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A cyclic and holistic methodology to exploit the Supply Chain Digital Twin concept towards a more resilient and sustainable future

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ABSTRACT

Recent major disruptions such as natural disasters, geopolitical tensions, Covid-19 pandemic have led supply chain managers to rethink strategies for achieving significant levels of sustainability and resilience. At the same time, new digital technologies are offering significant opportunities to increase company performance, while maintaining a high level of customer service. In this challenging context, the Supply Chain Digital Twin (SCDT) represents an emerging and promising concept, which deserves to be explored. In this paper, a holistic and cyclical methodology, based on simulation, is proposed to enable and exploit the SCDT Paradigm, with the main aim to increase sustainability and resilience of the chains. The proposed methodology is successfully tested and validated on a real case study in the agri-food sector, through the use of the anyLogistix software. The results return valuable information on the level of resilience of the supply chain in the face of any considered disruption and provide useful managerial insights on the actions to be taken to improve some performance indicators.

1. Introduction

Supply chains (SCs) are adopting novel digital technologies and paradigms to increase the overall performance. This includes the use of Artificial Intelligence (Baryannis et al., 2019; Modgil et al., 2022), Internet of Things (IoT), Digital Twins (Longo et al., 2023), Blockchain (Cole et al., 2019; Han and Fang, 2023), with the aim of improving critical aspects such as logistics, demand forecasting, warehouse management, and order processing. This trend has intensified significantly, in the wake of major recent disruptions such as natural disasters, geopolitical tensions, trade disputes, and especially the COVID-19 pandemic (Ivanov and Dolgui, 2020; Remko, 2020; Katsaliaki et al., 2021; Corvello et al., 2022; Ghadge et al., 2022; Müller et al., 2023). In this challenging context, aspects such as supply chains resilience and sustainability are becoming increasingly important (Parhi et al., 2022). From the point of view of companies, investing in resilience strategies means protecting customer satisfaction, guaranteeing the continuity of business activities, limiting the impact of disruptions, thus gaining a significant competitive advantage in an uncertain and volatile environment (Kim et al., 2015; Han et al., 2020). Supply chain managers are strongly interested in identifying disruption scenarios, understanding the level of resilience of each portion of the network, then determining actions to react in real time to any unexpected and harmful event (Psarommatis et al., 2020; Shekarian and Mellat Parast, 2021; Moosavi et al., 2022). In addition, Wieland et al. (2023) encourage managers to rethink their approach in responding to supply chain disruptions by considering resilience through three key dimensions: persistence, adaptation, and transformation. The authors recommend that managers incorporate these resilience dimensions into their operational strategies, ensuring effective management of disruptions in both short- and long-term perspectives. At the same time, there is an increasing focus on sustainability to reduce the environmental impact of supply chain operations (Wu and Pagell, 2011; Wilhelm et al., 2016; Khan et al., 2021; Tuni and Rentizelas, 2022). Final consumers are placing greater importance on sustainable and socially responsible products, leading to more transparent supply chains (Mollenkopf et al., 2022). Correspondingly, while in the past companies aimed almost exclusively at profit, today they tend to give significant importance also to social and environmental aspects (Rajeev et al., 2017; Mani et al., 2018).Fig. 1

The main purpose of this paper is to provide a holistic and cyclic methodology to make supply chains digital, sustainable and resilient. It is based on simulation to manage the disruption risks in supply chain (Ivanov et al., 2019; Ivanov and Dolgui, 2021). The holistic nature of the methodology is about enclosing multiple aspects in a single framework.

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Considering a supply chain holistically is essential to obtain a complete and integrated understanding of all phases involved in the production and distribution of goods or services. The holistic approach aims to see the entire supply chain as an interconnected system, rather than focusing only on individual isolated elements. The cyclic nature of the methodology includes the possibility of reusing it over time, in order to adjust and correct the considered supply chain, based on the current challenges. This feature of the framework is extremely critical because supply chains can be subject to unexpected changes such as market fluctuations, new regulations, political, environmental, or economic crises. Through reuse, it is possible to constantly identify areas for improvement and implement new solutions that take into account the most recent developments and lessons learned from previous iterations. Indeed, a supply chain structure, that is valid and useful today, may not be as effective and efficient tomorrow. Therefore, the proposed methodology is in accordance with the continuous improvement principles (Sanchez and Blanco, 2014). It is characterized by several steps and is tested and validated on a real case study in the agri-food sector, through the use of the anyLogistix software.

The rest of this paper is structured as follows. Section 2 explores the theoretical background, by detecting the main research trends around the Supply Chain Digital Twin (SCDT) and discussing the most relevant simulation-based approaches for supply chain management, with a focus on anyLogistix. Section 3 describes the holistic and cyclic framework proposed to enable SCDTs. Such a framework is tested and validated, in Section 4, through a real case study in the agri-food context as well as the main results of the study are discussed. The conclusions are outlined in Section 5.

2. Theoretical background

In the scientific literature, contributions related to digitization, resilience and sustainability of supply chains are growing significantly in recent years (Verdouw et al., 2016; Martins and Pato, 2019; Zavala-Alcívar et al., 2020; Spieske and Birkel, 2021; Evangelista and Hallikas, 2022; Lahane et al., 2023). In the next subsections, a state-of-the-art analysis of SCDT and simulation-based approaches for supply chain management is provided, with a focus on the anyLogistix software (anyLogistix, 2023).

2.1. The supply chain digital Twin: Research trends

The Digital Twin, which aims to create a digital or virtual replica of physical assets and processes, is one of the pillars of Industry 4.0. Psarommatis and May (2023a) propose a standardized design methodology to develop DTs regardless of the domain. The adoption of DTs is increasingly becoming a standard in industry (Psarommatis and May, 2023b) with this paradigm gaining widespread recognition, particularly in the manufacturing sector (Elbasheer et al., 2023). In manufacturing, DTs serves different purposes such as predictive maintenance (Aivaliotis et al., 2019), monitoring and control (Wang et al., 2020), training (Kaarlela et al., 2020), product design (Tao et al., 2018) and achieving

