Journal of Simulation

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tjsm20

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JOURNAL OF SIMULATION
https://doi.org/10.1080/17477778.2024.2341015

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RESEARCH ARTICLE

A simulation model for addressing supply chain disruptions under a multi-capital sustainability perspective: a case study in the agri-food sector

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ABSTRACT

In recent years, interest in the resilience and sustainability of supply chains has significantly increased. In fact, various events, such as the COVID-19 pandemic, have highlighted the weakness of global and local supply chains. Further, people are giving increasing importance to concepts such as social well-being, human rights, environmental protection. The maximisation of shareholder value is no longer the only goal for companies. The main purpose of this paper is to answer the following question: is there a strategy to address agri-food supply chains disruptions while revitalising local economies and improving – at the same time – a number of sustainability-related aspects? To this aim, a simulation model is designed, then tested and validated through a supermarket supply chain case study. The results show that disruptions can be exploited to revitalise small local suppliers and simultaneously increase several sustainability indicators from a multi-capital perspective. Several managerial insights are also provided.

ARTICLE HISTORY
Received 26 June 2023
Accepted 18 March 2024

KEYWORDS
Simulation; disruption; resilience; sustainability; supply chain management

1. Introduction and scientific background

Some recent and disruptive events such as the spread of COVID-19 (H. Zhu et al., 2023), the Russia-Ukraine conflict (Jagtap et al., 2022), the Suez Canal blockage (Fan et al., 2022) have highlighted several supply chains weaknesses. As a main consequence, scientific interest in topics such as supply chain sustainability and resilience has significantly increased in the last few years (Sauer et al., 2022).

Further, it should be noted that the vision of sustainable development has progressively changed (Ruggerio, 2021; Z. Zhu et al., 2018): while in the past the utmost importance was given to the traditional managerial approach of maximising shareholder value, today people also look at other variables such as social well-being, human rights, environmental protection. If we refer specifically to the agri-food context, consumers, policy makers and organisations are putting pressure on the markets to improve resource management at each stage of the chain (Iakovou et al., 2015). Furthermore, consumers are increasingly demanding and expect reliable information on the quality, safety, origin of products, and the processes necessary to manufacture and distribute them (Sunny et al., 2020). Basically, organisations can no longer consider economic profitability as the one and only goal to be pursued, but paradigms are needed that are capable of simultaneously considering people, nature, society together with economic and financial aspects. In the literature, there are attempts that go in this direction (Atkisson & Hatcher, 2001; Figge et al., 2002; McElroy et al., 2015), but an effort is necessary to support companies from a more strictly quantitative perspective. In this challenging context, Longo et al. (2018) have recently reviewed and redefined the way to assess enterprise's performance, under a novel sustainability-oriented perspective, characterised by twelve capitals (see Table A1 in Appendix A for the meaning of each capital). This multi-capital perspective jointly considers aspects of different type: material, financial, linked to stakeholders and shareholders, relational, image, natural, ethical, intellectual, human, social (internal and external to the organisation). The overall aim is to assess company performance in a quantitative way considering not only economic, but also environmental and social factors, in accordance with the triple bottom line approach (Elkington, 1998).

Additionally, the recent global damaging events highlighted the need for more resilient systems (Falcone & Sapienza, 2023; Ivanov & Dolgui, 2020; Longo et al., 2022; Vanany et al., 2021), able to react effectively and efficiently to disruptions. To this aim, according to several scholars, short food supply chains (SFSC), represent a great opportunity (Bui et al., 2021; Malak-Rawlikowska et al., 2019; Sellitto et al., 2018). According to the European Union (Reg. 1305/13), a SFSC is "a supply chain involving a limited number of economic operators committed to cooperation, local economic development, and close geographical and social relations between producers, processors

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and consumers" (European Union, 2013). Placing production facilities very close to consumers means more flexibility and less vulnerability, when cross-border disruptions happen (Paciarotti & Torregiani, 2021). Additionally, in recent years consumers have become increasingly aware of the possible negative externalities linked to globalised food systems, therefore they often prefer a direct relationship with producers (Sellitto et al., 2018) and are willing to consume healthier foods (Nielsen, 2020), characterised by a more limited environmental impact (Paciarotti & Torregiani, 2021). It is very important to underline that the recent disasters, especially COVID-19, have emphasised even more the difficulties and problems of local food suppliers. According to McCullough et al. (2010), they generally operate under quite difficult conditions: inadequate infrastructures (e.g., roads, wholesale market), difficulties in accessing credit, few opportunities to develop business. Moreover, local food systems are usually unable to respond quickly and efficiently to shocks (e.g., disruptions of national economies).

There are two main perspectives in the literature when dealing with disruptions. The first refers to the geographical location. Hence, it is possible to deal with local (e.g., single factory closure) or global disruptions (some or all the actors of the supply chain are simultaneously affected). The second perspective refers instead to the supply chain functions, which are affected: supply-side disruption, demand-side disruption, production disruption, transportation disruption, and the combination of two or more of them (Chowdhury et al., 2020). In the past, various strategies have been proposed to adequately manage disruptions and make supply chain more resilient (Cheng et al., 2022; Fahimnia et al., 2016; M. Xu et al., 2014), such as inventory stockpiling or suppliers' diversification (Tomlin & Wang, 2009).

1.1. Research gaps and our contribution

Currently, most of the approaches proposed to deal with food supply chain disruptions concern COVID-19 outbreak. Some of the most relevant ones are listed below. Perdana et al. (2020) proposed a multi-objective location-routing model under uncertainty, with the aim to tackle the impact of COVID-19, through regional food hubs (RFHs), that connect producers in rural areas with customers in urban ones. S. Singh et al. (2020) proposed a simulation model, where supply of rice and wheat are examined within a real public distribution system network in India. Three different scenarios were considered: normal operations, failure of supply from a facility due to lockdown, activation of a backup facility to maintain a reasonable service level for the end customers. Q. Zhu and Krikke (2020) addressed the problem of managing a perishable food supply chain after an outbreak. They applied a systems dynamic simulation to a cheese supply chain with three tiers. Vali-Siar and Roghanian (2022) proposed a multi-objective linear programming model for dealing with a supply chain network design problem. The aim was to offer a tool for designing sustainable and resilient supply chains. For a broader view on the proposed approaches to face pandemic events, especially simulation-based, the reader is addressed to some recent and comprehensive literature reviews (Gupta et al., 2022; Pujawan & Bah, 2022; R. Singh & Mathirajan, 2022).

The COVID-19 pandemic also marked the spread of the anyLogistix tool (anyLogistix, 2023) within the scientific landscape. It is a software aimed at supporting supply chain management through the paradigms of optimisation and simulation. If you run a query on Scopus, using the word "anyLogistix" in the "Article title, Abstract, Keywords" field, only 32 documents come up in a time range from 2019 to 2024, confirming that the scientific interest is extremely recent. Specifically, only few papers so far have applied anyLogistix for solving issues in the agri-food sector. They are discussed below. Huang et al. (2021) proposed a simulation-based methodology to examine the effects of the pandemic on food supply chains. Specifically, lobster supply in different areas of Canada was considered as a case study. In this context, real events are simulated such as the closure of facilities and unexpected trends in product demand. Two research works (Vitorino, Costa, et al., 2022, 2022b) adopted anyLogistix to analyse the distribution of table grapes in Brazil. In this case, disruptions are not simulated, and the key performance indicators addressed are mainly economic and social. The paper by Burgos and Ivanov (2021) is quite pioneering and analyses the impact of the COVID-19 pandemic on food retail supply chains. Overall, it is possible to state that the number of papers that have so far adopted anyLogistix in the agri-food sector is extremely limited.

To be more exhaustive, Table 1 collects and classify the most relevant papers that have adopted simulation tools to address disruptions in the food supply chain. Five dimensions are considered: Product moved along the supply chain, Simulation Tool used, Disruption(s) addressed, Actors modelled within the supply chain (e.g., suppliers, producers, distributors, etc.), Key Performance Indicators (KPIs) adopted to assess the supply chain performance under different scenarios.

Based on the literature review, some research gaps clearly emerge:

- Despite the recent spread of simulation-based approaches to improve the resilience and sustainability of supply chains, to the best of our

Table 1. Relevant research regarding simulation-based approaches for addressing disruptions in the agri-food sector.

Reference	Product	Simulation Tool	Disruption(s)	Supply Chain Modelling	KPIs
Chakraborty and Sarmah (2020)	Food grains	Arena	Random supply (i.e., stock out at distributor level) and transportation (i.e., unavailability of vehicles) disruptions	Distributor, responsible for the replenishment of fair price shops	Inventory shortage, total system cost (i.e., ordering cost, transportation cost, holding cost)
S. Singh et al. (2020)	Rice and wheat	anyLogistix	Failure of supply from a facility due to lockdown	2 central warehouses, 3 state warehouses, 6 district-level warehouse, 60 fair price shops	Service level, revenue and total cost (i.e., profit)
Q. Zhu and Krikke (2020)	Cheese	Stella	Producer capacity disruption, logistic service provider disruption, hoarding disruption	Producer, logistic service provider, retailer	Shipment time of the logistic service provider, lost sales rate
Huang et al. (2021)	Lobster	anyLogistix	Closure of facilities, unexpected trends in product demand	2 suppliers, 2 distribution centres, 4 factories, 47 customers	Inventory (including backlog), service level, revenue and total cost (i.e., profit), lead time
Burgos and Ivanov (2021)	10 product categories	anyLogistix	Increase in demand, shutdown at suppliers' factories, bottleneck in transport	3 suppliers, 3 distribution centres, 28 supermarkets	Service level, lead time, financial indicators, available inventory
Rahman et al. (2022)	Potato	AnyLogic	Drought and snowstorm	Farmers, shippers, processors, retailers, consumers	Price, harvested amount, sales, revenue, lead time
Tsiamas and Rahimifard (2021)	Dairy	WITNESS	Road closure, shortage of ingredients	3 farmers, 1 dairy product manufacturer, 2 wholesalers	Dairy products manufactured and distributed
This paper	Mozzarella	anyLogistix	Unexpected increase in product demand, facility closure, labour shortage in transportation	7 factories, 1 DC, 9 supermarkets	Financial capital, natural capital, image capital, stakeholders-related capital, external social capital

knowledge, there are still no solutions in literature capable of exploiting the disadvantage caused by disruptions to jointly improve the conditions of small food producers.

