three screening steps were utilized to select the articles, as detailed in Table II. Out of 171 articles in Scopus, only 15 remained relevant after all three filters were applied. Similarly, out of 100 articles in EBSCO, only 12 passed the third filter. Despite the considerable number of articles published on technologies and resilience, our focus was on those directly contributing to addressing the review question, as advised by Tranfield et al. [33]. Following the screening process, only 19 articles were deemed pertinent for addressing the review question. At this stage, the use of NVivo software facilitated the

TABLE III
CONSTRUCTS, KEYWORDS, AND SEARCH STRINGS

CONSTRUCTS	KEYWORDS	SEARCH STRINGS
	Resilien* (Resilience, Resilient)	
	Additive Manufactu* (Manufacturer, Manufacturing)	
	3-D Print* (Printing, Printer) Augmented Reality	
Resilience	Autonomous Robot* (Robot, Robots)	((resilien*) AND ("Industr* 4.0" OR "I4.0" OR "4th Industrial Revolution") AND ("3D print*" OR "additive manufact*" OR "augmented reality" OR "autonomous robot*" OR "big data" OR "data analytic*" OR "cyber security" OR "systems integration" OR "simulation" OR "cloud manufacturing" OR "cloud" OR "Internet of Things"))
Enabling technologies	Big Data Data Analytics Cybersecurity	
	SI Simulation	
Industry 4.0	Cloud Manufactur* (Manufacturing, Manufacturer)	
	Cloud	
	Internet of Things	
	Industr* (Industry, Industries) 4.0 OR I4.0, Fourth Industrial Revolution	

reading and comprehension of the content by coding the EoR and enabling the technologies discussed in the papers—a critical factor for the inclusion and exclusion criteria. The qualitative analysis was further aided by identifying cross-references to establish relationships between ET and EoR.

3) *Reporting and Dissemination*: The final stage consists of the analysis, synthesis, and representation of the results. The EoR presented by Karl et al. [25] and Costa et al. [26] inspired the development of a code list. In the same vein, codes pertinent to ET within the context of Industry 4.0 were inspired by the umbrella terms listed by Rüßmann et al. [30] and Danjou et al. [31]. The outcome of these data supported the development of the research framework discussed in Sections IV and V.

B. Multiple Case Studies

On the basis of these theoretical results, a multiple case study was then performed to investigate the nature and complexity of the empirical phenomena through semistructured interviews and documents in the private and public domains [39]. The first case involves a large agribusiness company that manages a cooperative of agricultural producers in an emerging economy context (Brazil). The second case describes a pet food production company in Canada (developed economy context), centered around a small company. The third case, also in a developed economy context (Italy), describes a multimodal transport company focused on the management of integrated road–rail modal exchange platforms.

The first two case studies refer to a traditional product supply chain involving the gathering of raw materials, acquiring materials, processing, and distributing to end consumers. In both cases, the supply process involves external companies, which supply/demand raw materials and ensure the distribution and transport of the final product to the end market, highlighting the

collaborative nature of supply chain management. The third case refers to a logistic Italian company that ensures and promotes the strengthening and development of the rail system for different types of goods. In this case, the supply chain involves supplier management, order processing, transport, customer service and return management. The rail system plays a crucial role in this supply chain, allowing for the efficient transport of a variety of goods.

Collecting data from multiple sources allows the researcher to obtain a more comprehensive view of the historical and behavioral data of a given organization [32]. Therefore, although the core businesses of the three companies identified are very different, their selection was planned to investigate how different businesses of different sizes and locations (operating in countries with very different social, political, and demographic conditions) use ET to build resilience in their supply chain operations. In particular, the eligible criteria supporting the choice are focused on the identification of companies supported by supply chains that are more product-oriented (Brazil and Canadian companies) and service-oriented (Italian companies) and operating in countries with very different social, political, and demographic conditions. Consistent with this, the study identified how ET can help build resilient operations throughout globalized supply chains independently of external factors. The cases complement each other by providing a broad view of the food sector and nonfood sector in nonrelated networks and commercial activities.

Although the interviews were mostly conducted with individuals within these core companies, an interview questionnaire was developed to capture their understanding of operations at the supply chain level (see Appendix A). In addition, supply chain experts (with more than 15 years of experience in supply chain operations) were consulted during the case studies to provide a broader understanding of the use of ET to build

TABLE IV
CASE STUDY DETAILS

CASE	GEOGRAPHIC LOCATION	BUSINESS SECTOR	NUMBER OF EMPLOYEES	ECONOMIC CONTEXT	PRODUCT PORTFOLIO	ANNUAL REVENUE
Case B	Brazil (South America)	Agribusiness	~1630 employees and 680 cooperative members	Emerging economy	Six categories (seed, food nutrition, barley, oil, flour, and cereals)	US\$ 1.2 billion
Case C	Canada (North America)	Pet food	21	Developed economy	Dog food	US\$4 million
Case I	Italy (Europe)	Multimodal transport	25	Developed economy	Integrated roadrail modal exchange platforms	US\$5 million