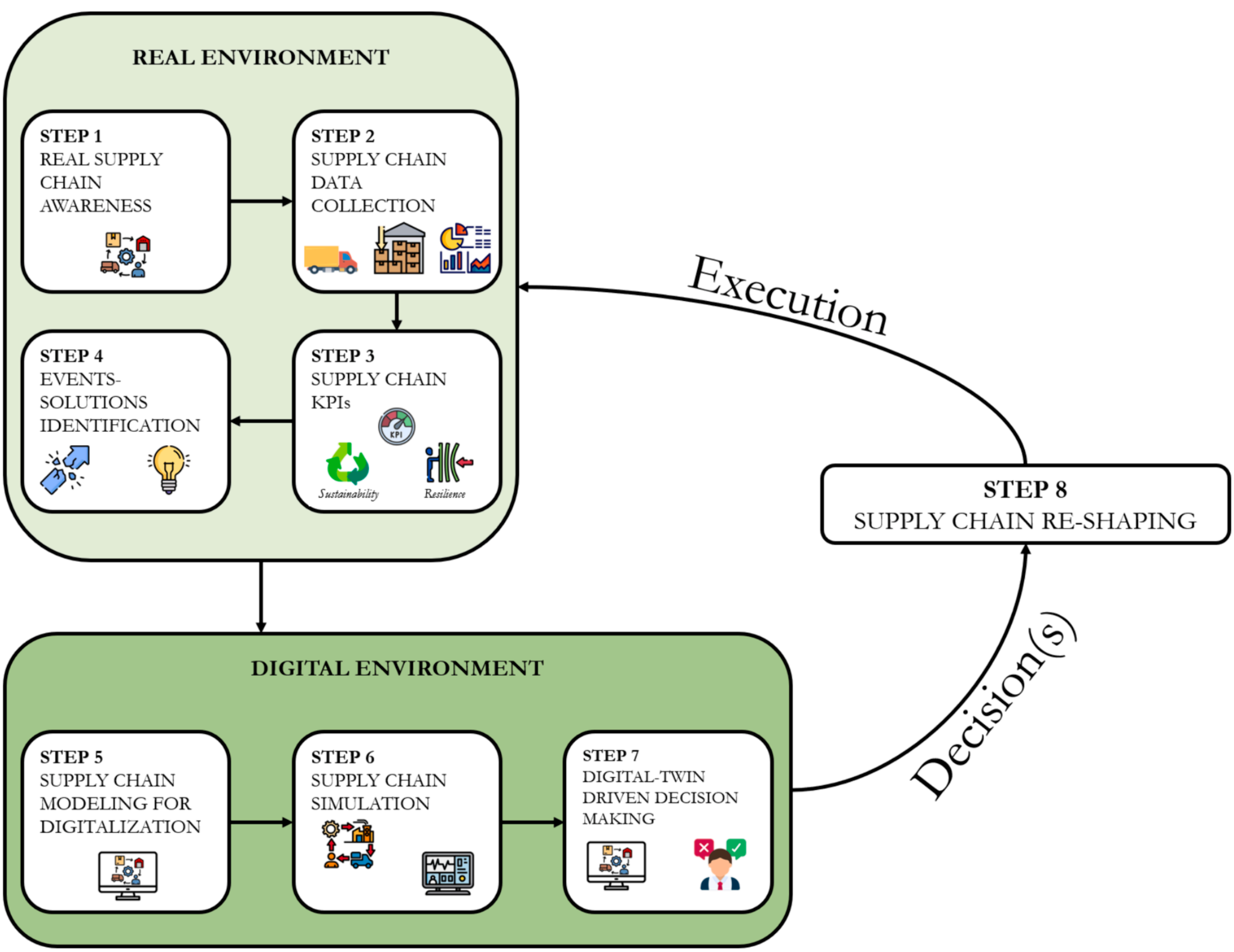


Fig. 1. Holistic and Cyclic framework for SCDT.

zero defect condition (Psarommatis, 2021; Psarommatis and May, 2023a).

The application of the Digital Twin concept to Supply Chains is instead much more recent and has begun to spread especially after the Covid-19 pandemic (Ivanov and Dolgui, 2021; Burgos and Ivanov, 2021; Park et al., 2021). This is because the scientific community is recognizing the importance of replicating supply chains in a digital environment, where it is possible to evaluate different scenarios efficiently and without risk, in order to make the best decisions in terms of sustainability and resilience. Running a query on Scopus, by using the field "Article title, Abstract, Keywords" and the words "Digital Twin" AND "Supply Chain" (filter Document type: article), what clearly emerges is the limited number of scientific contributions, which are all very recent. The first papers on this topic are dated 2018, while starting from 2020 there was a boom caused by the Covid-19 pandemic. Ivanov et al. (2019) analyze how digital technologies can support the management of disruption risks towards cyber-physical supply chains. Hence, this paradigm has been applied in several other contexts. Ivanov (2020) used a simulation-based methodology oriented to the concept of Digital Twin of a SC, in order to examine and predict the impacts of epidemic outbreaks on SC performance. Binsfeld and Gerlach (2022) highlighted the benefits of using digital twin of supply chain through a simulation study concerning an organic food supply chain. Different scenarios were simulated and their effects on logistics and supply chain management were evaluated. Burgos and Ivanov (2021) developed a discrete event simulation model using the anyLogistix supply chain software. The aim was to evaluate the level of resilience of food retail supply chains in Germany, based on the impact of the Covid-19 pandemic. They revealed significant managerial insights mainly related to inventory management. A recent research work by Ivanov (2023) claims that digital twins in supply chain and operations management are not just a simulation-based replica of a real object, but something more complex involving 7 main elements: technology, people, management, organization, scope, task, and modelling. A digital twin of a supply chain can be definitely used for various purposes such as improving decision-making in supply chains through real-time data-driven decisions (Ivanov, 2021), supporting inventory and cash management (Badakhshan and Ball, 2023), enabling end-to-end supply chain visibility and digital collaboration (Holzwarth et al., 2022).

According to Ivanov (2023), there is currently ambiguity on how to design and adopt digital twins in terms of decision-making principles and data usage. As evidence of it, to best of our knowledge there no papers proposing structured approaches on digital twin implementation of supply chain.

What clearly emerges from the study of the literature on digital twin of supply chain is that this topic is absolutely new and today of great interest and scientific relevance. However, this paradigm has not yet spread on a large-scale, although it could bring undoubted benefits to companies. Greater scientific effort is needed to confirm the goodness and usefulness of SCDT.