- Using a multi-capital perspective to evaluate supply chain performance and make managerial decisions has not yet been explored.
- Scientific interest in anyLogistix has been growing in recent years, but there are still few contributions in the literature, despite the significant potential of this tool.

Therefore, our contribution can be summarised as follows:

- We propose and design a discrete-event simulation model, by using anyLogistix, with the aim to answer the following research question: is there a strategy to reduce agri-food supply chains disruptions while revitalising local economies and improving – at the same time – a number of sustainability-related aspects?
- We test and validate the proposed simulation model through a supermarket supply chain case study in Italy. The results show that agri-food supply chain disruptions can be addressed and even exploited to revitalise small local suppliers, and simultaneously increase several sustainability indicators from a multi-capital perspective.
- We provide managerial insights, concerning agri-food supply chain resilience and adaptability.

The remainder of this paper is organised as follows. Section 2 describes the main assumptions underlying the simulation model and the meaning of the indicators to discriminate the different scenarios. Sections 3 and 4 describe the case study and results related to the application of the simulation model, respectively. Section 5 provides useful managerial insights, which concern agri-food supply chain resilience and adaptability. The conclusions are summarised in Section 6.

2. Materials and methods

The proposed approach exploits the strengths of discrete-event simulation to support decision-makers in dealing with unexpected and disruptive events, with reference to supply chains. Simulation has always been recognised as a powerful tool for evaluating different scenarios efficiently and then making effective decisions on the real system (Banks, 1998). Specifically, in this paper, we consider the COVID-19 pandemic as an example of disruption, and we focus on the agri-food sector.

During the COVID-19 pandemic, agri-food chains were affected by supply- and demand-side disruptions (Puyawan and Bah, 2022). As regards supplies, travel restrictions imposed by governments have often caused delays with respect to the normal operation of the chain (Chinazzi et al., 2020). Moreover, the severe symptoms of the disease and its high contagiousness have frequently caused a shortage of workforce or even temporary closure of production departments, with the aim to limit its spread. The demand for agri-food products has instead shifted significantly to large-scale retail operators (e.g., supermarkets, hypermarkets, discounts), due to the imposed closure of bars, restaurants, open-air local markets, school canteens, shopping malls (and even due to the consumers fear of COVID-19 and their perception of the food quantity needed to survive to long lockdown periods) (Spiegel et al., 2021).

In this paper, we focus on the challenges faced, during the COVID-19 pandemic, by supermarket supply chains, which are intended as a particular case of agri-food supply chain where retailers are supermarkets. They are usually characterised by 4 main players or levels: suppliers, distribution centres, supermarkets, consumers. During the pandemic, supermarkets had to deal with conflicting situations: on the one hand, the sudden increase in demand from consumers and therefore the greater business opportunities, on the other the difficulties in procuring the required quantity of products in a resilient and efficient way. We refer to supermarket supply chains, characterised by the presence of both global and local suppliers. The distinction between the two types of suppliers is based on two fundamental concepts: (1) the proximity to the supermarket (retailer), (2) the size of the supplier. Basically, the global suppliers are large food producers located at a significant distance from the supermarket. On the contrary, the local suppliers are small producers, located sufficiently close to the supermarket. We make the following main assumptions regarding global suppliers:

- they are subject to significant supply-side disruptions as their procurement of raw materials and ancillary materials (e.g., packaging materials) takes place on a global basis, therefore it can be severely affected by restrictions imposed by different countries (Hayakawa & Mukunoki, 2021; Z. Xu et al., 2020);
- they deliver goods through long-haul tracks, therefore they are significantly influenced by any travel restrictions measures (e.g., limitations on moving between different areas) (Z. Xu et al., 2020);
- they are located in geographic areas, that were heavily affected by the pandemic, therefore there is a good chance of temporary closure of one or more departments, due to the high spread of infections (Z. Xu et al., 2020).

The following assumptions concern instead local suppliers:

- they have lost significant sales opportunities from the frequent closure of multiple local distribution channels such as bars, restaurants (Liu et al., 2022), open-air markets, shopping malls, school canteens (Benè, 2020);
- their deliveries to customers are scarcely influenced by any travel restrictions due to the pandemic as they concern very short routes (i.e., zero-kilometre deliveries) (Chi Ffoleau, 2020; Paciarotti & Torregiani, 2021).

From the assumptions made above, it is clear that in a pandemic period, the operators of large-scale retail had to make novel decisions to better face supply chain disruptions and to catch the new market opportunities, offered by the limitations imposed on the other distribution channels. Given a well-defined planning horizon, which can be divided into a set J of periods, we define Δ_j as the increase in product demand in period j at supermarkets, due to the pandemic, compared to the normal situation. The strategy proposed in this paper should be adopted by large-scale retail operators and consists in transferring this increase in demand from global to local suppliers, with the aim of limiting the damage of supply chain disruptions and, at the same time, revitalising local economies. Two additional parameters are considered:

- p: the percentage of Δ_j to be transferred equally from global to local suppliers;
- n: the number of new local suppliers with whom to activate supply contracts.

Multiple scenarios can be obtained by varying p and n. With the aim to assess the impact that different values of p and n have on agri-food supply chain performance, in Table 2 we define 10 indicators, that follow a multi-capital sustainability perspective (Longo et al., 2018). It is important to observe that they take into account not only economic but also social and environmental sustainability, in accordance with the triple bottom line approach (Correia, 2019):

- α_1 and α_2 mainly aim to assess the economic sustainability of the large-scale retail operator as they take into account revenues and profits, respectively.
- β refers to CO_2 emissions from vehicles, which transport food on two different supply chain stages: supplier-to-distribution centre, distribution centre-to-supermarket. The decrease in this indicator indicates that the large-scale retail operator pays attention to environmental wellbeing.
- Image capital is defined in two ways: γ_1 is the ratio between CO_2 emissions and revenues, then it answers the following question: how many kg of CO_2 are emitted for each € of revenue achieved? The decrease in this indicator, especially when linked to the simultaneous decrease in CO_2 emissions and increase in revenues, improves significantly the green image of the large-scale retail

Table 2. Multi-capital sustainability indicators.

Indicator: Category	Definition	Sustainability type addressed: Economic (Ec), Social (S), Environmental (En): Ec	S	En
Financial capital (α_1, α_2)	$\alpha_1 = revenuefromsupermarkets$	✓		
	$\alpha_2 = revenuefromsupermarkets - transportationcost - inventorycost(DC)$	✓		
Natural capital (β)	$\beta = CO_2emissionsfromvehicles$			✓
Image capital (γ_1, γ_2)	$\gamma_1 = \frac{CO_2 \text{emissions from vehicles}}{\text{revenue from supermarkets}}$	✓		✓
	$\gamma_2 = \frac{\text{traveled distance}}{\text{amount of products in the successful orders}}$		✓	✓
Stakeholders-related capital ($\theta_1, \theta_2, \theta_3$)	$\theta_1 = \frac{\text{number of successful orders}}{\text{number of total orders}}$		✓	
	$\theta_2 = \frac{\text{amount of products in the successful orders}}{\text{amount of products in all the orders}}$		✓	
	$\theta_3 = 1 - \frac{\text{lost revenue from unsuccessful orders}}{\text{potential revenue from all the orders}}$	✓		
External social capital ($\varepsilon_1, \varepsilon_2$)	$\varepsilon_1 = \frac{revenuefromlocalsuppliers}{totalrevenue}$		✓	
	$\varepsilon_2 = \frac{\text{number of local suppliers}}{\text{number of total suppliers}}$		✓	

operator, who can invest the growing economic resources in sustainable initiatives. γ_2 is the ratio between the distance travelled and the number of products in the successful orders (i.e., orders delivered on time and in the right quantities) and answers the following question: how many km are travelled for each kg of food delivered to supermarkets? The decrease in this indicator improves the perception that people have about the brand of the large-scale retail operator. Reducing the distance travelled means looking at environmental sustainability, while increasing the number of products successfully delivered to supermarkets means guaranteeing social equity, giving all consumers the opportunity to find food on the shelves, a crucial aspect during a pandemic event.

- As for the stakeholders-related capital, the increase of θ_1 and θ_2 goes towards social sustainability. In this context, we refer to two main stakeholders: supermarkets and consumers. The percentage increase in successfully fulfilled orders allows supermarkets to expand the range of products made available on the shelves and to emphasise their social role of guaranteeing food for the community, even in the presence of disastrous and unexpected disruptions. On the other hand, consumer satisfaction and trust in the large-scale retail operator's brand increase. θ_3 measures the percentage of revenues achieved compared to the total, on the basis of orders successfully fulfilled. The increase in this indicator improves the economic sustainability of supermarkets and meets the expectations of other stakeholders such as shareholders and banks.
- External social capital takes into account the importance of surrounding social communities. ε_1 computes how much revenue comes from local suppliers out of the total, while ε_2 refers to the percentage of active local suppliers out of the total. Increasing these two indicators improves social cohesion and reduces social disparities between global and local suppliers. Social disparities concern the different opportunities that large global producers have, compared to small local producers, who often have difficulty accessing credit and inadequate infrastructures (e.g., roads). Basically, despite the closure of multiple distribution channels, the large-scale retail operator gives local suppliers the opportunity to continue their business, even in a pandemic period, avoiding their collapse. This improves the perception from external actors, such as associations and political parties, towards the large-scale retail operator brand, which makes the revitalisation of the local economy possible. In addition, end consumers feel reassured to find local products on the shelves, as they are easier to be tracked & traced.