TABLE V
CONSTRUCTS, KEYWORDS, AND SEARCH STRINGS

CASE	INTERVIEWEES' POSITION	INTERVIEW DURATION	SOURCE OF INFORMATION	COMPANY SECTOR
B	Information Technology and Systems Coordinator	46 min	 	Agribusiness
	Logistics Coordinator	35 min	 	
	Strategy Analyst	51 min	 	
	Marketing Coordinator	41 min	 	
C	Financial Manager (supplier)	42 min	 	Health, nutrition, and bioscience
	Chief Product Officer	52 min	 	Pet food industry
	Senior Account Manager	53 min	 	Logistics solutions
	Scientific Affairs Manager	38 min	 	Pet products
I	CEO	~45 mi		Logistic solutions
	Planning Manager	~45 mi		Intermodal trucking
	Senior Designer	~45 mi		Railway maintenance
-	Supply Chain Expert (1)	53 min	 	Oil, gas, energy management, and consulting
	Supply Chain Expert (2)	56 min	 	Consulting, automotive supply, and civil construction

Note:  (documented interviews; nonauthorized recording) and  (recorded and transcribed interviews).

resilience in supply chain operations. The interview scripts from the experts and secondary data from the organizations embedded in these case studies were used to triangulate the data analysis.

The cases vary in terms of economic sector, development context, geographical location, and company size, offering a rich dataset for generalization (see Table IV).

Table V details the interview participants across the three cases and the supply chain experts. For confidentiality reasons,

the cases were identified using the initials of the respective countries: Case B for Brazil, Case C for Canada, and Case I for Italy. The two supply chain experts were denoted as SC specialists. Each interview lasted approximately 30–45 min and adhered to the interview protocol outlined in Appendix A. Most interviews were authorized to be recorded and subsequently transcribed to facilitate content analysis. In addition, any notes, observations, and ideas were carefully documented and incorporated into the case study database.

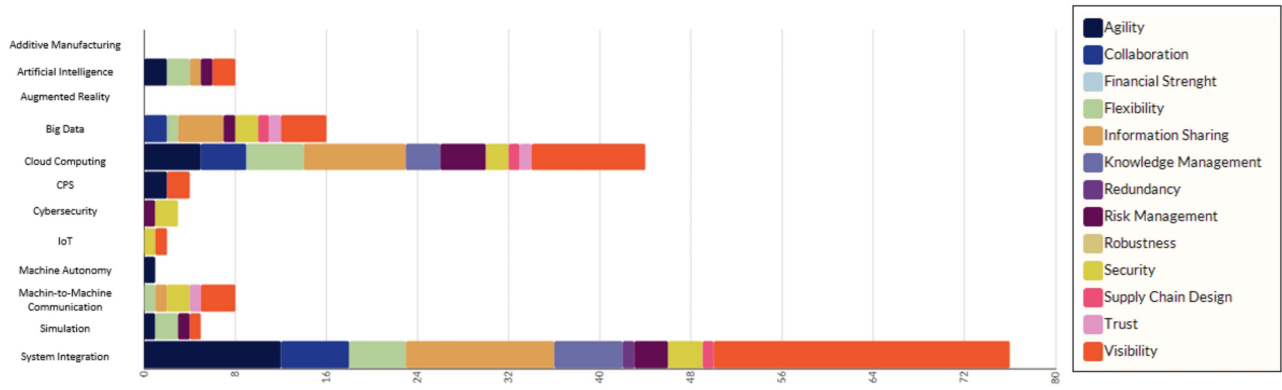


Fig. 2. Empirical relationship between ET and EoR.

TABLE VI
SUMMARY OF FINDINGS FROM EMPIRICAL DATA (SUPPORTED BY EXTANT LITERATURE)

GROUP OF ET	INTERVIEWEES' POSITION													OBSERVATIONS
	AGILITY	COLLABORATION	FINANCIAL STRENGTH	FLEXIBILITY	INFORMATION SHARING	KNOWLEDGE MANAGEMENT	REDUNDANCY	RISK MANAGEMENT	ROBUSTNESS	SECURITY	SUPPLY CHAIN DESIGN	TRUST	VISIBILITY	
System integration (SI)	x	x		x	x	x		x		x			x	SI enables data centralization, which enables automatic dashboards (visibility and information to support knowledge management), which allows for faster decision-making (agility and flexibility). In addition, data can more easily be shared along the supply chain (information sharing and collaboration) and allow for geopolitical derisking (risk management and security) during the pandemic crisis
Cloud computing (CC)	x	x		x	x	x							x	CC enhances documentation generation ('visibility'), reading and sharing ('information sharing'), which enhances tacit knowledge diffusion ('knowledge management'), remote work collaboration throughout the supply chain and procedural flexibility.
Big data (BD)		x			x					x		x	x	Among other benefits, BD enables the use of product passports, which enhances visibility, information sharing and security throughout the supply chain. In the same vein, this enhanced traceability increases trust within the supply chain.
Machine-to-machine communication (M2MC)										x			x	M2MC-enabled tracking and tracing systems can identify disruptions and revise schedules, enhancing the visibility and security of supply chains.
Artificial intelligence (AI)	x			x									x	AI can be used to generate intelligent dynamic dashboards that can be customized ('flexibility') to optimize operational agility and visibility to external stakeholders. It is also helpful for intelligence purposes, especially for forecasting.