2.2. Simulation-based approaches for supply chain management: Focus on anyLogistix

Simulation is recognized as a powerful tool to support supply chain management (Saisridhar et al., 2023). Simulation-based approaches have always been used for several purposes such as risk management (Oliveira et al., 2019), inventory management (Akhtari et al., 2019), resilient supplier selection (Cavalcante et al., 2019), production and distribution planning (Kabiri et al., 2022), evaluation of response strategies to disruptions (Aldrighetti et al., 2019; Moosavi and Hosseini, 2021). Over the years, scholars have employed various tools for supply chain management such as AnyLogic (Muravev et al., 2021), Arena (Ravichandran et al., 2020), Flexsim (Zhang et al., 2021), Simul8 (E-Fatima et al., 2022). However, in the last few years scientific interest in anyLogistix, which is a software specifically designed to optimize supply chain networks, is growing significantly. Its main functionalities are Network Design and Optimization, Simulation and Analysis, Inventory Optimization. It also provides Supply Chain Analytics and can be easily integrated with other business software such as ERP (Enterprise Resource Planning). To give the reader an idea of the degree of novelty of this software, it must be observed that by running a query on Scopus (Search within: "Article title, Abstract, Keywords"; Search documents: "anyLogistix") only 33 documents are returned, which go from 2019 onwards. Until now, the use of anyLogistix has mainly involved facing the challenges related to the Covid-19 pandemic. Some authors have used it to improve the distribution of Covid-19 vaccines in Europe (Sun et al., 2021) and Africa (Prosser et al., 2021).

To date, only four research papers have utilized anyLogistix to address challenges within the agri-food sector, which are discussed below. Huang et al. (2021) introduced a simulation-based methodology to investigate the impact of the pandemic on food supply chains. The study specifically focused on the lobster supply in various areas of Canada, simulating real events such as facility closures, workforce shortages due to the pandemic's spread, and unexpected shifts in product demand. The outcomes of this study provided valuable insights. Burgos and Ivanov (2021) explored the impact of the COVID-19 pandemic on food retail supply chains in Germany. Overall, the application of anyLogistix in the agri-food sector remains notably limited based on the current body of research.

Two studies by Vitorino et al. (2022a, Vitorino et al. 2022b), employed anyLogistix to analyze the distribution of table grapes in Brazil. These works did not simulate disruptions, and the primary focus was on economic and social key performance indicators.

Basically, the range of applications based on anyLogistix and currently present in the literature is still extremely limited, despite the fact that this software can be of great help to supply chain managers in facing the current challenges related to digitalization, resilience and sustainability.

2.3. Research gaps and our innovative contribution

What emerges from the study of the literature is that:

- the concept of SCDT is of great interest to the scientific community today. However, despite the possible benefits deriving from its adoption, it has not yet spread on a large scale. Research efforts are therefore needed to push its use, with the aim of increasing the resilience and sustainability of the supply chains. According to Ivanov and Dolgui (2019), so far limited consideration has been given to how data analytics can be leveraged to manage SC disruption risks;
- there is a lack of sequential and well-structured methodologies, which can enable the SCDT and guide the users step-by-step in its adoption;
- according to a very recent literature review (Gerlach et al., 2021), the amount of research on SCDT is currently mostly theoretical and studies should move into a practical direction;
- anyLogistix is a new and promising tool to support supply chain management. However, the number of applications based on this software in the scientific literature is still very limited, especially in the agri-food sector.

Based on the above-mentioned research gaps, the innovative contribution of this paper can be summarized as follows:

- we propose a cyclic and holistic methodology, aimed at enabling the concept of SCDT and supporting the user in decision-making, towards more sustainable and resilient supply chains;
- we test and validate the proposed methodology on a real case study in the agri-food sector, through the use of anyLogistix;

- additionally, our paper represents the first to consider the triple helix (economic, social, environmental sustainability) of the sustainable development and to address multiple disruptive events.

3. The holistic and cyclic methodology for enabling Supply Chain Digital Twins

The framework proposed in this paper arises from the need to support global and local supply chains in achieving sustainability and resilience goals. The main objective is to increase their level of readiness in the face of unexpected and disruptive events (e.g., COVID-19 pandemic, wars, interruptions in the supply chain flow such as the case of the ship stranded in the Suez Canal in 2021, etc.). It is aimed at supply chain managers and has a holistic and cyclic nature. The framework is also visually represented in Fig. 1, in order to make it fully understandable for the reader.

Basically, it is characterized by some fundamental steps, listed and described below:

STEP 1 – Real supply chain awareness: the starting point is the real supply chain. The framework can be applied to the entire supply chain, as the set of nodes and arcs that go from the first supplier to the last final consumer, or to a portion of it. In any case, in correspondence with this step, it is necessary (1) to become aware of the macro-structure of the entire supply chain, (2) to choose which portion of it to focus attention on. The term awareness refers to the concept of supply chain visibility.

STEP 2 – Supply chain data collection: once the portion of the supply chain on which to focus attention has been identified, it is extremely important to collect data on its current functioning. First of all, it is necessary to understand the geographic positioning of each individual node. Next, there are two categories of data that need to be collected: (1) node data (2) connection data. Node data refers to the internal functioning of each node such as historical production or sales data, warehousing policies, etc. On the other hand, the connection data refer to the transfer of goods between each pair of nodes, therefore they mainly concern the modes of transport (e.g., truck, train, plane, ship, etc.), the types of vehicles (e.g., large, small, etc.) used, the frequency of logistic activities (e.g., daily, weekly, monthly), etc. Basically, at this step, it is necessary to know in detail all the mechanisms that regulate the functioning of the supply chain of interest.

STEP 3 – Supply chain KPIs: the third step of the methodology concerns the identification of indicators for evaluating the performance of the supply chain under multiple scenarios. They refer to two main domains: sustainability (economic – EC, environmental – EN, social SO) and resilience. These indicators are crucial for discriminating between different supply chain work configurations both from a strategic-tactical and operational point of view and help the decision-maker in guiding the actors towards the achievement of the objectives.

STEP 4 – Events-solutions identification: once all the data relating to the real functioning of the supply chain have been collected and the performance indicators have been identified, it is necessary to hypothesize events that can significantly shake its balance and then possible response solutions. In this context, reference is made to disruptive events that have important effects on the functioning of the entire supply chain. Each event must therefore be placed in one or more of the following categories: supply-side (SuS), middle-side (MiS), demand-side (DeS). Supply-side and demand-side refer to actors who are respectively in the first and last level of the supply chain considered, while all the actors who are in the middle are labeled as middle-side. Likewise, each response solution will be included in one or more of the categories above identified on the basis of the expected effects deriving from its application (e.g., if the identified solution is to open a new node in the most upstream level of the supply chain, then the response solution will be classified as supply-side).

