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Procedia Computer Science 217 (2023) 1940–1947

Procedia Computer Science

www.elsevier.com/locate/procedia

4th International Conference on Industry 4.0 and Smart Manufacturing

The Digital Supply Chain Twin paradigm for enhancing resilience and sustainability against COVID-like crises

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Abstract

In recent years, scientific interest in the concepts of sustainability and resilience has grown considerably. The Covid-19 pandemic has indeed emphasized all the fragility of manufacturing systems and supply chains both globally and locally. The disruptive effects of the outbreak on production systems, warehouses and distribution networks are evidence of the urgent need for digital twins, which are able to reproduce supply chains behavior and guarantee adequate levels of performance.

In this paper, a Simulation-Based Decision-Making Framework, which exploits the Digital Supply Chain Twin paradigm to enhance resilience and sustainability in the face of COVID-like crises, is proposed. Preliminary computational tests, carried out on a real agri-food supply chain, show that the framework is extremely promising for evaluating the validity of multiple response strategies, based on resilience and sustainability indicators. The research represents a first significant step in the design and development of a ready-to-use decision support tool, based on simulation principles and the novel concept of Digital Supply Chain Twin.

Peer-review under responsibility of the scientific committee of the 4th International Conference on Industry 4.0 and Smart Manufacturing

Keywords: Supply Chain Management; Digital Twin; COVID-19; Digitalization; Resilience; Sustainability

1. Introduction

The recent Covid-19 pandemic has highlighted all the weaknesses of supply chains both locally and globally. In recent months, the interest of the scientific community towards the concept of resilience has grown significantly. Basically, traditional supply chains are no longer able to deal effectively and efficiently with rapid market changes. In

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1877-0509
Peer-review under responsibility of the scientific committee of the 4th International Conference on Industry 4.0 and Smart Manufacturing
10.1016/j.procs.2022.12.394

the modern era, there is a need for agility and flexibility to properly meet the needs of end consumers and face unexpected events. In this challenging context, the digitization of supply chains represents a significant opportunity to exploit the potential of new Industry 4.0-related technologies. According to Dolgui et al. [1], one of the most common questions today concerns how to improve the profitability and performance of supply chains trying to respect sustainability standards (economic, environmental, social) and guaranteeing high levels of resilience. The Digital Supply Chain Twin paradigm represents a possible way to answer this question comprehensively. According to General Electric [2], Digital Twins [3] are software representations of processes and assets aimed to understand and optimize performance. More specifically, the Digital Supply Chain Twin was recently defined as "a computerized digital SC model that represents the network state for any given moment in real time, allowing for complete end-to-end SC visibility to improve resilience and test contingency plans" [4].

In this paper, a Simulation-Based Decision-Making Framework is proposed, which exploits the Digital Supply Chain Twin paradigm to increase sustainability and resilience.

The remainder of the paper is structured as follows. Section 2 reviews the state of the art about recent attempts to use the Digital Supply Chain Twin concept. Section 3 is aimed at explaining the proposed framework, which is applied to a case study in Section 4. Section 5 shows conclusions and possible future developments.

2. Literature Review

With the occurrence of the Covid-19 pandemic, scientific research has significantly intensified around the determination of strategies to increase the sustainability and resilience of supply chains [5-6]. The outbreak has had a significant impact on manufacturing systems, material procurement, distribution systems in various fields. Specifically, in the agri-food sector [7], the complexity in terms of supply chain management has considerably increased, due to the occurrence of some critical events such as: panic buying by final consumers, closure of several distribution channels (e.g., open-air markets, school canteens, bars, restaurants, etc.) to limit the spread of the infection, shortage of workforce in the fields due to travel restrictions. Furthermore, in many cases it was necessary to completely redefine internal work processes given the new rules on social distancing and a significant increase in the standards about food quality & safety [8]. The most significant contributions on the use of simulation-driven approaches and methodologies, aimed at supporting supply chains in the face of COVID-19, are reviewed below.