The data analysis was carried out via NVivo software, following the procedures outlined by Voss et al. [39]. All transcripts were added to the software for coding on the basis of the codebook developed through a review of the literature. Additional codes were derived from the actual data through reading and coding. Finally, a code matrix was created by correlating the references to ET with the EoR.

In Section IV, we delve into the findings of this stage. Since not all ET were thoroughly identified in the empirical cases, we utilized the ABC analysis (Pareto Principle) to prioritize the discussion and ensure that the study's validation remained consistent [40]. As a result, Section IV empirically examines five ET that accounted for 80% of the codifications (see Fig. 2). Furthermore, the section extends the discussion to the remaining ET with the support of the SLR outcomes. The results from this section (see Tables VI and VII) are integrated into our research framework, which is explored in Section V.

IV. FINDINGS AND DISCUSSION

Fig. 2 (generated by NVivo software) illustrates the relationship between EoR and ET, which were identified through the interviews (see Table IV). Among the ET, systems integration had almost double the number of coding references compared with CC, followed by BD, M2MC, and AI. Five others (simulation, cyber-physical system (CPS), cybersecurity, IoT, and machine autonomy) had some inputs, but not enough to draw any conclusions. The remaining two (augmented reality and additive manufacturing) were not mentioned at all.

This section discusses all ET, albeit in a different manner. Section IV-A-IV-E present empirical findings from the interviews, linking them with the literature identified in our SLR. Although the remaining ET were not empirically observed, their relationship with EoR is explored in Section IV-F-IV-L, on the basis solely of the SLR findings. Throughout these sections, the

TABLE VII
SUMMARY OF FINDINGS FROM SLR

GROUP OF ET	INTERVIEWEES' POSITION													OBSERVATIONS
	AGILITY	COLLABORATION	FINANCIAL STRENGTH	FLEXIBILITY	INFORMATION SHARING	KNOWLEDGE MANAGEMENT	REDUNDANCY	RISK MANAGEMENT	ROBUSTNESS	SECURITY	SUPPLY CHAIN DESIGN	TRUST	VISIBILITY	
Simulation				x				x			x		x	Simulation technologies allow companies to test different scenarios, which provides flexibility to decision-making and boosts supply chain design. They also enable digital twins/shadows that provide visibility to abnormalities and, therefore, contribute to risk management.
Cyberphysical systems (CPS)		x		x	x				x					Interconnected devices (the core of a CPS) improve supply chain robustness through information sharing and collaboration. The potential of reconfiguring a supply chain based on real-time data provides flexibility to overcome periods of crises.
Cybersecurity					x				x	x		x		Cybersecurity provides robustness and security to all collaboration based on information sharing. It is a prerequisite to benefit from all industry 4.0 advancements; otherwise, it compromises the trust of the system.
IoT					x			x					x	IoT provides systems with visibility in several aspects, including information about product usage and supply chain logistics through information sharing. When combined with AI, IoT-provided data can be used to predict failures and accidents, contributing to effective risk management.
Machine Autonomy (MA)	x			x						x				Real-time data and data analytics combine agility to flexibility within automated systems, an advance from autonomous technologies prior to I4.0. In addition, MA reduces risks associated with human factors to zero, contributing to its security.
Augmented reality (AR)	x				x	x				x			x	AR provides a platform for information sharing in a visible way, aimed at increasing agility and security. To be implemented, it required a good knowledge management system to codify the tacit knowledge that feeds the system.
Additive manufacturing (AM)	x		x	x										AM allows for more flexible production at reduced costs (financial strength), which in some cases may justify the repatriation of production. This, in turn, contributes to more agility with a simplified supply chain and logistics.

focus is on how ET can support the development of resilience at the supply chain level.