The first 4 steps of the framework refer only to the existing physical supply chain. The steps described below instead address the digital twin of the real supply chain.

STEP 5 – Supply Chain Modeling for Digitalization: once the data on the operational functioning of the supply chain has been collected, and indicators, events and response solutions have been defined, the supply chain is digitized, i.e., it is replicated in the form of a digital twin within a specific tool (e.g., anyLogistix). In this context, with the aim of adequately developing the Digital Twin, reference is made to a structured methodology, proposed by Psarommatis and May (2023a), which concerns the definition of some fundamentals (i.e., industry, purpose of the DT, process or asset that the DT describes, type of use, technologies used for the DT, input parameters, output parameters).

STEP 6 – Supply Chain Simulation: once the supply chain is available in digital form, the user of the framework can start the simulations. In this context, it is necessary to define different scenarios, combining the occurrence of events and the implementation of response solutions, identified in STEP 4. It is important that each scenario is run several times, in order to obtain statistically reliable results.

STEP 7 – Digital Twin-Driven Decision Making: at the seventh step, the different scenarios are compared, based on the sustainability and resilience indicators previously defined. The output of this step is a decision, which will impact the supply chain (e.g., closing/opening a node, closing/opening a connection between nodes, upgrading a node, increasing the number of vehicles to be used on an arc, change inventory policy on a specific node, etc.).

STEP 8 – Supply Chain Re-Shaping: in the end, the real supply chain is reshaped, based on the decision(s) made. At this point, the cyclic nature of the proposed framework is activated. In fact, once the decision made is actually implemented, you can go back to STEP 1 to reset the application of the framework and then exploit its potential.

Basically, the framework, for its cyclic structure, provides for a continuous improvement of the supply chain considered. Indeed, decisions made today may be profitable in the short term, but they may become obsolete and unprofitable after a few months or years. Therefore, a continuous analysis of the performance of the supply chain in terms of sustainability and resilience is crucial. At each cycle, decision makers can update the list of response events and solutions, based on what is happening in reality. In the same way, they can update the sustainability and resilience indicators useful for assessing the performance of the supply chain (e.g., on the basis of technological evolution, over time new indicators can be added that are more in line with the current characteristics of the supply chain, in the same way as those previously defined may become useless and then deleted). Consequently, the scenarios for comparing supply chain performance under different operating conditions may also change. Therefore, one of the strengths of the proposed framework is its long lifecycle.

As it can be seen, the first 4 steps refer to the real environment and represent the foundation for the next 3 phases, which are carried out within the digital environment. Finally, there is a phase of supply chain re-shaping which jointly represents the output of the digital environment and the input of the real environment. Basically, based on the analyzes conducted through the use of simulation, it is possible to make decisions that have an impact on the real environment.

4. Framework implementation, results and managerial insights

With the aim of demonstrating the effectiveness of the proposed methodology, we address a case study in the agri-food sector, which takes into account, a supply chain characterized by 4 main levels: suppliers, distribution center (DC), customers, retailers. It is important to underline that the supplier's customers are wholesalers. In this specific case, the word "customer" is used as a synonym for "wholesaler". Product is cauliflower, which tends to have a limited harvesting/distribution season, which usually runs from December to April. The main actions carried out by each level of the supply chain are listed below. The supplier takes care of the harvesting, storage and distribution of the product to the DC. The DC collects agri-food products from multiple suppliers and autonomously organizes logistics activities towards customers, located in different areas of Italy. The customers deal with the distribution to the retailers and therefore to the final consumers, which are out of the scope of this paper.

The rationale behind the choice of this specific supply chain is to rigorously test and demonstrate the adaptability and effectiveness of the proposed methodology in a real-world scenario characterized by the complexities of perishable products, intricate inventory policies, and the critical role of distribution in meeting customer service levels. In fact, perishable goods introduce a level of complexity that amplifies the intricacies of supply chain management. The sensitivity of inventory management policies is heightened due to the perishable nature of the cauliflowers. Finally, the time-sensitive nature of distributing these products adds a layer of complexity in ensuring elevated levels of customer service, thereby emerging as crucial objective to be achieved.

4.1. Framework implementation: real environment

With the aim of to show the reader the potential of the proposed framework, its step-by-step implementation is shown below. This subsection refers to the framework implementation in the real environment.

STEP 1 – Real supply chain awareness: the point of view of the case study is that of supplier 1, who wants to understand how to improve continuously its performance in terms of resilience and sustainability. At this step, it is important that the actor understands that it is part of a supply chain, which is characterized by a certain number of levels, 4 in this case. Subsequently, it is necessary to choose which portion of the supply chain to take into consideration to perform the different analyses. Practically, the output of this step is represented by the nodes and arcs in blue in Fig. 2.

STEP 2 – Supply chain data collection: practically, this is one of the most critical and difficult steps of the methodology as it can be very complicated to acquire data on the overall functioning of the supply chain. In this specific case, the authors took advantage of the direct contact with the supplier, who provided relevant data about supply chain operations. The data collection process unfolded over a dedicated two-month period, during which the authors conducted direct meetings with the supplier. To enhance the accuracy and reliability of the obtained data, ad hoc meetings were also organized, involving the operators of DC and customers. These additional sessions were necessary in confirming the precision of the provided data and ensuring the understanding of the intricacies of the supply chain. Moreover, recognizing the diverse nature of supply chain data, the authors employed supplementary methods to validate their dataset: (1) through scrutiny of relevant documents, including logistics records, and supplier operational reports and (2) through direct observations on-site.