3. Case study

With the aim to demonstrate the validity and usefulness of the proposed strategy, we address a real-life case study, which refers to a supermarket supply chain, located in Italy.

3.1. Data, information and simulation model

Our case study refers to an existing Italian supermarket supply chain, characterised by three main levels: factory (i.e., supplier), distribution centre, supermarket. We focus on mozzarella, which is one of the dairy products whose demand has increased the most during the COVID-19 pandemic in Italy. The factories are responsible for the procurement of raw materials and the manufacturing of finished products. The distribution centre (DC) collects the supplies from the different factories and sends the products to the supermarkets, which deal with sales to final consumers. The case study includes 7 factories, 1 DC and 9 supermarkets, that are located in Cosenza, which is one of the main cities in Calabria, a region in Southern Italy. For data confidentiality reasons, the retailer's name cannot be revealed. Figure 1 shows the considered three-level supply chain.

The simulation model was designed and built through a map, to geolocate all the nodes of the agri-food supply chain of the case study, and tables for entering the input data. It was implemented through the software anyLogistix on a PC running Windows 10 Pro with AMD Ryzen 7 2700X Eight-Core Processor 4.00 GHz/16 GB. It should be observed that all the main challenges faced by the agri-food supply chains during the COVID-19 pandemic have been taken into account: travel restrictions, labour shortage, closures due to outbreaks. There are 4 suppliers located in Northern Italy, which are labelled as global, while there are two in Calabria, which are considered local. Further, there is a supplier located in the East area, which is considered hybrid (i.e., neither global nor local) as it is large in size, but it is "close enough" to supermarkets.

Basically, to define each scenario we have built and filled in a set of tables with critical information that concern the characteristics of the agri-food supply chain of the case study (e.g., Customers, DCs and Factories, Demand, Events, Products, Vehicle Types, etc.). The demand from supermarkets was assumed to be daily and with uniform distribution, the minimum and maximum values of which are respectively 10% lower and higher than the average value, which is the result of historical data. This choice was motivated by the fact that, based on historical data provided by supermarkets, it was noted that within certain time intervals of limited length, the uniform distribution approximates demand behaviour very well. Note that the average value of this uniform distribution is not constant during the year but varies depending on the time period. Two types of vehicles were considered for transport: large and small. The first has a capacity of 1,100 kg and is used to transport mozzarella from the suppliers to the distribution centre. The second has a capacity of 600 kg and handles the transport of products from the distribution centre to the different supermarkets. For both of them, an average speed of 70 km/h was assumed, based on the historical data available in terms of travel times. As regards the calculation of the cost of transport and CO_2 emissions, a direct proportionality with the distance travelled was assumed. In all cases, a less than truckload (LTL) policy was adopted, which means that the truck does not necessarily travel with a maximum load, but can also travel partially loaded. With regard to inventory management, the following assumptions were made: the backorder policy is never allowed for supermarkets and the expected lead time is equal to 2 days. This means that, in the event of delays due to travel restrictions or labour shortages, orders are lost. For the DC, a min-max policy and an initial stock were assumed, deriving from historical data. The price of the products considered is real and therefore differs based on the brand. The carrying cost (with reference to the DC) was considered to be 3% of the market value of each product.

Simulation was run for a period of 12 months, in order to exactly reproduce what happened in Italy throughout 2020. Two kinds of supply-side disruptions have been

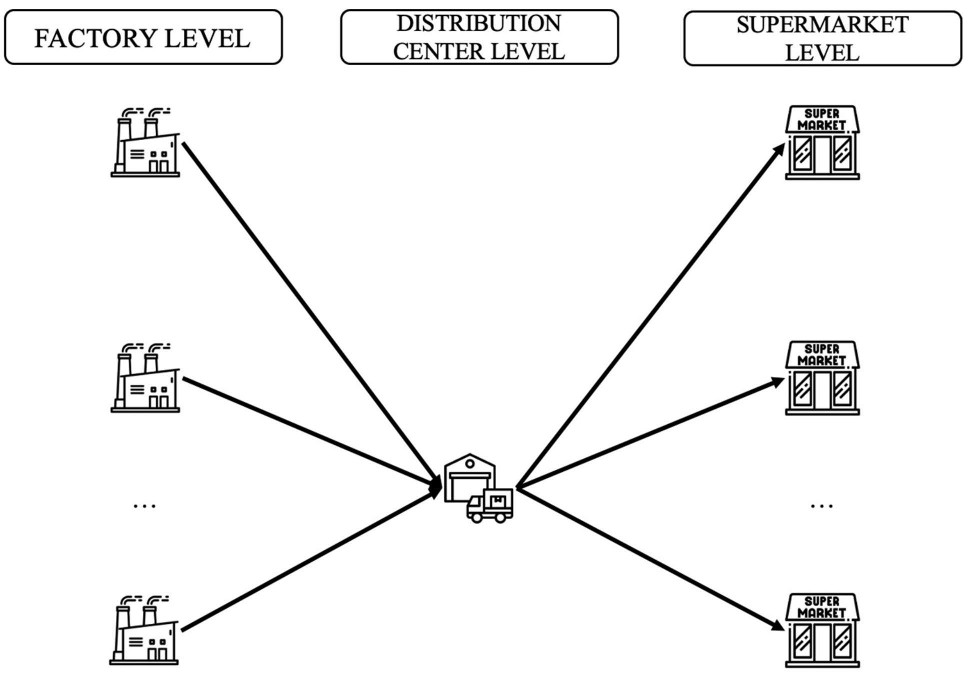

Figure 1. Three-level supply chain of the case study.

considered: temporary closure of a factory (due to a significant increase in workers infections), inability to deliver goods (due to labour shortage). More details about the supply-side disruptions are shown below. In particular, the periods indicated for the temporary closure of factories are those in which the peaks of infections occurred in 2020 in Italy. Supply-side disruptions were only supposed for global suppliers, in accordance with the assumptions contained in Section 2:

1. Supply-side disruption: Temporary closure of one or more factories, due to a significant increase in workers infections.

Periods: March 17-30 2020 (two weeks), November 10-16 2020 (one week), December 21-27 2020 (one week).

Implications:For each of the periods indicated, the simulation model randomly chooses one or more of the 4 factories located in Northern Italy and imposes a temporary closure, with consequent interruption of production activities.

2. Supply-side disruption: Inability to deliver goods, due to unavailability of operators (labour shortage because of multiple infections).

Period: February 23 2020–December 31 2020.
For each week of the indicated period, the simulation model randomly selects one or more of the 4 suppliers located in Northern Italy and prevents the delivery of the goods for two consecutive days.

As regards the demand-side disruptions, we referred to the data made available by Italian National Institute of Statistics (ISTAT) and Institute of Services for the Agricultural and Food Market (ISMEA), which highlighted a significant increase in dairy product sales in 2020 compared to 2019 (ISTAT, 2020; ISMEA 2020; ISMEA 2021). Eleven scenarios were designed to demonstrate the validity of the proposed strategy (see Table 3), which aims to mitigate the effects of supply chain disruptions caused by COVID-19, revitalise local economies, increase the performance of the chain from the point of view of economic, social, and environmental sustainability. The proposed scenarios vary according to the variation of p and n. In this case, the planning horizon is the year 2020, which can be divided into a set $J = \{1, 2, \ldots, 12\}$ of months. The parameter Δ_j, $j \in J$, represents the increase in demand for mozzarella at supermarkets in month j, compared to the same period in 2019. Since in Italy, the supply chain disruptions occurred starting from March, we have imposed $\Delta_1 = \Delta_2 = 0$. Table 3 shows the main characteristics of the 11 scenarios of the simulation model. Basically, the first 4 scenarios foresee that, for each period, the supply-side disruptions concern one and only one global supplier (SS = Scenario with Single simultaneous closure of global suppliers). Conversely, the last 7 scenarios impose multiple simultaneous supply-side disruptions for global suppliers (SM = Scenario with Multiple simultaneous closure of global suppliers). The meaning of the variation of p and n is explained below:

- $p = 0$: no new agreements are made with local suppliers in terms of shifting the demand for goods from global suppliers.
- $p = 50, 75, 100; n = 0, 1, 2$: following the not very reassuring news from China and in the proximity of the spread of the pandemic in Italy, agreements are made between the large-scale retailer and the $(2 + n)$ local suppliers, which belong to a cooperative. According to the agreement, the members of the cooperative undertake to deliver a greater amount of goods, to compensate for any supply-side disruptions concerning the factories located in Lombardy and Emilia-Romagna, whose significant distance makes the supply chain less resilient. In practical terms, the simulation model transfers p % of $_j$, $j = \{March, April, \ldots, December\}$, with reference to the 4 suppliers in the Northern Italy, equally between the $(2 + n)$ active local suppliers. The increase in demand is evenly distributed among local suppliers as they are small producers, who have similar dimensions and market capabilities.

Table 3. The eleven scenarios of the simulation model.