Ivanov [9] has recently proposed a simulation-based methodology to examine and predict both short-term and long-term impacts of epidemic outbreaks on supply chain performance. The presented approach can be of great help to understand which elements have the greatest impact and to identify the best countermeasures. Singh et al [10] have developed a simulation model related to a public distribution system network to increase the resilience of food supply chains in response to frequent changes in demand and their readiness in re-routing of vehicles in the event of travel restrictions imposed. Nikolopoulos et al. [11] simulate different government decisions (in terms of lockdowns) to assess the impacts on the demand for products and services. In their proposal, COVID-19 growth rates are predicted through statistical, epidemiological and machine learning models. Rahman et al. [12] aim to face global supply chains disruptions through the agent-based modeling method. They propose a set of strategies in order to minimize the cost and increase the availability of crucial items in case of disruptive events. The experimental parts confirm the goodness of the proposed approach and of the main outcome is the awareness that the delayed implementation of response strategies can lead to irremediable shocks, especially from a financial point of view.

Healthcare was one of the areas most impacted by COVID-19. Govindan et al. [13] have developed a decision support system to mitigate the impacts of disruptions on the healthcare supply chain and support demand management, based on physicians' knowledge and fuzzy inference system.

Basically, the disruptive effects of COVID-19 on production systems, warehouses and distribution networks are evidence of the urgent need for digital twins, which are able to digitally reproduce supply chains and guarantee visibility and resilience. Currently, the research results around this topic are still very limited and there is a need for a general framework that can help the decision-making of supply chain players in a practical way and by exploiting the potential and flexibility of simulation systems. For all these reasons, a Simulation-Based Decision-Making Framework is proposed in this paper, which exploits the Digital Supply Chain Twin Paradigm to increase the sustainability and resilience of supply chains in the face of COVID-like crises.

3. The Simulation-Based Decision-Making Framework for enhancing resilience and sustainability

In this section, we present the Simulation-Based Decision-Making Framework for enhancing resilience and sustainability (see Figure 1).