As result of the data collection phase, it is important to say that the planting of the product is agreed with the customers in terms of quantity and days, therefore it is not too complicated to estimate the quantities that will be harvested in the December-April period. The company processes approximately 700,000–800,000 units of cauliflower each harvesting season. Each product unit can be sent immediately to the distribution center or stored in refrigerated cells and be shipped a few days later (on the basis of the supplier-customer contractual agreements, it is necessary to ensure a certain level of quality to the final consumer, therefore the product does not may remain in stock for more than 4–5 days). Two vehicles owned by the supplier, of identical capacity, are used for the distribution of the products to the DC. The supplier's

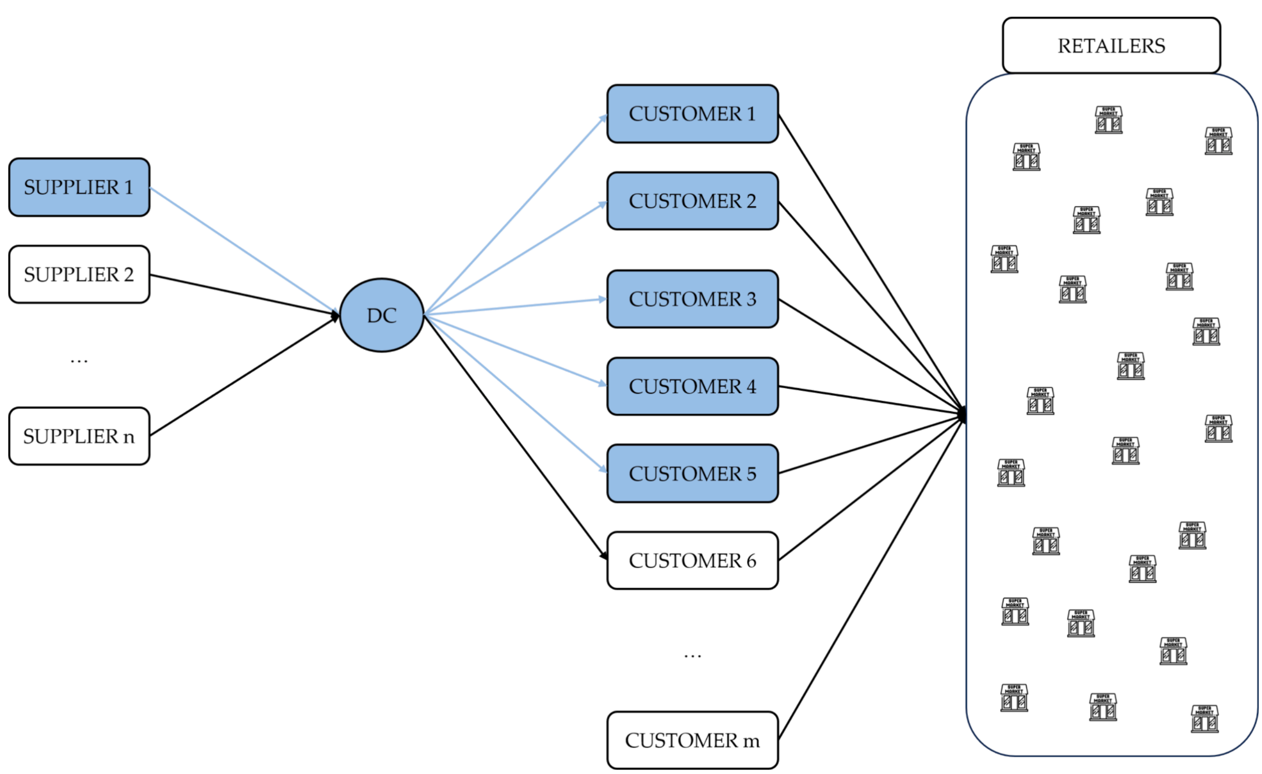


Fig. 2. Real supply chain and portion of interest.

warehouse policy is not well defined because it depends on 3 main factors: (i) the product units that can gradually be collected based on the degree of ripeness, (ii) the previously mentioned quality constraint, (iii) the need to ensure the customer a certain amount of product for each week, on the basis of the contractual agreements. From a geographical point of view, the supplier is located in Southern Italy.

STEP 3 – Supply chain KPIs. The assessment of the supply chain performances under diverse scenarios involves the utilization of the KPIs listed and described in Table 1.

4.2. Framework implementation: digital environment and results

This subsection refers to the framework implementation in the digital environment.

STEP 5 – Supply Chain Modeling for Digitalization: after successfully conducting all the previous phases, it is possible to proceed with the modeling of the supply chain from a digital point of view. Basically, the real supply chain is reproduced on an appropriate software/tool, to obtain the SCDT. For the specific needs related to the case study, it was decided to use anyLogistix 3 for building the simulation model. All the operating mechanisms of the supply chain (i.e., product demand, warehouse policies, times and methods of transport of agri-food products, etc.) were appropriately inserted within the software, in order to faithfully reproduce the supply chain. Fig. 3 shows the list of tables (i.e., "Customers", "DCs and Factories", "Demand", etc.) that have been filled in anyLogistix to enable the Supply Chain Digital Twin and a graphical view of the supply chain (the orange circle represents the supplier; the red circle represents the DC; the blue circles represent the customers).

Based on the structured methodology proposed by Psarommatis and May (2023a), the following fundamentals were defined for the creation of the digital twin:

- Industry: agri-food sector.
- Purpose of the DT: Replicate a real agri-food supply chain, with the aim of simulating multiple operating scenarios and identifying the best operational configuration to increase resilience and sustainability.
- Process or asset, described by the DT: functioning of a real agri-food supply chain.
- Type of use: DT will adapt to alterations, then will be dynamic, and used periodically, based on the needs of the decision-maker.
- Technologies used for the DT: anyLogistix 3, a discrete event simulation software.
- Input parameters: all the parameters, already described in STEP 2 – Supply chain data collection.
- Output parameters: all the parameters, already defined in STEP 3 – Supply chain KPIs.

Table 2
Main disruptions (D) considered.

ID	Type	Description	Main effect
D1	SuS	Lack of human resources in the field	Difficulty in conducting harvesting activities in the right time and way. Unharvested products, then food waste (i.e., perished products)
D2	SuS	Lack of human resources for the transport and/or breakdown of one or more vehicles used to transport the products	Difficulties in transporting product from supplier to distribution center on time. This could lead to a loss of product quality, therefore a lowering of the satisfaction of the final consumer, or even a deterioration (i.e., food waste)
D3	MiS	Distribution center closure	Based on the current structure of the supply chain, this implies the impossibility of transporting the product from the supplier to the customer
D4	DeS	Demand fluctuations (i.e., unexpected increase or decrease)	The sudden increase in demand, if not adequately foreseen, leads to loss of business opportunities. On the other hand, the sudden decrease in demand does not allow the timely distribution of the product, which perishes with significant damage in terms of environmental sustainability

Correspondingly, the main solutions proposed are schematized in Table 3.

STEP 6 – Supply chain simulation: regarding the sixth step of the proposed framework, it is necessary to define scenarios, based on disruptions and solutions identified in STEP 4. There are no well-defined rules for defining scenarios, which can be built by combining (even all) disruptions and solutions. However, it is good practice to always define one or more scenarios, in which there are disruptions and no solutions implemented; this makes it possible to evaluate the current level of resilience of the supply chain, thus answering the following question: how much is the supply chain currently "vulnerable" to the disruptions identified? Table 4 shows the list of identified scenarios.