			Simultaneous closure of global suppliers	
Scenario	*p*	*n*	Single	Multiple
SS1	0	0	✓	
SS2	50	0	✓	
SS3	75	1	✓	
SS4	100	2	✓	
SM1	0	0		✓
SM2	50	1		✓
SM3	50	2		✓
SM4	75	0		✓
SM5	75	2		✓
SM6	100	0		✓
SM7	100	1		✓

Before showing and discussing the results of the simulation, in Figure 2 it is represented the flowchart used for carrying out this study. The first phase consisted in formulating the problem in a clear and concise manner, with the aim of identifying parameters and constraints. Then, the main objectives of the study were set. Subsequently, we proceeded with a conceptualisation of the simulation model, and in parallel with a collection of data regarding the supply chain considered (i.e., characteristics and geographical positioning of nodes and arcs, historical data, inventory policies, distribution policies, etc.), with the aim of modelling it in the most realistic way. At this point, the conceptual model was translated into a simulation

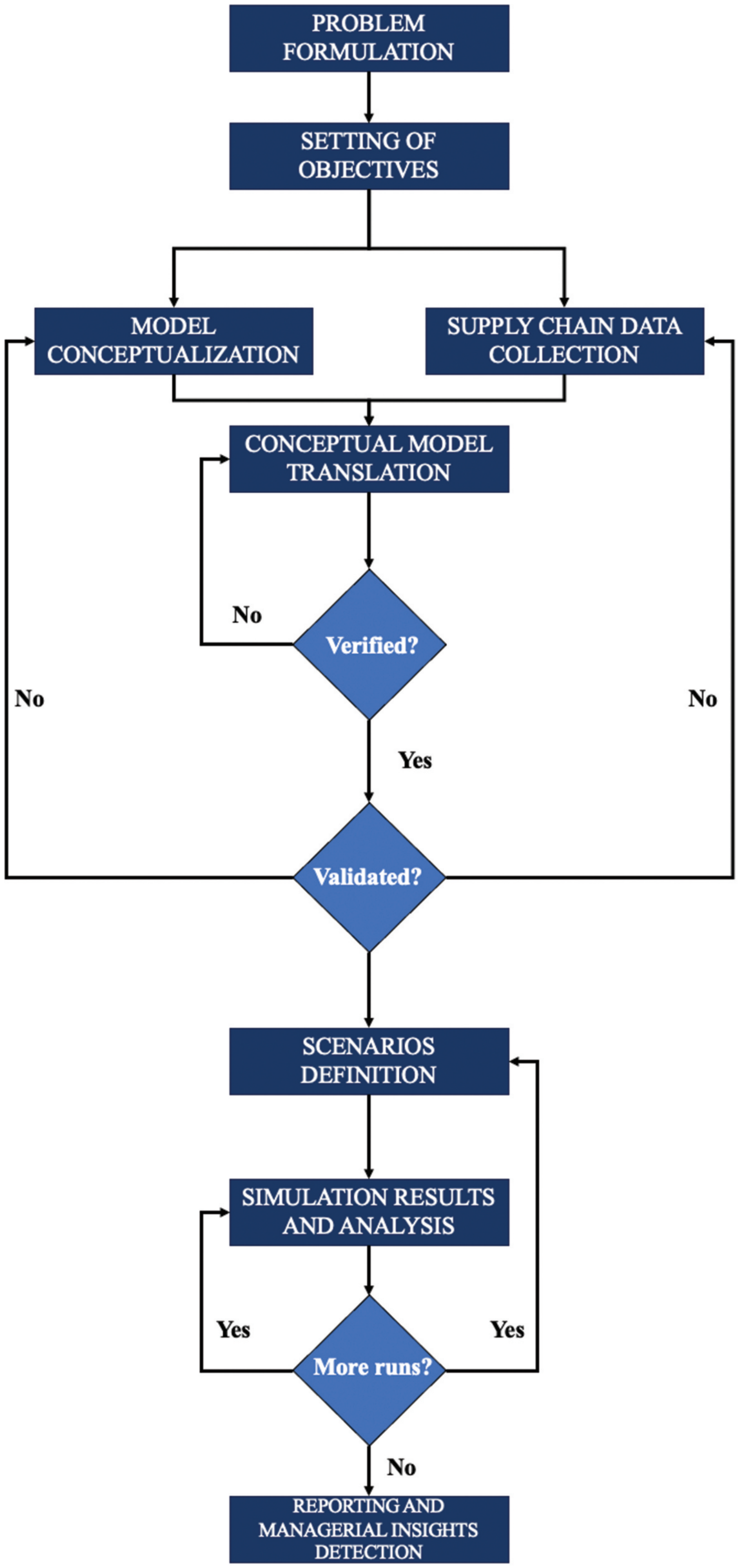

Figure 2. Flowchart of the approach used, adaptation from Banks (1998).

model using the anyLogistix tool. First, through test runs, a check was made on its technical correctness, through multiple iterations. Then, the model was validated, checking its ability to faithfully reproduce the behaviour of the real system. Once the verification and validation phases were carried out, the scenarios to be tested were defined (see Table 3) and the related number of replications. At this point, the model has been run. Note that in a first iteration only the SS type scenarios were defined, but later was it deemed necessary to introduce the SM type scenarios. The reporting in Section 4 was then constructed and the managerial insights described in Section 5 were detected.

4. Results and discussion

In this section, we report and discuss the results related to the execution of the simulation model previously described. 10 replications were performed for each scenario. Each replication took a few seconds in terms of simulation time. Tables 4–10 point out the respective values of the multi-capital sustainability indicators, in order to assess the performance of the supermarket supply chain, under the different scenarios designed. We show for each scenario and for each indicator, the mean (μ), the max and min values over the 10 replications; moreover, we compute the standard deviation (stdDev) and the 95% confidence interval. The results are very promising and interesting. The proposed strategy increases the resilience and sustainability of the supply chain not only economically, but also from a social and environmental point of view. The discussion presented below refers to the mean values of each indicator. It must be specified that, considering the hypotheses presented in Table 3 regarding the simultaneous (single or multiple) closure of global suppliers, a full and coherent comparison is possible respectively between scenarios SS1-SS4 and SM1-SM7, respectively.

Table 4 shows the results about financial capital under the different scenarios. α_1 significantly increases from SS1 to SS4. Specifically, the transfer of a part of the product demand from suppliers in Northern Italy to existing local suppliers leads to an increase in revenues of 3.40% under SS2, compared to the starting situation (SS1). On the other hand, when two new local suppliers are activated (SS4), for a total of 4, such an increase is even 6.22%. In the event of possible simultaneous closure of multiple global suppliers (i.e., SM1-SM7), revenue losses increase significantly, and the use of local suppliers becomes even more critical in an attempt to minimise the economic damage suffered by the large-scale retail operator. In fact, in the absence of agreements with local suppliers, the possible simultaneous closure of multiple global suppliers (see SM1) leads to a reduction in revenue of 7.46% compared to the case of single closure (SS1). As it can be noted, the effect of these multiple supply-side disruptions is well mitigated, by increasing the parameter p: basically, α_1 increases as p increases, therefore going respectively from SM1 to SM2-SM3, SM4-SM5, SM6-SM7. When p is constant, the deviations in revenue are mainly due to the differences in the price of local products: for example, in SM4 the increase in product demand is divided between the two existing local suppliers, while in SM5 there are also two new suppliers entering the market with a slightly more limited price for reasons of competitiveness, hence the 0.77% reduction in revenue from SM4 to SM5. It should be noted that also the other component of the financial capital (α_2), follows a very similar trend. Specifically, α_2 increases from SS1 to SS4 up to 11.25%. When

Table 4. Values of $\alpha_1 = \textit{revenue from supermarkets}$ and $\alpha_2 = \textit{revenuefromsupermarkets} - \textit{transportationcost} - \textit{inventorycost}(DC)$ under the 11 scenarios.

Scenario	Indicator	Mean [€]	Min [€]	Max [€]	StdDev [€]	95% confidence interval [€]
SS1	α_1	762,865.53	761,868.99	764,537.76	795.44	(762,296.55; 763,434.52)
	α_2	495,993.91	494,459.64	497,333.14	792.35	(495,427.14; 496,560.68)
SS2	α_1	788,797.68	788,067.04	789,433.31	511.46	(788,431.83; 789,163.53)
	α_2	536,628.14	535,785.58	537,436.26	529.04	(536,249.72; 537,006.57)
SS3	α_1	798,649.20	798,121.70	799,264.50	306.92	(798,429.66; 798,868.74)
	α_2	547,891.97	547,423.62	548,454.52	283.08	(547,689.49; 548,094.46)
SS4	α_1	810,352.09	809,467.22	810,780.90	369.82	(810,087.55; 810,616.62)
	α_2	551,823.46	550,919.10	552,279.02	372.58	(551,556.95; 552,089.96)
SM1	α_1	705,926.60	703,806.27	709,215.15	1,774.78	(704,657.08; 707,196.11)
	α_2	463,270.31	461,034.19	467,289.04	2,044.76	(461,807.69; 464,732.95)
SM2	α_1	735,188.83	731,281.14	738,774.65	2,127.60	(733,666.94; 736,710.72)
	α_2	497,979.31	494,027.95	500,780.89	2,171.99	(496,425.67; 499,532.95)
SM3	α_1	735,144.62	732,527.50	738,245.39	1,934.54	(733,760.83; 736,528.42)
	α_2	491,910.36	489,952.07	495,013.80	1,658.61	(490,723.94; 493,096.78)
SM4	α_1	758,185.37	757,272.50	760,361.01	1,019.21	(757,456.32; 758,914.42)
	α_2	522,827.32	521,852.81	524,570.07	840.50	(522,226.10; 523,428.54)
SM5	α_1	752,384.56	750,007.81	755,189.37	1,375.17	(751,400.89; 753,368.22)
	α_2	510,692.01	507,612.43	513,552.65	1,550.69	(509,582.80; 511,801.23)
SM6	α_1	776,808.37	776,096.26	778,372.58	703.78	(776,304.95; 777,311.79)
	α_2	540,368.44	539,674.35	541,640.70	637.60	(539,912.36; 540,824.52)
SM7	α_1	770,557.45	769,834.56	771,498.95	477.91	(770,215.59; 770,899.30)
	α_2	531,963.47	531,308.43	532,872.00	441.59	(531,647.60; 532,279.35)

simultaneous closure of multiple global suppliers (i.e., SM1-SM7) happen, revenue losses increase significantly, then α_2 decreases (i.e., comparison between SM1-SM7 and SS1-SS4). Regarding the increase in profit (i.e., the difference between revenue from supermarkets and the sum of inventory and transportation costs), we can say that it lies mainly in the decrease in transportation costs in the scenarios in which local suppliers are exploited more.