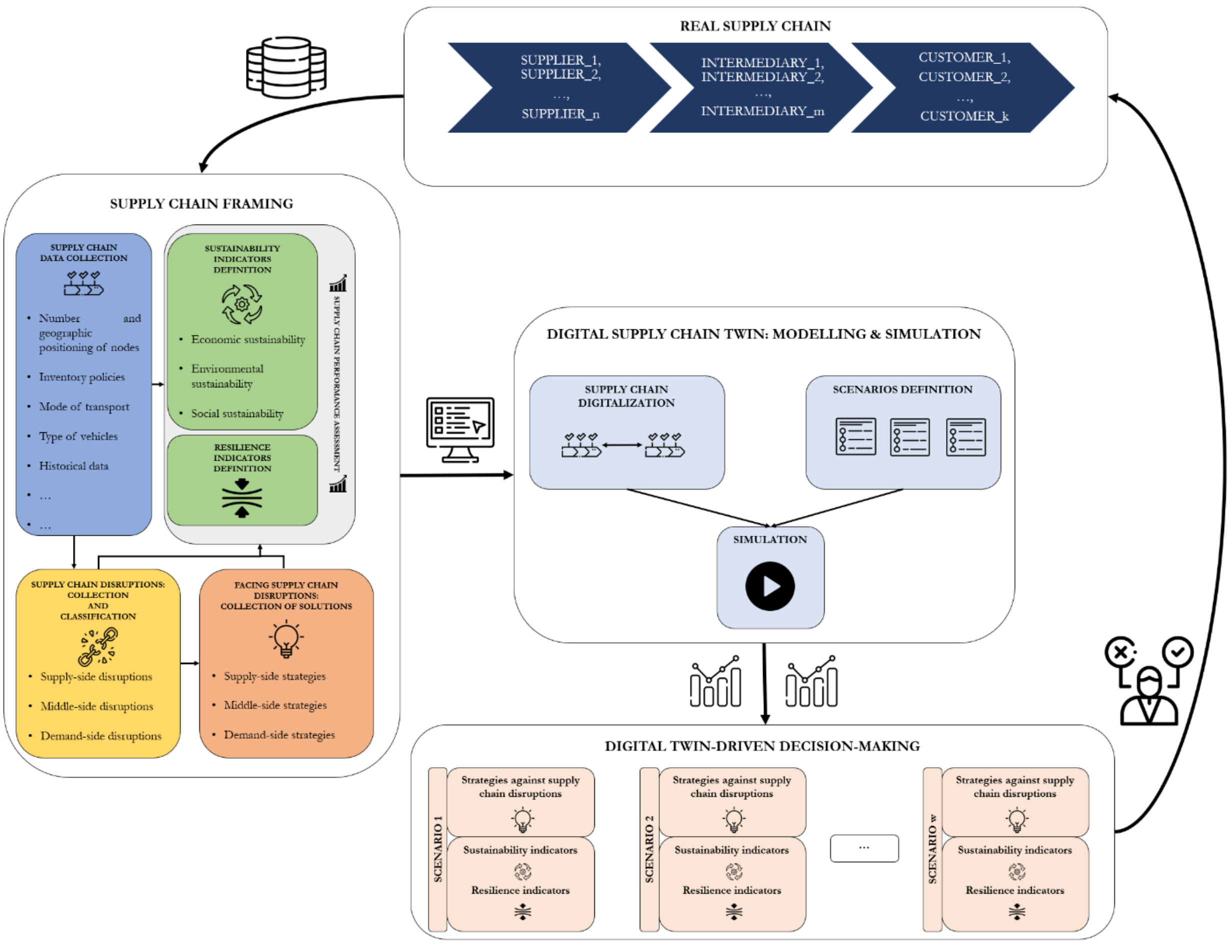

Fig. 1. Simulation-Based Decision-Making Framework

Basically, given a generic supply chain, the proposed framework can be used to protect its performance in the face of disruptions. The main recipients of our proposal are supply chain managers. The framework refers to a series of steps, which must be carried out cyclically for the continuous improvement of the supply chain over time. The very first step, called data management, is related to the supply chain framing and implies a deep knowledge of all its mechanisms. The user of the framework must know the structure of the supply chain in terms of products, nodes, connections, modes of transport and their characteristics (e.g., if the mode of transport is the truck, it means the number of trucks, their capacity, routes, etc.), inventory policies adopted in the various nodes, characteristics of product demand (e.g., historical data, probability distribution, etc.), costs and revenues. Therefore, the supply chain manager must be able to conduct a risk analysis, the result of which is a list of supply chain disruptions, which are classified on the basis of the supply chain level affected: conventionally, supply-side disruption means disruption on the first level of the supply chain, while symmetrically demand-side disruption refers to the last level of the supply chain; all disruptions involving intermediate nodes in this paper are referred to as middle-side disruptions. The disruptions identified may refer to events that have occurred in the past or to events that are expected to occur in the future.