As it can be seen, the first 4 scenarios represent the occurrence of the 4 types of identified disruptions, separately. The next 4 scenarios (i.e., 5–8) aim to understand how effective each identified solution is in dealing with each identified disruption. The scenarios were designed on anyLogistix through the "Events" table, which allows you to simulate the occurrence of events and associate a probability level with each of them. Fig. 4 shows an extract from this table with reference to Scenario 3, which considers the closure of the DC in some time periods as a disruption.

Table 1
Key Performance Indicators for evaluating the different scenarios.

KPI	Additional information	Sustainability			Resilience
		EC	EN	SO	
$KPI_{S1} = \textit{revenue from product sales}$	It refers to the revenue generated by the sale of the product by the supplier to customers.	✓			
$KPI_{S2} = \frac{\textit{wasted product units}}{\textit{total product units}} * 100$	It refers to two types of products: (1) products not harvested on time for various reasons; (2) products left too long in the finished good warehouse. In both cases, they are classified as food waste, as they are no longer marketable products. Such an indicator computes the percentage of food waste.		✓		
$KPI_{S3} = \frac{\textit{fulfilled orders}}{\textit{total orders}} * 100$	It computes the orders that have been fulfilled correctly out of the overall number of orders. It is classified as an indicator of social sustainability because its value has an impact on the availability of food on the shelf. The greater the number of successfully fulfilled orders, the more the possibility will be guaranteed for everyone to obtain supplies even despite disruptions, with a view to social equity.			✓	
$KPI_{R1} = \frac{KPI_{S1}^{D} - KPI_{S1}^{N}}{KPI_{S1}^{N}} * 100$	It refers to the percentage change in revenue in the presence of a disruption, compared to "normal" (N) working conditions.				✓

STEP 4 – Events-solutions identification: based on the historical data made available by the players in the supply chain, the main disruptions taken into account are listed and classified in Table 2, in accordance with the notation introduced in Section 3. In addition, interviews with supplier 1 also helped to identify both past disruptions that could most likely occur in the future, and disruptions that have never occurred, but which deserve to be taken into consideration.

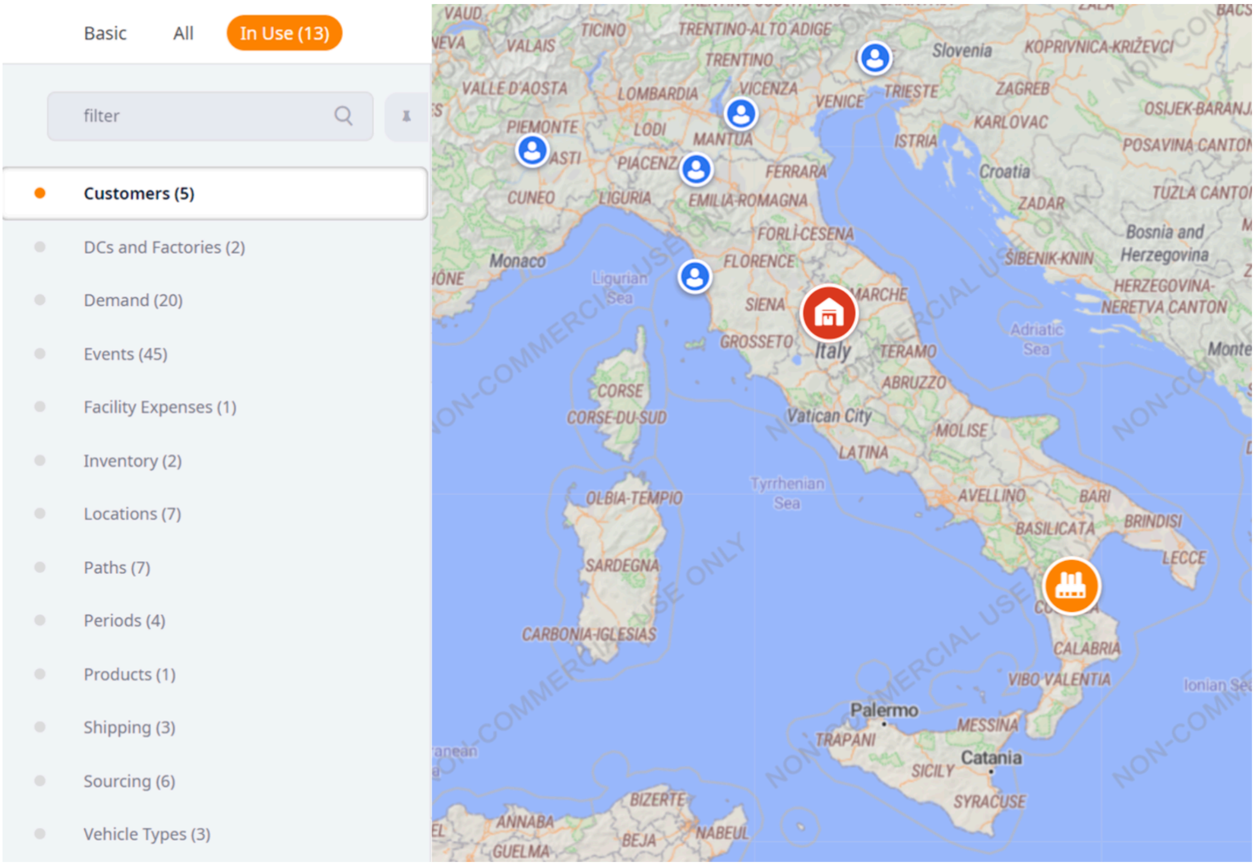


Fig. 3. Input tables and graphical view of the supply chain.

Table 3
Main solutions (S) considered.

ID	Type	Description	Main effect
S1	SuS	Collaboration with temporary employment agencies	These agencies can support the supplier in finding workers available in the short term and therefore cover any personnel gaps
S2	SuS/ MiS	Agreements with third-party logistics (3PL) providers	Agreements with 3PLs may face efficiently transport problems by the supplier's own vehicles
S3	MiS	Activation of emergency direct routes supplier-to-customer and customer-to-supplier	Reduced dependency on the only distribution center that currently exists
S4	DeS	Agreements with product suppliers / Agreements with spot customers	Agreements with other cauliflower producers help meet demand, even in the event of sudden peaks. Agreements with spot customers help to place the product on the market and therefore to deal with any limitations in demand. This solution is essential to limit food waste

Table 4
Scenarios identified.