A. System Integration

System integration (SI) is by far the enabling technology that was most cited in our sample. It consists of business software that processes, manages, and connects organization functions, such as logistics, manufacturing, and procurement [41]. *Visibility* and *agility* were the EoR that contributed to this technology's relevance. According to the logistics coordinator from the focal company in Case B, "SI adds value in the supply chain and ensures delivery to consumers by the resource planning technology that is used to automate the processing of purchase requests, facilitating the tracking and follow-up of each department's demands." To illustrate this, the logistics coordinator gives an example of his own warehouse management: "the code of the requested item is received with the order, tracking with the system on which shelf the item will be located, thus avoiding shortages, losses, or even a greater waste of time to find it." Therefore, SI can be a solution for the lack of accountability of information from which productive systems often suffer [20]. In addition, in Case C, the senior account manager states that the organized dashboard provided by the software diminishes the complexity of tracking multiple warehouse invoices, promoting agility in the process. This is confirmed by SC Specialist 1,

who perceived greater speed and integrity of the process by automating what previously required direct and time consuming manipulation of databases. All the interviewees affirmed that by facilitating the visibility of the process through SI, faster decision-making can be enhanced to respond to supply chain demands.

Information sharing was the third EoR with the highest degree of code saturation. In Cases B and C, supplier companies mentioned order entry platforms that communicate not only with the administrative sales team but also with all customers, which is possible only because of effective SI. These platforms collect business and production information and then centralize it in the integrated business management system. Similarly, the CEO of the Italian logistics company added that "the sharing capacity also enables us to monitor individual performance of administrative staff, which was convenient during the pandemic of COVID-19." This aligns with Spieske and Birkel's [16] rationale, which points out that integrating structured, semistructured, and unstructured data from different sources into processable information enables proactive response planning and reactive real-time control.

Finally, the SC Expert provided an example where the use of SI enables a rich diversity of EoR simultaneously. The integrated management platform allows for geopolitical *risk management* of suppliers by country of operation. The system conducts a thorough investigation of the supplier's financial background

before registration. Once registered, the portal transmits the supplier's risk on the basis of geopolitical criteria, such as its location in relation to other members of the supply chain and the political stability of the country in which it is located. This evaluation provides the company with *visibility*, *flexibility*, and *security* through the concentration of important variables for decision making, which consequently feed into *knowledge management* and *collaboration*. In times of turbulence, the company can choose to hedge or strengthen its supply chain on the basis of the risk presented by the platform. However, despite the benefits offered by the strategy, the interviewee noted that its maintenance demands a deep qualitative analysis that loses value over time. Therefore, it is up to the company to decide if it has the necessary resources to maintain such functions of the technology.

B. Cloud Computing

CC offers a remotely accessible environment for storing, sharing, and accessing computing resources such as data repositories and network service applications with high reliability, dynamicity, and scalability [42], [43]. For this technology, *visibility*, *information sharing*, *flexibility*, *agility*, and *collaboration* were the EoR that had an impact on resilience development, which coincides with the advantages presented by Rodríguez-Espíndola et al. [42].

In Case B, faced with dissatisfaction about the efficiency of documentation processes, the Strategy Analyst reports difficulty in processing the sector's *knowledge management*. The interviewee commented that *"although the reports are documented at the end of each process, consulting them causes an unnecessary waste of time given the possibility of scanning and sharing them virtually."* This technology benefits the company because its production processes are dynamic and require constant adaptations that present a mismatch with the pace at which they are documented by management. According to the same interviewee, *"cloud computing could avoid disruptions if employees take tacit knowledge with them."* This statement is validated by the capability presented by Rodríguez-Espíndola et al. [42], specifically that this technology ensures data availability, backup, and secure and safe storage. Digitally documenting the critical paths encountered by employees could increase their process visibility and risk management capability, facilitating preventive management of disruptions to the process.

This capability is validated in Case C and by SC Specialist 2. During the COVID-19 pandemic, managing hundreds of units across 12 parallel construction sites via traditional methods became impractical. To address this, the company digitized its communication through CC-integrated business management systems. This transition allowed the company to operate remotely and collaboratively without altering existing processes, demonstrating the flexibility and agility provided by CC. According to the senior account manager, this cloud-based approach enables managerial processes to extend beyond the company's physical sites.

In addition, SC Expert 2 highlighted that CC-enabled business intelligence tools were crucial in visualizing and determining

the critical path during the pandemic's disruptions. In the construction industry, where each site operates like an independent company, the expert noted that before the adoption of CC tools, purchase requisitions were manually filled out on paper. The shift to digital tools streamlined operations and provided essential insights during a challenging period.

C. Big Data

BD is enabled by high volume, velocity, variability, and variety and is capable of visualizing data to create value for consumers and business organizations [44]. The most present EoRs in relationships with this technology were *visibility*, *information sharing*, and *security*.

One aspect mentioned in Cases B and C is the use of a product passport that keeps all its technical details, allowing traceability of its steps until it reaches the final consumer. This, therefore, facilitates not only the *visibility* and *information sharing* of the entire process but also the security of its transportation. Thus, this capacity provided by the technology could directly address the concerns of the IT and systems coordinator. According to the planning manager in Case C, *"the full digitalization of the communication has been propelled by the constraints imposed by the pandemic of COVID-19, especially, for cargo and shipment management."* This statement is particularly interesting because it shows that the crisis accelerated the company's transition to more intensive use of data, which in turn allowed the company to benefit from BD.