Subsequently, it is necessary to define indicators, through which it is possible to quantify the supply chain performance under multiple scenarios. We refer to two main domains: sustainability and resilience. Sustainability is considered in three ways: economic, environmental and social. Furthermore, it is necessary to define resilience indicators, which can answer the following question as a whole: how resilient is the supply chain? They are defined according to the disruptions, output of the previously conducted risk analysis. Finally, the supply chain manager must be able to define one or more possible strategies (intended as solutions), in response to each identified disruption. Then there is the digitalization phase of the supply chain. Basically, a twin supply chain of the really existing one is modeled through an appropriate simulation software, exploiting the concept of Digital Supply Chain Twin. The advantages of using such an approach can be manifold. Through simulation, it is indeed possible to understand in a few seconds how the supply chain reacts to unexpected events under multiple scenarios. Furthermore, it is possible to immediately understand the impact that each strategy has in terms of sustainability and resilience. This approach obviously involves significant savings from an economic point of view, as it is not necessary to actually implement any response strategies to understand whether they are effective or not. Furthermore, errors and waste are minimized. Once the simulation software to be used has been chosen, the type of simulation to be conducted (e.g., discrete-event simulation, etc.) and the scenarios within which to move, computational tests are launched. Based on the results obtained, the supply chain manager has all the information to make decisions effectively and efficiently. In this context, it is of fundamental importance to underline that it is possible to evaluate the strategies from different perspectives, then in the short-term, but also in considering the medium/long term impacts. Once the most promising strategies have been identified, they are implemented on the real supply chain, which therefore now has a different aspect than the previous one. Consequently, the data management phases are repeated, etc. Basically, the proposed framework has a cyclic nature, according to the continuous improvement paradigm. In any case, at any time, it will always be possible to simulate the behavior of the real supply chain through the corresponding Digital Twin, taking into consideration possible perturbations.

4. Case Study

With the aim to demonstrate the validity and usefulness of the previously explained framework, we propose a real-life case study, which refers to a 3-level agri-food supply chain, located in Italy. The different steps of the framework are detailed in the subsections below.

4.1 Real supply chain and data management

The supply chain under study consists of 3 main players: a supplier-node, a distribution center (DC), a set of customer-nodes. Specifically, the supplier is a farm located in southern Italy, which deals with the planting, growing, harvesting, storage and distribution of cauliflowers. It has an exclusive contract with a customer company, which has several nodes scattered between central and northern Italy. The cauliflower harvesting season varies between December and April. After the harvesting phase, the agricultural product can be stored for a few days or sent directly to the distribution center, based on the availability of the fleet of vehicles owned by the farm. Once at the distribution center, the main customer uses vehicles that are responsible for distributing the product to its customer nodes. In this context, there are two significant constraints: (i) harvesting must be carried out in specific days, based on the planting period; (ii) consistently, products not shipped immediately may remain in stock for no more than 3-5 days. Both constraints are linked to significant quality standards to be ensured by contract to the customer.

Based on the historical data collected in the 2019-2020, 2020-2021, and 2021-2022 seasons, there is strong interest in analyzing the impacts of the following disruptions:

- D1 - Supply-side disruption: outbreak of COVID-19 among workers in the fields and inability to properly conduct harvesting activities. Main consequence: unharvested agricultural products, therefore food waste.
- D2 - Middle-side disruption: temporary closure of the DC, due to the spread of the COVID-19 infection. Main consequence: inability to ship products to customers on time.

- D3: Demand-side disruption: closure of some connections between DC and customers, due to restrictive government measures (i.e., red zones) or absence of transporters, sick due to COVID-19. Main consequence: deterioration of products at the distribution center.

In this challenging context, the aim is to evaluate the goodness of 3 possible response strategies (RSs), one for each disruption previously defined:

- RS1: The supplier enters into agreements with additional seasonal workers through pre-contracts. They are available at any time, in case of need, to carry out harvesting activities.
- RS2: Activation of an additional distribution center.
- RS3: The customer enters into agreements with a third-party logistics provider (3PL), who is available, in exchange for a fee, every day to make deliveries from the distribution center to the customer-nodes, if needed.

In order to evaluate the impacts of the disruptions and the goodness of the proposed RSs, in Table 1 some performance indicators are defined based on two crucial aspects: sustainability and resilience.