In Table 5, we show the results relating to natural capital, which considerably improves in SS2, SS3, and SS4, compared to SS1. Basically, the use of local suppliers reduces the travelled distance, consequently CO_2 emissions. In the event that simultaneous closures of global suppliers are possible (SM1-SM7), the trend of average reduction of β is confirmed, when greater importance is given to local suppliers (SM2-SM7 compared to SM1). The only exception is SM3, where a slight worsening of the natural capital, compared to SM1, can be noted, mainly due to the fact that a very high number of additional orders can be successfully carried out and therefore further distances, albeit limited, must be covered. The minimum value of natural capital is reached in SM4, where the distribution of the increase in product demand to only the two existing local suppliers involves a reduction of 4.05% compared to the starting situation in which there is no agreement with local suppliers (SM1). The improvement of natural capital, achieved through the greater importance given to local suppliers, demonstrates to the different stakeholders the interest of the large-scale retail operator towards environmental sustainability issues. Finally, it can be noted that, given the same p (e.g., SM4 and SM5, SM6 and SM7), β increases as n increases. The main cause of this behaviour is due to the greater distance travelled, considering that the availability of more suppliers increases the orders that can be fulfilled more successfully.

The results are also very encouraging from the point of view of image capital (see Tables 6–7), which improves under SS2, SS3, SS4, compared to SS1. γ_1, which represents the amount of kg of CO_2 emitted for each € of revenue achieved, decreases between 8.80% and 10.49%, when local suppliers are better exploited. At the same time, γ_2 is reduced between 4.47% and 7.46%, therefore it is necessary to travel a more limited number of km for each kg of food delivered to supermarkets. When simultaneous closures of global suppliers are allowed (SM1-SM7), the reduction of γ_1 in scenarios where local suppliers are better exploited fluctuate between 3.29% and 12.45% compared to SM1 (no agreements with local suppliers). Under the same operating conditions, the improvement in γ_2 varies between 1.17% and 8.00%. The reduction of γ_1 and γ_2 improves the image of the large-scale retail operator both from an environmental and a social point of view. On the one hand, the reduction of distances travelled and then CO_2 emissions feeds the green perception of the brand. On the other hand, the increase in the quantity of food delivered successfully goes towards social equity: basically,

Table 5. Values of $\beta = CO_2 emissionsfromvehicles$ under the 11 scenarios.

Scenario	Mean [kg]	Min [kg]	Max [kg]	StdDev [kg]	95% confidence interval [kg]
SS1	428,948.20	427,565.15	429,764.37	685.93	(428,457.55; 429,438.84)
SS2	404,476.30	403,783.29	405,446.47	508.35	(404,112.67; 404,839.93)
SS3	401,959.31	401,851.59	402,058.03	79.83	(401,902.21; 402,016.42)
SS4	415,553.79	415,487.19	415,736.81	78.01	(415,497.99; 415,609.59)
SM1	389,782.50	388,175.39	390,967.02	887.83	(389,147.42; 390,417.57)
SM2	380,377.05	378,519.97	381,681.16	1,005.76	(379,657.62; 381,096.47)
SM3	392,581.07	390,228.03	394,517.58	1,225.86	(391,704.20; 393,457.93)
SM4	374,010.39	372,624.66	375,749.35	1,048.95	(373,260.07; 374,760.72)
SM5	389,673.09	389,079.84	391,140.08	695.90	(389,175.31; 390,170.87)
SM6	375,507.07	375,330.54	375,656.19	100.95	(375,434.86; 375,579.28)
SM7	379,863.50	379,711.54	380,110.16	130.05	(379,770.47; 379,956.52)

Table 6. Values of $\gamma_1 = \frac{CO_2 emissionsfromvehicles}{revenuefromsupermarkets}$ under the 11 scenarios.

Scenario	Mean [kg/€]	Min [kg/€]	Max [kg/€]	StdDev [kg/€]	95% confidence interval [kg/€]
SS1	0.56229	0.56065	0.56409	0.00091	(0.56163; 0.56294)
SS2	0.51277	0.51192	0.51415	0.00065	(0.51231; 0.51324)
SS3	0.50330	0.50303	0.50356	0.00016	(0.50319; 0.50341)
SS4	0.51281	0.51254	0.51331	0.00022	(0.51265; 0.51296)
SM1	0.55216	0.54909	0.55376	0.00173	(0.55092; 0.55340)
SM2	0.51739	0.51503	0.51970	0.00153	(0.51630; 0.51848)
SM3	0.53402	0.52981	0.53702	0.00248	(0.53225; 0.53580)
SM4	0.49330	0.49006	0.49499	0.00159	(0.49216; 0.49443)
SM5	0.51792	0.51631	0.51927	0.00102	(0.51719; 0.51864)
SM6	0.48340	0.48222	0.48403	0.00051	(0.48303; 0.48376)
SM7	0.49280	0.49225	0.49354	0.00036	(0.49271; 0.49323)

Table 7. Values of $\gamma_2 = \frac{traveled\ distance}{amount\ of\ products\ in\ the\ successful\ orders}$ under the 11 scenarios.

Scenario	Mean [km/kg]	Min [km/kg]	Max [km/kg]	StdDev [km/kg]	95% confidence interval [km/kg]
SS1	25.8792	25.8006	25.9509	0.0409	(25.8499; 25.9085)
SS2	24.3086	24.2674	24.3656	0.0277	(24.2888; 24.3285)
SS3	24.0835	24.0725	24.0969	0.0073	(24.0783; 24.0888)
SS4	24.7709	24.7538	24.7938	0.0110	(24.7630; 24.7787)
SM1	26.0117	25.8609	26.1786	0.1065	(25.9356; 26.0879)
SM2	24.8978	24.7273	25.0592	0.0945	(24.8302; 24.9654)
SM3	25.7065	25.5133	25.9852	0.1143	(25.6248; 25.7883)
SM4	24.1694	24.0816	24.3286	0.0722	(24.1177; 24.2210)
SM5	25.2230	25.1440	25.3773	0.0774	(25.1677; 25.2784)
SM6	23.9308	23.9014	23.9615	0.0169	(23.9187; 23.9429)
SM7	24.2421	24.1571	24.2980	0.0399	(24.2135; 24.2706)

despite harmful and unexpected supply chain disruptions, it is crucial to ensure that everyone can find food on the shelves.

The greater use of local suppliers also leads to an improvement in stakeholders-related capital, as shown in Table 8. θ_1 grows from 96.5% to 97.5%, shifting from SS1 to SS4, then a greater number of orders is successfully fulfilled. In scenarios where simultaneous closure of multiple global suppliers is possible (SM1-SM7), this indicator drops considerably to 90.4%, in case of no agreements with local suppliers (SM1). However, even in this case, the greater use of local suppliers guarantees greater fulfilment of orders and θ_1 reaches values between 91.1% and 92.8% (SM2-SM7). This leads to a significant improvement in satisfaction from supermarkets, but above all from final consumers, who are more likely to find the product they need on the shelf. This is a crucial aspect during a pandemic. The trend is similar for θ_2 and θ_3. In particular, the growth of θ_3 tends to reduce the loss of revenues due to unfulfilled orders and this particularly improves the satisfaction rate of each supermarket.

SS2, SS3, and SS4 also guarantee growth in external social capital, compared to SS1, as shown in Table 9. ε_1 increases from 16.82% to 31.38% and this means that the share of revenues deriving from local suppliers grows. The same happens when there is the possibility of simultaneous closure of multiple global suppliers (SM1-SM7): in this case, from the starting value of 18.18% (SM1), such an indicator fluctuates between 26.02% and 33.60%. These trends are extremely

Table 8. Values of $\theta_1 = \frac{numberofsuccessfulorders}{numberoftotalorders}$, $\theta_2 = \frac{amountofproductsinthesuccessfulorders}{amountofproductsinalltheorders}$, $\theta_3 = 1 - \frac{lostrevenuefromunsuccessfulorders}{potentialrevenuefromalltheorders}$ under the 11 scenarios.

Scenario	Indicator	Mean	Min	Max	stdDev	95% confidence interval
SS1	θ_1	0.96514	0.96439	0.96639	0.00069	(0.96465; 0.96563)
	θ_2	0.94846	0.94748	0.95035	0.00095	(0.94778; 0.94914)
	θ_3	0.954	0.953	0.955	0.00082	(0.953; 0.954)
SS2	θ_1	0.96579	0.96504	0.96639	0.00042	(0.96549; 0.96609)
	θ_2	0.95438	0.95337	0.95522	0.00058	(0.95396; 0.95479)
	θ_3	0.961	0.960	0.961	0.00052	(0.960; 0.961)
SS3	θ_1	0.97073	0.97051	0.97086	0.00012	(0.97064; 0.97082)
	θ_2	0.95868	0.95834	0.95897	0.00020	(0.95854; 0.95883)
	θ_3	0.965	0.964	0.965	0.00048	(0.964; 0.965)
SS4	θ_1	0.97548	0.97536	0.97567	0.00011	(0.97540; 0.97556)
	θ_2	0.96403	0.96372	0.96431	0.00021	(0.96388; 0.96417)
	θ_3	0.970	0.969	0.970	0.00052	(0.969; 0.970)
SM1	θ_1	0.90432	0.90121	0.90663	0.00175	(0.90307; 0.90557)
	θ_2	0.85855	0.85403	0.86395	0.00326	(0.85621; 0.86089)
	θ_3	0.883	0.878	0.886	0.00222	(0.881; 0.884)
SM2	θ_1	0.91712	0.91436	0.92046	0.00198	(0.91571; 0.91854)
	θ_2	0.87725	0.87447	0.88021	0.00186	(0.87592; 0.87857)
	θ_3	0.898	0.894	0.903	0.00280	(0.896; 0.900)
SM3	θ_1	0.92628	0.92426	0.92796	0.00116	(0.92544; 0.92711)
	θ_2	0.87743	0.87412	0.87924	0.00172	(0.87619; 0.87865)
	θ_3	0.898	0.896	0.900	0.00125	(0.897; 0.899)
SM4	θ_1	0.91099	0.90892	0.91365	0.00126	(0.91009; 0.91190)
	θ_2	0.88905	0.88708	0.89171	0.00140	(0.88805; 0.89005)
	θ_3	0.910	0.908	0.913	0.00145	(0.909; 0.911)
SM5	θ_1	0.92817	0.92709	0.93005	0.00083	(0.92758; 0.92876)
	θ_2	0.88831	0.88555	0.89101	0.00162	(0.88715; 0.88947)
	θ_3	0.910	0.908	0.914	0.00181	(0.909; 0.911)
SM6	θ_1	0.91625	0.91595	0.91660	0.00019	(0.91612; 0.91639)
	θ_2	0.90094	0.90059	0.90138	0.00029	(0.90073; 0.90114)
	θ_3	0.922	0.921	0.923	0.00084	(0.921; 0.922)
SM7	θ_1	0.92561	0.92491	0.92665	0.00050	(0.92525; 0.92597)
	θ_2	0.90129	0.90065	0.90465	0.00099	(0.90067; 0.90200)
	θ_3	0.921	0.920	0.921	0.00032	(0.921; 0.921)

Table 9. Values of $\varepsilon_1 = \frac{revenue from local suppliers}{total revenue}$ under the 11 scenarios.