In the context of tracking, the use of BD can increase *collaboration* among companies throughout the supply chain. For the focal company's malt shipments in Case B, this technology can provide detailed information about the crop, including its origin, region, and the environmental standards under which it was harvested. This tracking service offers crucial information that can be a key link between companies. This helps them understand the process better, leading to improved collaboration. As a result, companies can align customer deadlines with environmental and quality requirements more effectively.

D. Machine-to-Machine Communication

M2MC refers to technologies that allow computers, embedded processors, sensors, smart devices, and mobile devices to communicate, collect measurements, and make decisions without the need for human interaction [45]. In our sample, M2MC relates primarily to *visibility* and *security*.

Returning to the tracking capability and its opportunity for malt loads mentioned in the previous subsection, another example given is the use of transmitters to indicate the location of work tools. This M2MC-enabled feature makes these work tools traceable and safe. This finding resonates with the conclusions of Ivanov et al. [46] that M2MC-enabled tracking and tracing systems and feedback control can be effectively used to identify disruptions and help with revising initial schedules.

In this sense, embedding SC visualization through record-keeping can enhance the logistics systems in Cases B and I. For example, it can help prevent or quickly respond to instances of malt load loss in Case B. However, the interdependent

relationship between tracking and the two ET requires implementing BD tools before M2MC. This highlights the interconnectedness of Industry 4.0 technologies, as emphasized by several recent studies (e.g., [20], [47], and [48]).

E. Artificial Intelligence

AI is a key tool for supply chain management if it can autonomously make decisions that lead to successful outcomes in a partially unknown SC environment [49]. For this enabling technology, *visibility*, *agility*, and *flexibility* are the EoR that stood out from the interviews. According to the strategy analyst in Case B, the company presented difficulties in managing the changes caused by cost cuts and customer mapping during the pandemic crisis. For this purpose, SC Experts highlighted two examples of the use of AI.

First, AI can be employed for the construction of dashboards that emerge from the SI. The intelligent algorithm dynamically optimizes the *visibility* of data related to the production process as performance indicator dashboards. This feature is presented in Case C, where the Senior Account Manager states that “*the report that I am most interested in is financial performance, which is easily accessed and automatically calculated in our transportation management system,*” promoting the company’s *agility* and *flexibility* in reporting its performance to clients.

The second example showcases a technology that automatically predicts monthly sales for an oil brand with over 150 000 points of sale across Brazil. This tool supports decision making with 93% accuracy by analyzing the profile data of local residents and buyers. The insights gained from this marketing intelligence are also applied to supply chain management, helping to identify and define the location and nature of demand. Since the marketing analyst in Case B highlights the company’s beers as flagship products, this mapping could be adapted to identify the geodemographic and socioeconomic profiles of consumers at the end of the supply chain.

F. Simulation

Digital simulation was not extensively discussed in the interviews, limiting our ability to draw empirical conclusions. However, the SLR provided valuable insights. Innovations driven by Industry 4.0’s digital simulation technologies enhance the ability to model products and predict production behavior via real-time data. This technology is particularly powerful for enabling digital twins and digital shadows, which can anticipate bottlenecks and failures (thus improving robustness) and improve decision making through the simulation of different scenarios [50], which provides *flexibility* and enhances *supply chain design*.

In this context, managers can incorporate information-gathering tools such as the IoT to analyze historical data and predict future impacts and reactions, thereby optimizing strategic and logistical decisions, such as enhancing contingency plans and *risk management*. Similarly, Eirinakis et al. [51] propose a theoretical model that promotes organizational resilience by

improving visibility through the identification of abnormalities in physical systems.

G. Cyber-Physical System

The SLR results reveal that several authors discuss emerging trends in cyber-physical system technologies. Fraga-Lamas and Fernández-Caramés [52] noted the potential for interconnected devices (e.g., their sensors, control units, and wireless adapter devices) to monitor their operations and facilitate communication with other technologies through *information sharing* and *collaboration*. Such functionality could be leveraged by companies to optimize stock replenishment routes in their supply chains, thereby enhancing *robustness*, and consequently, resilience in the face of disruptive crises.

Moreover, Ivanov et al. [46] who also claim that the future of industrial networks is through the collaboration of CPSs, describe joint production stations capable of changing their operational processing and sequence configurations according to demand and production capacity, facilitating company *flexibility*. This example highlights the possibility of configuring the assets purchased on the basis of the reputation indices and demand and production capacity situation.