Table 1. Supply chain performance indicators

Indicator	Category
$I_1 = \frac{unharvested\ products}{total\ products}$	Environmental Sustainability
$I_2 = \frac{products\ perished\ in\ the\ inventory}{harvested\ products}$	Environmental Sustainability
$I_3 = \frac{fulfilled\ demand}{total\ demand}$	Social Sustainability
$I_4 = revenue$	Economic Sustainability
$R_1 = [(I_4^N - I_4^D)/I_4^N] * 100$	Resilience

Indicators I_1 and I_2 refer to two typical events within the agri-food supply chains during the COVID-19 pandemic: (1) the difficulty of harvesting agricultural products on time, due to the lack of labour force; (2) the inability to distribute the products on time due to the travel restrictions imposed by the governments. In both cases, the main consequence was food waste, therefore a decrease in environmental sustainability. I_3 refers to social sustainability as satisfying the demand for products along the supply chain implies the presence of the “product on the shelf” in the right quantities, for the benefit of final consumers. It is a concept of social equity, according to which everyone can have access to food even during the most acute periods of the crisis. With regard to economic sustainability, on the other hand, reference is made to the revenue generated by sales to final customers in the supply chain. In this specific case, only one resilience indicator is defined, where the letters "N" and "D" refer respectively to the condition of normal and under disruption operations of the supply chain. Basically, R_1 measures the percentage reduction in revenue following the occurrence of a disruption; the higher such a percentage, the less resilient the supply chain respects to that disruptive event.

4.2 Digital supply chain twin: modeling & simulation

At this phase, the digital twin of the supply chain is created through a simulation software. Specifically, in this paper, we adopted anyLogistix, which is widely recognized in the scientific literature. As it can be seed from Figure 2, through the various functions available, it was possible to model each supply chain actor (i.e., supplier, DC, set of customers), each connection between actors, warehouse policies, customer demand, but also and above all the disruptive events previously introduced and described.

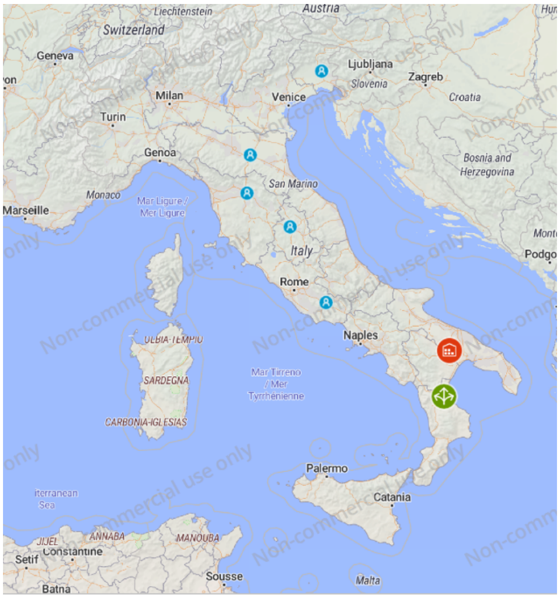

Fig. 2. Supply chain of the case study

Furthermore, anyLogistix made it possible to model and assess the performance of the supply chain under multiple scenarios, defined in Table 2.

Table 2. Scenarios of the case study

Scenario	D1	D2	D3	RS1	RS2	RS3
Scenario 0						
Scenario 1	✓					
Scenario 2		✓				
Scenario 3			✓			
Scenario 4	✓			✓		
Scenario 5		✓			✓	
Scenario 6			✓			✓
Scenario 7	✓	✓	✓			

Basically, scenarios 1-3 are extremely useful for assessing, separately, the impacts of disruptions on the supply chain. Scenarios 4-6, on the other hand, allow to evaluate separately the goodness of each response strategy with respect to each disruption. Scenario 7 takes into consideration the simultaneous occurrence of the 3 defined disruptions, without reacting. Finally, as it can be easily seen, Scenario 0 concerns the functioning of the supply chain under normal conditions.