Scenario	Mean	Min	Max	StdDev	95% confidence interval
SS1	0.1682	0.1679	0.1685	0.00018	(0.1681; 0.1683)
SS2	0.2468	0.2463	0.2470	0.00020	(0.2466; 0.2469)
SS3	0.2805	0.2803	0.2805	0.00011	(0.2804; 0.2806)
SS4	0.3138	0.3135	0.3138	0.00018	(0.3137; 0.3139)
SM1	0.1818	0.1810	0.1822	0.00042	(0.1815; 0.1821)
SM2	0.2608	0.2596	0.2620	0.00071	(0.2603; 0.2613)
SM3	0.2602	0.2593	0.2612	0.00065	(0.2597; 0.2606)
SM4	0.3004	0.2994	0.3008	0.00045	(0.3000; 0.3007)
SM5	0.2962	0.2953	0.2973	0.00052	(0.2958; 0.2966)
SM6	0.3360	0.3354	0.3364	0.00030	(0.3358; 0.3362)
SM7	0.3309	0.3306	0.3314	0.00025	(0.3307; 0.3311)

Table 10. Values of $\varepsilon_2 = \frac{number\ of\ local\ suppliers}{number\ of\ total\ suppliers}$ under the 11 scenarios.

Scenario	Value
SS1	0.2857
SS2	0.2857
SS3	0.3750
SS4	0.4444
SM1	0.2857
SM2	0.3750
SM3	0.4444
SM4	0.2857
SM5	0.4444
SM6	0.2857
SM7	0.3750

important because the perception of the retailer brand by society grows considerably. Local citizens are happy to see an increase in the number of local products on the shelves, especially in a historical period when local economies are severely impacted. The greater incidence of local economies on global economies is also confirmed by the growth of the second component of external social capital, ε_2, which goes from 28.57% to 44.44% (see Table 10).

For clarity reasons, Figure 3 shows the trend of the 10 previously mentioned and discussed indicators under the 11 different scenarios. Observe that to guarantee full understanding and readability of Figure 3, the two scenarios SS1 and SM1, which represent the lack of agreements with local suppliers respectively in situations of single and multiple simultaneous closure of global suppliers, are marked in black. Basically, looking at the figure, the reader is invited to visually compare separately SS1 with SS2-SS4, and SM1 with SM2-SM7. In this way, it is really easy to notice the improvement (intended as an increase or decrease, based on the meaning) of each indicator under the scenarios that concern greater involvement of local suppliers.

The reliability of the previously described results is confirmed by the 95% confidence interval. In the vast majority of cases, there is no intersection between the 95% confidence intervals. The main exceptions can be found in pairs of scenarios that both concern agreements with suppliers (with the aim of facing supply chain disruptions), and have the same value of p.

Basically, the results show that there are effective strategies to face the pandemic in agri-food chains, transforming a critical and dangerous situation into an advantage: the revitalisation of local economies, from a multi-capital sustainability perspective.

5. Managerial insights

The approach tested in this article and the results obtained are extremely useful for supporting the decision-making of managers of large-scale retail, during critical and unexpected crises such as the COVID-19 pandemic. Some important managerial insights are framed in Figure 4. The crisis, albeit global and unexpected, is characterised by a phase in which it shows the first symptoms. At this stage, the large-scale retail manager should make agreements with existing local suppliers to have more foodstuffs, in order to make the supply chain ready to face the most acute phase of the crisis. To give an example, a manager of an Italian supermarket supply chain would have had to make agreements with local suppliers immediately after the first cases of COVID-19 infection in China and then in Europe. In the most critical moment of the crisis, in order to respond effectively and efficiently to supply-side and demand-side disruptions, managerial insights consist in partially transferring the demand for food from global to local suppliers. This approach makes the supply chain more resilient because the number of successfully fulfilled orders can be maximised and food on the shelf guaranteed to consumers. After the first disruptive events, the early supply chain to-the-event-adaptations occur, therefore the manager should effectively face the crisis situation and derive benefits. At this stage, the suggestion is to activate additional local suppliers to definitely transform the disadvantaged situation into a significant advantage from an economic, environmental and social point of view. A new normal is expected after the most acute and harmful phase of the crisis. In this context, it is important that the large-scale retail manager communicates the results obtained externally to reinforce the image, the brand, and therefore the perception by the majority of the stakeholders. The media should be used to translate the indicators

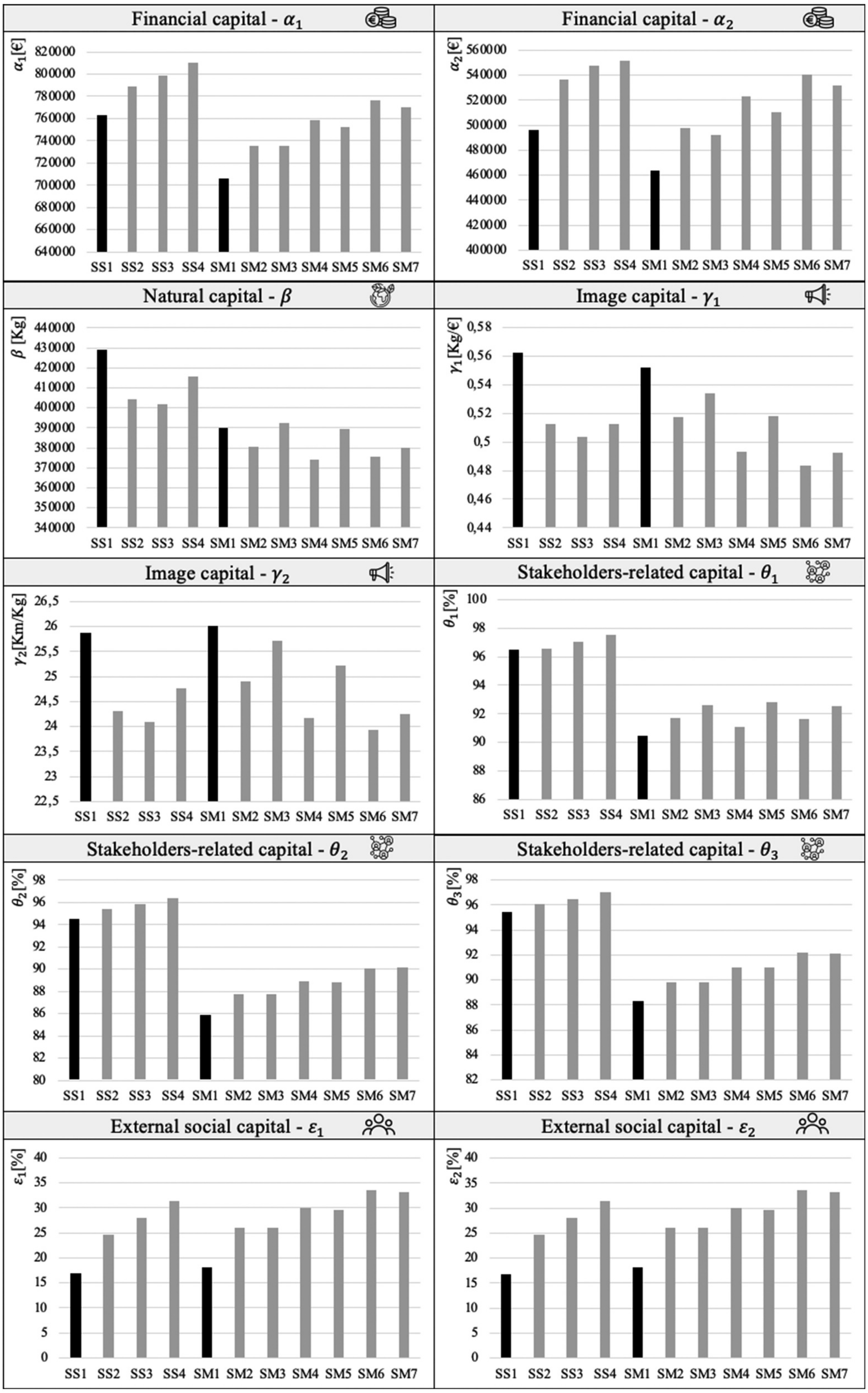

Figure 3. Trend of all the indicators under the 11 scenarios.

into something understandable to all. From an environmental point of view, the reduction in CO_2 emissions achieved through the use of shorter routes should be emphasised. From an economic point of view, the growth of revenues and profits should be highlighted to increase the confidence of shareholders and banks, but any investments in sustainable initiatives should also be communicated. Furthermore, the social role played by the large-scale retail operator, during the crisis, should be widely stressed. In fact, the adopted approach goes towards cohesion and social equity, as food on the