H. Cybersecurity

Despite the benefits of data sharing proposed by the Industry 4.0 IoT, Fraga-Lamas and Fernández-Caramés [52] and Spieske and Birkel [16] noted that such a concentration of data may become the target of criminal activities and malicious attacks, compromising supply chain security and trust. Considering the cybersecurity challenges mentioned in the previous topics and the conservatism of the focal company motivated by fear of exposure to threats, cybersecurity as a digital technology refers to data and information protection devices. To this end, Bécue et al. [29] cite the customized and adapted technologies used by Airbus. This company has developed different system platforms that map their objects into a network that also indicates how they are related. This map of technologies is followed by a list of attacks, incidents mapped as unintentional and intentional, and models and simulations of the technological operation capability to increase *robustness*. Aheleroff et al. [28] and Fraga-Lamas and Fernández-Caramés [52] call attention to the unexploited potential of blockchain technologies to enable cybersecurity and state that blockchain technologies present security risks due to the lack of skilled labor. To this end, Fraga-Lamas and Fernández-Caramés [52] describe interactive activities that benefit those who find flaws in the system amid simulations of cyberattacks. In their example, these authors note that *information sharing* is used among companies to combat such attacks.

I. Internet of Things

IoT devices facilitate the capture and collection of data that provide visibility and, in turn, possibly provide some solutions for the focal company within a supply chain. In the

face of globalization, digitalization, and personalization, IoT-based technologies are responsible for monitoring and controlling devices remotely to explore alternatives from real-time data [52]. IoT-supplemented mask production, explored by Ahleroff et al. [28], demonstrates that its use also assists in enabling companies to achieve their personalization goals through the sharing of information about product usage. It can also improve risk management when combined with AI because of its capacity to predict accidents or failures via real-time data, as Fraga-Lamas and Fernández-Caramés [52] observed in the automotive industry. The same applies to supply chain management, as IoT technologies provide *visibility* within supply chain logistics.

J. Machine Autonomy

Machine autonomy has the potential to eliminate accidents caused by human factors, which are often the leading cause of accidents [29], [52]. This presents a significant opportunity to enhance security within systems, including supply chains. Spieske and Birkel [16] emphasized the potential for autonomous machines to reduce potential human error and mitigate health risks for workers, particularly in crisis situations such as the COVID-19 pandemic.

Bécue et al. [29] discuss the use of autonomous machines to facilitate complementary EoR. The authors highlight that Industry 4.0 factories offer preventive and reactive capabilities against physical and cyber threats, utilizing automatic reconfiguration as part of autonomous machines' capabilities. By monitoring activities and generating data, these machines can automatically adjust their programming to optimize processes in the event of a disruption, promoting flexibility and agility. The potential for implementing this capability is demonstrated by the IT and systems coordinator, who discusses the fully automated malt production at Company B. The authors emphasize the potential benefits of implementing autonomous machines.

K. Augmented Reality

Augmented reality technologies can instantly overlay information on the physical environment. According to Ahleroff et al. [28], augmented reality enables a differentiated customer experience whose personalization follows users' interests. In the production environment, augmented reality is often associated with manufacturing or maintenance operations. In these operations, instructions on how to perform a task are overlaid on the place where the task must be accomplished. This is intended to increase workers' agility and safety [53]. In the context of the pandemic crisis, this technology was particularly useful for worker training [54] and customer experience [55] during social distancing because of its potential to *share information* and provide *visibility* without personal contact. However, implementing it requires a good *knowledge management* system to codify tacit knowledge to be embedded in the system [53].

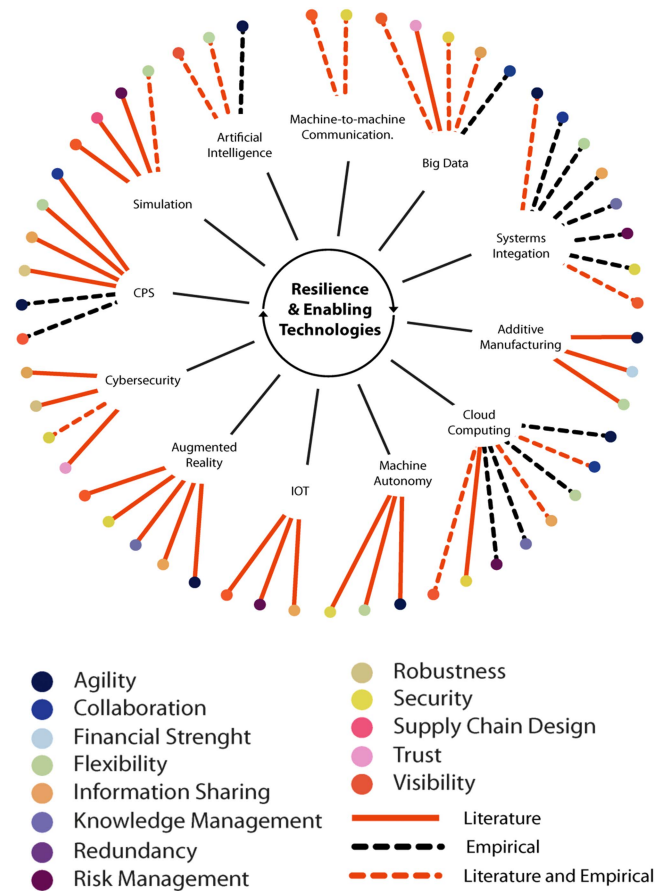


Fig. 3. Research framework (resilience and ET).