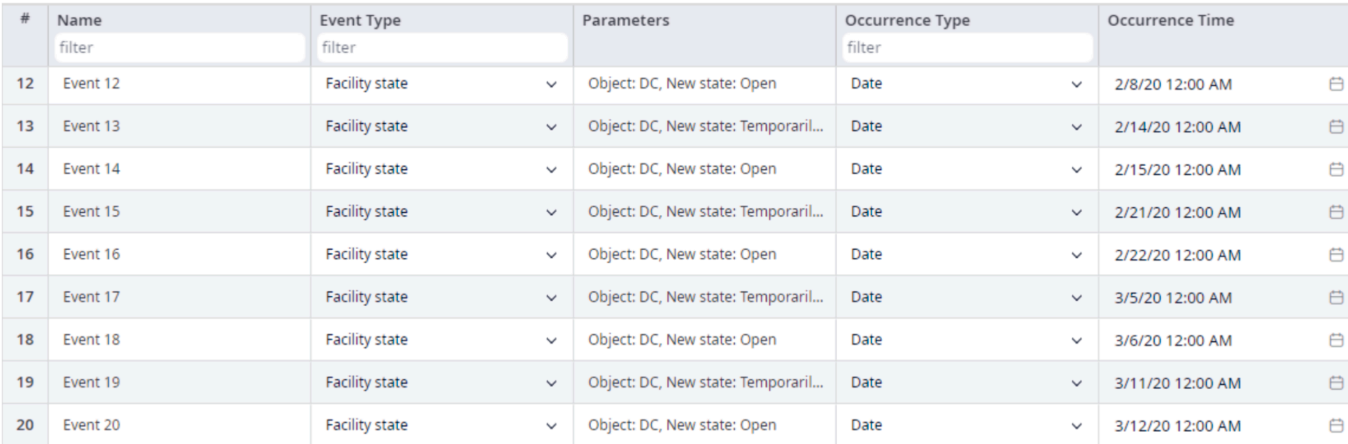
Scenario	Disruption							
	D1	D2	D3	D4	S1	S2	S3	S4
Scenario 0 (N)								
Scenario 1	✓							
Scenario 2		✓						
Scenario 3			✓					
Scenario 4				✓				
Scenario 5	✓				✓			
Scenario 6		✓				✓		
Scenario 7			✓				✓	
Scenario 8				✓				✓

The simulation model was run 10 times for each scenario, to adequately evaluate the reliability of the results obtained. Repeated execution of the model, containing probabilistic parameters, provides a more complete and reliable view of the system's behavior under conditions of uncertainty, helping to make more informed and robust decisions. This re-execution was enabled by changing the random seed of the experiment settings in anyLogistix.

Tables 5–8 show the values of the 4 KPIs under the different scenarios. For each KPI, the minimum, maximum and average value were calculated. Furthermore, in order to provide the reader with as much information as possible about the reliability of the results obtained, the standard deviation (std-dev) and the 95 % confidence interval (95 %-ci) were also provided. It is important to mention that anyLogistix provides directly some useful indicators.

Through scenario 0, the normal functioning of the supply chain was simulated, based on historical data provided by the company. In scenarios 1–4 the following disruptions were separately simulated: (i) lack of human resources in the field for a total of 4 weeks, randomly chosen; (ii) impossibility of transporting the agri-food product from the supplier to the DC within the right time and manner, in 4 randomly selected periods of 3 days; (iii) temporary closure of the DC in 2 different periods of 10 days; (iv) decrease in product demand of approximately 20 %. For all these 4 scenarios, the time horizon is equal to the harvesting period, which fluctuates from December to April. In scenarios 5–8, the application of the strategies mentioned in Table 4 was instead simulated.

The results give extremely important information to the decision



#	Name	Event Type	Parameters	Occurrence Type	Occurrence Time
	filter	filter		filter	
12	Event 12	Facility state	Object: DC, New state: Open	Date	2/8/20 12:00 AM
13	Event 13	Facility state	Object: DC, New state: Temporaril...	Date	2/14/20 12:00 AM
14	Event 14	Facility state	Object: DC, New state: Open	Date	2/15/20 12:00 AM
15	Event 15	Facility state	Object: DC, New state: Temporaril...	Date	2/21/20 12:00 AM
16	Event 16	Facility state	Object: DC, New state: Open	Date	2/22/20 12:00 AM
17	Event 17	Facility state	Object: DC, New state: Temporaril...	Date	3/5/20 12:00 AM
18	Event 18	Facility state	Object: DC, New state: Open	Date	3/6/20 12:00 AM
19	Event 19	Facility state	Object: DC, New state: Temporaril...	Date	3/11/20 12:00 AM
20	Event 20	Facility state	Object: DC, New state: Open	Date	3/12/20 12:00 AM

Fig. 4. "Events" table for Scenario 3 in anyLogistix.

Table 5
KPI_{S1} [€] under scenarios 0–8.

Scenario	Min [%]	Max [%]	Mean [%]	std-dev [%]	95 %-ci [%]
Scenario 0 (N)	90.23	94.68	92.50	1.66	(91.32; 93.69)
Scenario 1	82.08	84.75	83.49	0.94	(82.82; 84.16)
Scenario 2	89.69	90.31	90.18	0.20	(90.04; 90.33)
Scenario 3	90.14	94.15	91.75	1.62	(90.59; 92.91)
Scenario 4	93.03	96.67	95.17	1.24	(94.28; 96.06)
Scenario 5	90.60	94.68	92.36	1.81	(91.06; 93.65)
Scenario 6	90.53	94.48	92.93	1.63	(91.76; 94.09)
Scenario 7	90.60	94.68	92.64	1.68	(91.43; 93.84)
Scenario 8	90.00	94.68	92.53	1.96	(91.13; 93.93)

Table 6
KPI_{S2} [%] under scenarios 0–8.