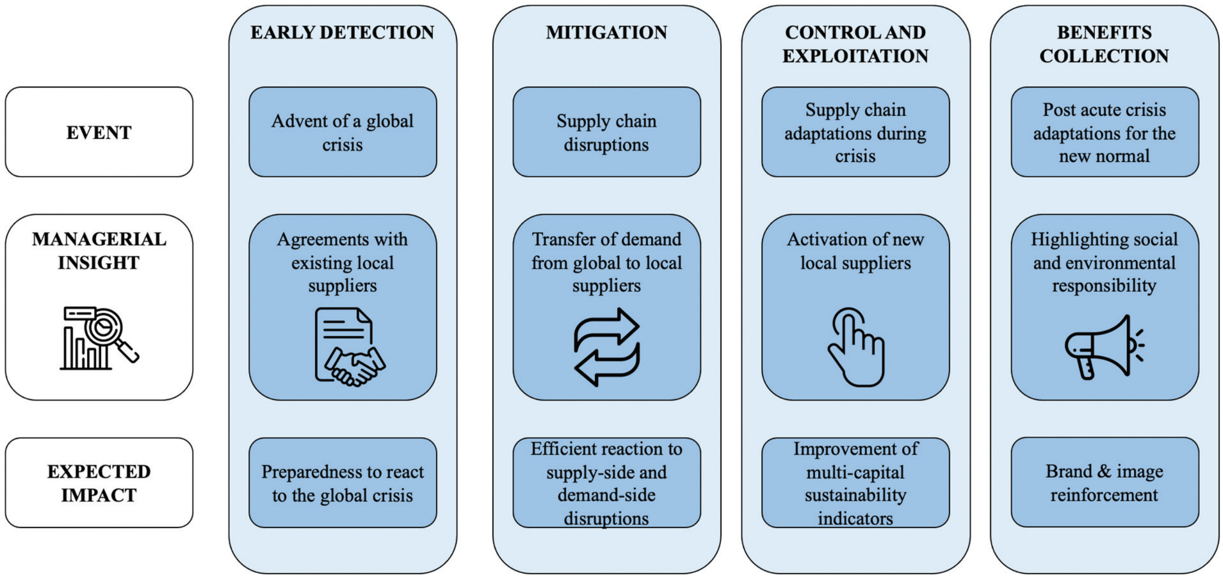

Figure 4. Managerial insights for agri-food supply chain resilience and adaptability.

shelf is guaranteed to everyone, despite the harmful disruptions. It is also important to give space to the effects on local economies, which are revitalised.

It is relevant to add that, based on the results presented in this article, the large-scale retail operator should retain local suppliers, even after the disruptions disappear, for the following reasons:

(1) First of all, the large-scale retail operator obtains, as demonstrated, undoubted benefits from the point of view of economic, social and environmental sustainability. In Italy, on the basis of Legislative Decree n. 254/2016 (derived from the European Directive 2014/95/EU), from 2017 it is mandatory to prepare a sustainability report for companies, based on the number of workers and revenue level. The sustainability report, which is currently presented by the major players in the large-scale retail sector, is a document published with the aim of communicating to the external stakeholders a set of results relating to the environmental and social impacts of the activities carried out during a well-defined time period (e.g., one year).
(2) Furthermore, strategies aimed at increasing the importance of local suppliers improve the resilience of the large-scale retail operator in view of possible future disruptive events. Basically, in the event of further disruptions, the large-scale retail operator could refer not only to global suppliers, but also and above all to consolidated and reliable local suppliers.
(3) During the pandemic, many consumers became fond of some local brands. According to the Coop Report (2020), the study annually carried out by Coop Italy to analyse the food distribution market in Italy, more than 40% of people think that in the coming years it will be more important than in 2019, to buy sustainable and local products.
(4) In this particular historical period, there is a high interest from the European Union towards solutions capable of guaranteeing the survival of small local agricultural producers, seriously affected by the COVID-19 pandemic. For instance, the PRIMA programme, an initiative supported and funded under Horizon 2020, recently proposed a call, whose topic is: “Increasing the resilience of small-scale farms to global challenges and COVID-like crisis by using adapted technologies, smart agri-food supply chain and crisis management tools”. (PRIMA, 2021).

6. Conclusions

The recent spread of COVID-19 has forced governments around the world to take drastic measures such as closure of facilities, restrictions on movement, partial or complete lockdown, which have damaged global and local economies. These measures have caused supply-side and demand-side disruptions, affecting the performance of multiple supply chains. As regards the agri-food sector, the pandemic has had different effects on the various actors. Bars, restaurants, pastry shops, ice cream parlours, shopping centres, school canteens, open-air markets have been forced to close for long periods of time, with considerable revenue losses. In this context, local suppliers were among the most penalised, as they were unable to exploit their main distribution channels (e.g., open-air markets, school canteens, etc.). On the other hand, these events diverted the demand for food products mainly to supermarkets, which had greater earning opportunities.

This article has positively and quantitatively answered the following question: is there a strategy to reduce COVID-19 agri-food supply chains disruptions while revitalising local economies and improving – at the same time – a number of multi-capital indicators referring to economic, environmental and social sustainability? The results showed that, through the implementation of the proposed strategy, a large-scale retail operator can achieve an increase in revenues between 3.40% and 6.22%, and between 4.15% and 9.16%, respectively in the case of simultaneous closure of exactly one, or more global suppliers. Consequently, an increase in profits of up to 14.85% is achievable in the best-case scenario. At the same time, CO_2 emissions can be reduced by up to 6.29%. The increase in the number of successfully fulfilled orders leads to a greater availability of food on the shelf, even during the crisis period, thus improving the satisfaction of the final consumer, who has more trust in the large-scale retail operator. The image of the large-scale retail operator improves with the reduction of two main indicators: the first one refers to the kg of CO_2 generated for each € of revenue achieved, while the second one computes the distance to be covered for each kg of product delivered; they can be reduced respectively up to 12.45% and 7.98%. The results show also that local economies can be widely revitalised: in the initial situation, only 16.82% of the large-scale retail operator's revenue depends on local supplies; this percentage grows up to 31.38% through the increasing number of agreements with local suppliers; Even, such a values become respectively 18.18% and 33.60%, when multiple and simultaneous closures are supposed for the global suppliers (Scenarios SM1-SM7). Basically, the results showed that it is possible to transform an extremely harmful event, such as the COVID-19 pandemic, into something beneficial for small local suppliers and for the economic, social and environmental sustainability of the supply chain. Moreover, important managerial insights for agri-food supply chain resilience and adaptability, can be provided.

One of the main limitations of this study concerns the specific supermarket supply chain taken into consideration. Therefore, the proposed approach should also be tested in other sectors and contexts, in order to make it more general. Future developments mainly concern the integration of emerging technologies such as blockchain, Internet of Things, and artificial intelligence to enhance supply chain visibility, traceability, and overall efficiency. Moreover, anyLogistix could be integrated with optimisation models, in order to exploit the strength of simulation-optimisation approaches.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was partly co-founded by the PRIMA Program–Section 2 Call multi-topics 2021 through the research project entitled "Smart Models for Agrifood Local vaLue chain based on Digital technologies for Enabling COVID-19 Resilience and Sustainability" (SMALLDERS).

References

AnyLogistix. (2023). *AnyLogistix, Supply chain design and optimization software*. Available online: Retrieved October 9, 2023, from. https://www.anylogistix.com/

Atkisson, A., & Hatcher, R. L. (2001). The compass index of sustainability: Prototype for a comprehensive sustainability information system. *Journal of Environmental Assessment Policy and Management*, *3*(4), 509–532. https://doi.org/10.1142/S1464333201000820

Banks, J. (Ed.). (1998). *Handbook of simulation: Principles, methodology, advances, applications, and practice*. John Wiley & Sons.

Béné, C. (2020). Resilience of local food systems and links to food security – a review of some important concepts in the context of COVID-19 and other shocks. *Food Security*, *12*(4), 805–822. https://doi.org/10.1007/s12571-020-01076-1

Bui, T. N., Nguyen, A. H., Le, T. T. H., Nguyen, V. P., Le, T. T. H., Tran, T. T. H., Nguyen, N.M., Le, T.K.O., Nguyen, T.K.O., Nguyen, T.T.T. and Dao, H.V. Lebailly, P. (2021). Can a short food supply chain create sustainable benefits for small farmers in developing countries? An exploratory study of Vietnam. *Sustainability*, *13*(5), 2443. https://doi.org/10.3390/su13052443

Burgos, D., & Ivanov, D. (2021). Food retail supply chain resilience and the COVID-19 pandemic: A digital twin-based impact analysis and improvement directions. *Transportation Research Part E: Logistics & Transportation Review*, *152*, 102412. https://doi.org/10.1016/j.tre.2021.102412

Chakraborty, S., & Sarmah, S. P. (2020). Managing supply and transportation disruptions: A case of Indian fair price shops. *Kybernetes*, *49*(11), 2773–2797. https://doi.org/10.1108/K-05-2019-0344

Cheng, Y., Elsayed, E. A., & Huang, Z. (2022). Systems resilience assessments: A review, framework and metrics. *International Journal of Production Research*, *60*(2), 595–622. https://doi.org/10.1080/00207543.2021.1971789

Chi Ffoleau, Y., & Dourian, T. (2020). Sustainable food supply chains: Is shortening the answer? a literature review for a research and innovation agenda. *Sustainability*, *12*(23), 9831. https://doi.org/10.3390/su12239831

Chinazzi, M., Davis, J. T., Ajelli, M., Gioannini, C., Litvinova, M., Merler, S., Pastore y Piontti, A., Mu, K., Rossi, L., Sun, K., Viboud, C., Xiong, X., Yu, H.,