L. Additive Manufacturing

The integration of additive manufacturing (AM) in supply chain management has a significant effect on two EoR: *flexibility* and *agility*. In a study focused on the sportswear industry, Ivanov et al. [46] reported that the adoption of AM equally enhanced both aspects. While the contribution of 3-D printing to increased flexibility is quite straightforward, its impact on agility is less intuitive. Surprisingly, 3-D printing played a role in repatriating production, enhancing autonomy, and simplifying the supply chain and logistics, thereby contributing to agility. Furthermore, recent research by Ahleroff et al. [28] highlighted that AM has the potential to be implemented on a larger scale at a reduced cost, thereby enabling greater *financial strength*. Although AM can decrease the need for inventory risk mitigation and reserve capacity due to its complexity, it is crucial to consider that exposure to outages could lead to more pronounced instances of the bullwhip effect.

V. RESEARCH FRAMEWORK

Drawing upon the empirical and theoretical results, Tables VI and VII summarize the discussion in the previous section, and Fig. 3 illustrates our research framework. To ensure consistency and internal validation, the research framework included

theoretical findings from the SLR and empirical findings validated by the discussion previously.

The most discussed EoR included agility, flexibility, information sharing, security, and visibility, which were found across the 12 groups of ET. All 13 EoR were associated with at least one enabling technology, except redundancy, which was not mentioned at all. Furthermore, only ET identified more than once in the interviews and in the literature are included in Fig. 3. As a result, four groups of ET lacked empirical support (IoT, augmented reality, machine autonomy, and additive manufacturing) in our study. On the other hand, the contributions of many EoR have been empirically identified in systems integration and CC, as illustrated in Fig. 3. Findings from these three cases (an agri-food company in Brazil, a manufacturing company in the food industry in Canada, and a logistics service in Italy) can also be subjected to market conditions, countries' economic development and the digital transformation maturity of each business. SI and CC were two relevant ET identified in all three cases but significantly discussed in Case C. The interviewees were confident in discussing how beneficial these two technologies are in supporting their operations, since they received raw material supplies (e.g., sweet potatoes, which are a common ingredient in pet food) to package final pet food and ship to customers in Canada or abroad. They mentioned that pet food demand intensively increased after the pandemic.

Therefore, SI ensures seamless coordination across various stages of pet food production, from sourcing ingredients to distribution, enabling companies in Case C to maintain high standards and efficiently manage complex supply chains. CC, on the other hand, enhances data accessibility and real-time decision-making, fostering innovation and allowing businesses to respond swiftly to market demands and consumer trends. As a leading country in terms of technology adoption, Case C (Canada) showed intensive use of these technologies to underpin their competitive advantage in the global pet food market.

BD emerged as a significant focus in Case B, where it was extensively discussed by the IT analyst. In contrast, it was only briefly mentioned in Case C and entirely absent from the discussions in Case I. The interviews suggest that Case B is at the forefront of BD adoption, with substantial efforts being made to integrate and develop this technology within its operations. Notably, Case B involves one of the largest companies among those studied, yet it operates within Brazil's agribusiness sector, which remains in a developmental stage. As the Strategic Coordinator noted, many agricultural producers (cooperative members) are old-fashioned and not fully accustomed to new technologies, highlighting a potential barrier to widespread technological adoption in this context.

AI was found to be present in Cases B and C but not in Case I. In Case B, there was a discussion on how essential AI is for business and the efforts being made to fully implement it. For example, by analyzing historical data, algorithms can provide insights and strategies to improve financial outcomes for cooperative members, thereby increasing profitability for

cooperative members. In addition, by understanding data and market trends, AI can help identify opportunities to enhance product sales, ultimately contributing to overall profitability.

Overall, Case C demonstrated significant utilization of ET at both the organizational and supply chain levels, likely driven by the country's advanced technological development and growing market demand. In contrast, Case B showed considerable effort in adopting these technologies to enhance operational resilience in the supply chain, but it is not as advanced as Case C. This disparity may be attributed to the sector's status in Brazil; despite being a cornerstone of the economy, it remains underdeveloped [56]. In addition, Case B's reliance on cooperative members, who often lack interest in innovation and the capital to invest, further limits progress. SI and CC in case C are not broadly adopted. Generally, both technologies in this business are adopted to track information management systems to support the whole range and provide the goods' position in real time and, in some cases, their physical conditions (e.g., temperature, humidity, etc.). The Italian company's business does not adopt these technologies according to these potentialities, since the kind of goods transported, as well as the transport units adopted (prevalence railway), do not require these technologies. Moreover, the investment needed to implement both ET is very high for an SME. Therefore, in Case C, CC and SI are used to track the location of their truck (adapted for transporting the goods in the last mile), manage their maintenance schedules, and optimize their routes by reducing maintenance costs and improving track uptime. Consistent with this strategy, the company is working to integrate geographic information system CC and GPS systems to implement an innovative vehicle traffic management system. Although technologies are available, the infrastructure cost currently represents a major challenge for SMEs.