Scenario	Min [%]	Max [%]	Mean [%]	std-dev [%]	95 %-ci [%]
Scenario 0 (N)	90.23	94.68	92.50	1.66	(91.32; 93.69)
Scenario 1	82.08	84.75	83.49	0.94	(82.82; 84.16)
Scenario 2	89.69	90.31	90.18	0.20	(90.04; 90.33)
Scenario 3	90.14	94.15	91.75	1.62	(90.59; 92.91)
Scenario 4	93.03	96.67	95.17	1.24	(94.28; 96.06)
Scenario 5	90.60	94.68	92.36	1.81	(91.06; 93.65)
Scenario 6	90.53	94.48	92.93	1.63	(91.76; 94.09)
Scenario 7	90.60	94.68	92.64	1.68	(91.43; 93.84)
Scenario 8	90.00	94.68	92.53	1.96	(91.13; 93.93)

maker, both in terms of sustainability and resilience. First of all, it can be stated that scenarios 1–4 show a significant average decrease in revenue, an increase in the amount of spoiled product, a decrease in the level of service offered to customers. In the case of scenario 1, the lack of human

Table 7
KPI_{S3} [%] under scenarios 0–8.

Scenario	Min [%]	Max [%]	Mean [%]	std-dev [%]	95 %-ci [%]
Scenario 0 (N)	90.23	94.68	92.50	1.66	(91.32; 93.69)
Scenario 1	82.08	84.75	83.49	0.94	(82.82; 84.16)
Scenario 2	89.69	90.31	90.18	0.20	(90.04; 90.33)
Scenario 3	90.14	94.15	91.75	1.62	(90.59; 92.91)
Scenario 4	93.03	96.67	95.17	1.24	(94.28; 96.06)
Scenario 5	90.60	94.68	92.36	1.81	(91.06; 93.65)
Scenario 6	90.53	94.48	92.93	1.63	(91.76; 94.09)
Scenario 7	90.60	94.68	92.64	1.68	(91.43; 93.84)
Scenario 8	90.00	94.68	92.53	1.96	(91.13; 93.93)

Table 8
KPI_{R1} [%] under scenarios 1–8.

Scenario	Mean [%]
Scenario 1	−15.01
Scenario 2	−9.88
Scenario 3	−19.93
Scenario 4	−13.54
Scenario 5	−0.83
Scenario 6	−0.65
Scenario 7	−0.88
Scenario 8	−1.72

resources in the field causes the impossibility of harvesting the products in time (i.e., raw materials deterioration), which deteriorate prematurely; as a result, there are customer orders that are not fulfilled. Similar consequences are present in scenario 2, where instead the deterioration is linked to the finished products. In scenario 3, the closure of the distribution center disables the transfer of products from suppliers to customers, with serious consequences in terms of revenue, product waste, and the level of service offered to customers. This scenario emphasizes the dependence of the supply chain on the single distribution center. In scenario 4, the sudden decrease in demand imposes not only a drop in revenue, but also a significant amount of wasted food. The last two steps of the methodology are reported in the next paragraph, which return some managerial insights.

4.3. Framework implementation: discussion and managerial insights

STEP 7 – Digital Twin-Driven Decision-Making and STEP 8 – Supply chain re-shaping: in this phase, it is necessary that the results obtained can help in decision-making. With reference to the case study, it is evident that the implementation of the response solutions is fruitful for the supplier because: (1) the revenue grows until reaching on average to the normal condition, defined in scenario 0; (2) food waste is reduced; (3) the level of service offered to the customer is increased, given that the rate of orders fulfilled on time increases. However, it cannot be overlooked that the implementation of every strategy has a cost. Therefore, before proceeding with the implementation of each of them, a cost-benefit analysis by the decision maker must be carried out. For the sake of clarity, let us consider scenarios 2 and 5. As it can be seen from the results in Table 5, the hypothesized disruption, i.e., D2, leads to an average decrease in revenue equal to € 44,162.45, compared to the normal functioning of the supply chain. The implementation of the S2 response strategy manages to almost compensate for this decrease in revenue, considering that in scenario 5 the average revenue is € 40,469.66 higher than in scenario 2. Substantially, the S2 strategy will be convenient for the supplier if its implementation cost is lower than the latter value. Knowledge of all these scenarios can significantly support the supplier in the negotiation phase with the 3PL, especially in agreeing the price for having the service. The same can be said for all the other scenarios and solutions identified. Basically, the Digital Twin enables a set of what-if analyzes and supports the decision maker, who can evaluate the convenience of different scenarios in the digital world, before actually implementing them in the real world. At the moment, we have no information on the decisions actually made by the supplier. Either way, the next step is to implement each chosen solution, then reshape the supply chain.

5. Conclusions

Supply chains around the world are experiencing a period of profound change. Recent disruptions such as wars, climate change, the Covid-19 pandemic have highlighted all their weaknesses. At the same time, new technologies are emerging under the umbrella of Industry 4.0/5.0 and opening up new opportunities. In this challenging context, the SCDT enables a digital replica of the supply chain to carry out multi-scenario analyzes and choose the best configuration to be actually implemented in order to face disruptions, then preserving supply chain resilience and sustainability.

In this paper, a holistic and cyclic methodology has been proposed to enable and exploit the SCDT concept. It has been successfully tested and validated using the anyLogistix simulation software on a real case study, belonging to the agri-food sector. On the basis of the historical data available, multiple disruptions have been hypothesized and the level of resilience of the supply chain with respect to each of them has been assessed. Then, the goodness of some possible response solutions was evaluated, based on indicators of environmental, social and economic sustainability.

The proposed framework aims to be impactful from both a theoretical and practical point of view. From a theoretical point of view, it represents an easy-to-use guide, which can be implemented by any decision-maker step-by-step. It aims to become a point of reference in the literature to enable Supply Chain Digital Twins, and therefore preserve the sustainability and resilience of supply chains through simulation tools. At the same time, the methodology has a strong practical character, as demonstrated by the tangible and measurable results resulting from its application to a real case study within this research work. It can be applied cyclically as the working conditions of the supply chain vary; therefore it has a very high longevity, exploiting the concept of re-usability.

The main limitation of the research lies in the low number of disruptions and response solutions considered. However, the case study does not claim to be fully exhaustive in the enumeration of every possible scenario but aims to be a means of explaining to the reader how to use the methodology efficiently and effectively (i.e., step-by-step). Possible future developments concern the use of the proposed methodology also in other case studies of different size, in order to understand its level of scalability. Furthermore, it would be important to take into consideration a longer time horizon to evaluate the adaptability of the methodology to changing conditions and contexts over time.

CRediT authorship contribution statement

Antonio Cimino: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Francesco Longo:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Giovanni Mirabelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Vittorio Solina:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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

The data that has been used is confidential.

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