4.3 Digital twin-driven decision-making: preliminary experimental results and discussion

In order to evaluate the effectiveness of the proposed framework, preliminary experiments were conducted, covering a month of work. Five runs were carried out and the simulation time was always few seconds. The discussion of the results is presented below, based on the mean value of the previously defined indicators:

- I_1: the analysis of this indicator was considered of interest especially for scenarios 1 and 4. In particular, the spread of an outbreak among operators, who remained unavailable for a period of approximately 10 consecutive days, was simulated. In the 5 runs considered, the beginning of this outbreak was varied. A worrying value of I_1 around 12% was noted, which through the application of RS1 was reduced almost completely.
- I_2: it was interesting to evaluate this indicator mainly under scenarios 2 and 5. The closure of the distribution center was simulated for a period of 8 days, the beginning of which varied in the 5 runs taken into consideration. Basically, due to the occurrence of D2, 7% of the products remained in the refrigerated warehouse, reaching a quality level not suited to customer standards. The application of the response strategy, concerning the activation of a new distribution center, made it possible to considerably reduce the amount of food wasted, but not to eliminate it, due to some wrong operational practices of the company.
- I_3: the impossibility of continuously guaranteeing the connection between the DC and the customer nodes, led to a reduction in the rate of satisfaction of the demand over time, under scenario 3. In this case, an outbreak of the transporters was simulated for a period of one week, the start of which was varied for each run. In this case, on the basis of the planned orders, I_3 assumed a value of around 15%, which was reduced to almost zero with the use of a 3PL.
- I_4 and R_1: the use of anyLogistix made it possible to evaluate the revenue under all scenarios, in the hypothesis of selling to final consumers all the products correctly delivered to the customer-nodes. In particular, it was noted that the proposed RSs could allow to cope very well with disruptions. Moreover, through the calculation of R_1 for each defined disruption, it was possible to realize that the supply chain is poorly resilient especially with respect to the disruption related to the lack of manpower in the fields.

The experiments carried out, referring to a very limited period of work, are not sufficient to make a final decision regarding the best response strategies. In fact, it would be necessary to evaluate their goodness at least over an entire harvesting season and with more indicators. However, the experimental campaign carried out shows that the proposed Simulation-Based Decision-Making Framework is extremely promising.

5. Conclusions

The recent COVID-19 pandemic has seriously affected manufacturing systems and global supply chains. This catastrophic, disruptive and unexpected event highlighted the limited resilience and sutainability of multiple systems and actors. As a consequence, scientific interest in the design of models capable of supporting decision-making for more sustainable and resilient supply chains has grown significantly in the last three years (i.e., 2020-2022). In this paper, a Simulation-Based Decision-Making Framework has been proposed, driven by the Digital Supply Chain Twin paradigm. Preliminary results on an agricultural case study demonstrated the usefulness of the framework in improving resilience and economic, environmental, and social sustainability indicators. However, the research carried out suffers from several limitations, which constitute ideas for possible future developments. First, only a limited number of indicators have been defined. In particular, as regards resilience, the future objective will be to exploit the model developed by Singh et al. [14], who associate resilience with concepts such as robustness, adaptability, visibility. Furthermore, the simulation covered only a month of work and, to have more exhaustive results, at least an entire harvesting season should be evaluated. In this context, future developments concern expanding the simulation time horizon, also to understand the impacts of medium-long term decisions, such as: the convenience in activating one or more distribution centers, the right amount of fee to correspond to a 3PL to have its availability in case of any emergency, the social and economic implications of making agreements with seasonal workers to be used only in case of need. Basically, it would be necessary to evaluate the proposed and tested response strategies from a broader perspective. However, this research represents a first significant step in the design and development of a ready-to-use decision support tool based on the simulation principles and novel concept of Digital Supply Chain Twin.

Acknowledgements

This work is part of the research project entitled "Smart Models for Agrifood Local vaLue chain based on Digital technologies for Enabling covid-19 Resilience and Sustainability" (SMALLDERS), co-funded by the PRIMA Program - Section 2 Call multi-topics 2021, through the following National Authorities: Ministry of Universities and Research (MUR, Italy), State Research Agency (AEI, Spain), Agence Nationale de la Recherche (ANR, France), Ministry of Higher Education and Scientific Research (Tunisia).

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