VI. CONCLUSION

Supply chains need to adapt constantly, learn from their failures, and seek opportunities for continuous improvement. In this context, internal and external factors constantly challenge the stream of these chains. Although scholars claim that information systems are too weak to support resilience strategies effectively in supply chains [19], technological advances in Industry 4.0 may have changed that perspective [2], [20].

This study extended the literature that discusses how ET can support the development of resilience in supply chain operations. In doing so and aiming to bridge the gap highlighted by Spieske and Birkel [16] concerning the lack of empirical studies that explore the relationship between I4.0 technologies and supply chain resilience, findings from three case studies provided some initial but insightful results.

Overall, 8 out of the 12 groups of ET were identified empirically, and 5 of them were discussed in depth within the cases. Among the 13 EoR considered in this study, redundancy was the only one not empirically observed in our sample. This absence may be attributed to the primary focus of ET, which are designed not for the mere accumulation and storage of data

but rather for enhancing the ability to identify, visualize, and analyze data across the supply chain. These technologies streamline decision-making processes related to resource management, emphasizing efficiency and agility over the traditional approach of maintaining redundant systems or resources.

SI, CC, BD, M2MC, and AI were the most coded technologies throughout the interviews and had a great impact on achieving visibility. Findings from the case studies showed that Case C presented extensive use of ET at both the organizational and supply chain levels, driven by advanced technological development and market demand. Case B, which involves efforts to adopt these technologies for supply chain resilience, lags behind Brazil in terms of its underdeveloped sector and reliance on cooperative members who resist innovation. Compared with Case C, Case I, operating in multimodal transport, showed limited adoption of ET, with some progress in systems integration and CC but less overall advancement.

To the best of our knowledge, this is the first study that explores how ET can support the development of resilient operations at the supply chain level by exploring the relationship between ET and EoR. We believe that ET, with their own functions and particularities, can support practitioners in analyzing the current supply chain situation (considering the market, economy, and location) and wisely identifying solutions to disruptive events or maintaining a steady flow and management of organizational resources. It also combines a set of ET and EoR in an integrated research framework (see Fig. 3).

In practice, the research framework can assist managers in the following two main ways.

- 1) Prompting reflection on their current technologies. Identifying each technology they are currently using allows them to consider how these technologies are contributing to resilience or how they could foster resilience through the implementation of different methods. For example, managers can explore how SI supports the development of collaboration between stakeholders and consider how this support could be enhanced. They can also discuss case studies.
- 2) Promoting the consideration of unused technologies and their potential benefits for creating resilience in the business. This research framework is a guide to how different ET could drive supply chain resilience. However, every business must consider its context, demand, and aspirations.

This research has limitations in terms of validating the research framework. Furthermore, studies could explore the framework in depth by collecting data and validating it through a larger sample, looking at the same sector or expanding it to other sectors. Moreover, exclusively theoretical relationships could be exploited in different supply chains to empirically validate such inferences. Another limitation of this study is the lack of digital maturity of the agribusiness sector with respect to the approach ET for I4.0. Thus, further studies can extend the results to more technologically equipped organizations to verify whether the highlighted EoR are also well developed in different environments and settings.

APPENDIX INTERVIEW PROTOCOL

A. GENERAL

Could you tell us about your personal experience with supply chain management and ET ?

Could you tell us a bit about the company's operations and supply chain management before the pandemic?

Were you experiencing any digital transformation improvements (technologies) before the pandemic?

B. COVID-19 Impacts

What was your overall experience like in the COVID-19 period? When did it start to affect the company's operations?

What kind of actions/practices did you (and the whole company) take in the first moment? Did you experience any particular events during the outbreak of COVID-19?

How did you react to this?

C. Recovery

Are your operations back to normal? If not, what is the current status? How long do you think it will take to recover completely? Will this improvement be constant?

What factors are/were important for the recovery? What do you think was good about your company not being shaken? Are your company's operations back to normal? If not, what stage are you at?

What is/was the role of ET for this recovery?

What kind of actions did you take to overcome this situation and recover your system?

D. Supply Chain Performance

How do you evaluate the performance of your supply chain?

Do you evaluate your supply chain performance based on different scenarios?

How do you evaluate the visibility of the information? Important? How much do they apply? Do you evaluate the operational risks that threaten the supply chain?

Do you consider the digital maturity of the company as beginner, intermediate or advanced compared to the supply chain?

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