Halloran, M. E., Longini, I. M., & Vespignani, A. (2020). The effect of travel restrictions on the spread of the 2019 novel coronavirus (COVID-19) outbreak. *Science*, *368*(6489), 395–400. https://doi.org/10.1126/science.aba9757
Chowdhury, M. T., Sarkar, A., Paul, S. K., & Moktadir, M. A. (2020). A case study on strategies to deal with the impacts of COVID-19 pandemic in the food and beverage industry. *Operations Management Research*, *15*(1–2), 166–178. https://doi.org/10.1007/s12063-020-00166-9
Correia, M. S. (2019). Sustainability: An overview of the triple bottom line and sustainability implementation. *International Journal of Strategic Engineering (IjoSE)*, *2*(1), 29–38. https://doi.org/10.4018/IJoSE.2019010103
Elkington, J. (1998). Accounting for the triple bottom line. *Measuring Business Excellence*, *2*(3), 18–22. https://doi.org/10.1108/eb025539
European Union. (2013). Regulation (EU) No. 1305/2013 of the European Parliament and of the Council of 17 December 2013 on support for rural development by the European Agricultural Fund for Rural Development (EAFRD) and repealing Council Regulation (EC) No 1698/2005. *EUR – Lex Edition OJ L*, *347*(2013), 487–548.
Fahimnia, B., Sarkis, J., & Talluri, S. (2016). Design and management of sustainable and resilient supply chains. *IEEE Transactions on Engineering Management*, *63*(3), 7514350.
Falcone, R., & Sapienza, A. (2023). An agent-based model to assess citizens' acceptance of COVID-19 restrictions. *Journal of Simulation*, *17*(1), 105–119. https://doi.org/10.1080/17477778.2021.1965501
Fan, S., Yang, Z., Wang, J., & Marsland, J. (2022). Shipping accident analysis in restricted waters: Lesson from the Suez Canal blockage in 2021. *Ocean Engineering*, *266*, 113119. https://doi.org/10.1016/j.oceaneng.2022.113119
Figge, F., Hahn, T., Schaltegger, S., & Wagner, M. (2002). The sustainability balanced scorecard–linking sustainability management to business strategy. *Business Strategy and the Environment*, *11*(5), 269–284. https://doi.org/10.1002/bse.339
Gupta, R., Rathore, B., & Biswas, B. (2022). Impact of COVID-19 on supply chains: Lessons learned and future research directions. *International Journal of Quality & Reliability Management*, *39*(10), 2400–2423. https://doi.org/10.1108/IJQRM-06-2021-0161
Hayakawa, K., & Mukunoki, H. (2021). Impacts of COVID-19 on global value chains. *The Developing Economies*, *59*(2), 154–177. https://doi.org/10.1111/deve.12275
Huang, Y., Li, J., Qi, Y., Shi, V., & Xie, L. (2021). Predicting the impacts of the COVID-19 pandemic on food supply chains and their sustainability: A simulation study. *Discrete Dynamics in Nature & Society*, *2021*, 1–9. https://doi.org/10.1155/2021/7109432
Iakovou, E., Bochtis, D., Vlachos, D., & Aidonis, D. (2015). Sustainable agrifood supply chain management. *Supply Chain Management for Sustainable Food Networks*, 1–39. https://doi.org/10.1002/9781118937495.ch1
Ivanov, D., & Dolgui, A. (2020). Viability of intertwined supply networks: Extending the supply chain resilience angles towards survivability. A position paper motivated by COVID-19 outbreak. *International Journal of Production Research*, *58*(10), 2904–2915. https://doi.org/10.1080/00207543.2020.1750727
Jagtap, S., Trollman, H., Trollman, F., Garcia-Garcia, G., Parra-López, C., Duong, L., Martindale, W., Munekata, P. E. S., Lorenzo, J. M., Hdaifeh, A., Hassoun, A., Salonitis, K., & Afy-Shararah, M. (2022). The Russia-Ukraine conflict: Its implications for the global food supply chains. *Foods*, *11*(14), 2098. https://doi.org/10.3390/foods11142098
Liu, W., Choi, T. M., Niu, X., Zhang, M., & Fan, W. (2022). Determinants of business resilience in the restaurant industry during the COVID-19 Pandemic: A textual analytics Study on an O2O Platform case. In *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2022.3187986
Longo, F., Mirabelli, G., Solina, V., Alberto, U., De Paola, G., Giordano, L., & Ziparo, M. (2022). A simulation-based framework for manufacturing design and resilience assessment: A case study in the wood sector. *Applied Sciences*, *12*(15), 7614. https://doi.org/10.3390/app12157614
Longo, F., Nicoletti, L., Padovano, A., Fusto, C., Gazzaneo, L., & diMatteo, R. (2018). Multi-capitals sustainability for firms competitiveness. In *Proceedings of the 20th International Conference on Harbour, Maritime & Multimodal Logistics Modelling and Simulation (HMS)*, Budapest (Hungary) (pp. 83–90).
Malak-Rawlikowska, A., Majewski, E., Wąs, A., Borgen, S. O., Csillag, P., Donati, M., Freeman, R., Hoàng, V., Lecoeur, J.-L., Mancini, M. C., Nguyen, A., Saïdi, M., Tocco, B., Török, Á., Veneziani, M., Vittersø, G., & Wavresky, P. (2019). Measuring the economic, environmental, and social sustainability of short food supply chains. *Sustainability*, *11*(15), 4004. https://doi.org/10.3390/su11154004
McCullough, E. B., Pingali, P. L., & Stamoulis, K. G. (2010). Small farms and the transformation of food systems: An overview. In R. Haas, M. Canavari, B. Slee, C. Tong, & B. Anurugsa (Eds.), *Looking east, looking west Organic and quality food marketing in Asia and Europe* (pp. 47–83). Wageningen Academic Publisher.
McElroy, M. W., Thomas, M. P., Coulson, A. B., & Carol, A., DR. (2015). The multicapital scorecard. *Sustainability Accounting, Management and Policy Journal*, *6*(3), 425–438. https://doi.org/10.1108/SAMPJ-04-2015-0025
Nielsen. (2020). *Key Consumer behavior thresholds identified as the coronavirus outbreak evolves*. *Link*. Retrieved July 27, 2022, from. https://nielseniq.com/global/en/insights/analysis/2020/key-consumer-behavior-thresholds-identified-as-the-coronavirus-outbreak-evolves-2/
Paciarotti, C., & Torregiani, F. (2021). The logistics of the short food supply chain. *Sustainable Production and Consumption*, *26*, 428–442. https://doi.org/10.1016/j.spc.2020.10.002
Perdana, T., Chaerani, D., Achmad, A. L. H., & Hermiatin, F. R. (2020). Scenarios for handling the impact of COVID-19 based on food supply network through regional food hubs under uncertainty. *Heliyon*, *6*(10), e05128. https://doi.org/10.1016/j.heliyon.2020.e05128
Pujawan, I. N., & Bah, A. U. (2022, January). Supply chains under COVID-19 disruptions: Literature review and research agenda. *Supply Chain Forum: An International Journal*, *23*(1), 81–95). Taylor & Francis. https://doi.org/10.1080/16258312.2021.1932568
Pujawan, I. N., & Bah, A. U. (2022). Supply chains under COVID-19 disruptions: Literature review and research agenda. *Supply Chain Forum: An International Journal*, *23*(1), 81–95. https://doi.org/10.1080/16258312.2021.1932568
Rahman, M. M., Nguyen, R., & Lu, L. (2022). Multi-level impacts of climate change and supply disruption events on a potato supply chain: An agent-based modeling approach. *Agricultural Systems*, *201*, 103469. https://doi.org/10.1016/j.agsy.2022.103469

Ruggerio, C. A. (2021). Sustainability and sustainable development: A review of principles and definitions. *Science of the Total Environment*, *786*, 147481. https://doi.org/10.1016/j.scitotenv.2021.147481

Sauer, P. C., Silva, M. E., & Schleper, M. C. (2022). Supply chains' sustainability trajectories and resilience: A learning perspective in turbulent environments. *International Journal of Operations & Production Management*, (ahead-of-print). *42*(8), 1109–1145. https://doi.org/10.1108/IJOPM-12-2021-0759

Sellitto, M. A., Vial, L. A. M., & Viegas, C. V. (2018). Critical success factors in Short Food Supply Chains: Case studies with milk and dairy producers from Italy and Brasil. *Journal of Cleaner Production*, *170*, 1361–1368. https://doi.org/10.1016/j.jclepro.2017.09.235

Singh, S., Kumar, R., Panchal, R., & Tiwari, M. K. (2020). Impact of COVID-19 on logistics systems and disruptions in food supply chain. *International Journal of Production Research*, *59*(7), 1993–2008. https://doi.org/10.1080/00207543.2020.1792000

Singh, R., & Mathirajan, M. (2022). Simulation modelling techniques for managing epidemic outbreak: A review, classification schemes, and meta-analysis. *Journal of Simulation*, *17*(6), 1–20. https://doi.org/10.1080/17477778.2022.2067012

Spiegel, M., Tookes, H., & Goldstein, I. (2021). Business restrictions and COVID-19 fatalities. *The Review of Financial Studies*, *34*(11), 5266–5308. https://doi.org/10.1093/rfs/hhab069

Sunny, J., Undralla, N., & Pillai, V. M. (2020). Supply chain transparency through blockchain-based traceability: An overview with demonstration. *Computers and Industrial Engineering*, *150*, 106895. https://doi.org/10.1016/j.cie.2020.106895

Tomlin, B., & Wang, Y. (2009). Operational strategies for managing supply chain disruption risk. In P. Kouvelis, L. Dong, O. Boyabatli, & R. Li (Eds.), *The Handbook of Integrated Risk Management in Global Supply Chains* (pp. 79–101). Wiley. https://doi.org/10.1002/9781118115800.ch4

Tsiamas, K., & Rahimifard, S. (2021). A simulation-based decision support system to improve the resilience of the food supply chain. *International Journal of Computer Integrated Manufacturing*, *34*(9), 996–1010. https://doi.org/10.1080/0951192X.2021.1946859

Vali-Siar, M. M., & Roghanian, E. (2022). Sustainable, resilient and responsive mixed supply chain network design under hybrid uncertainty with considering COVID-19 pandemic disruption. *Sustainable Production and Consumption*, *30*, 278–300. https://doi.org/10.1016/j.spc.2021.12.003

Vanany, I., Ali, M. H., Tan, K. H., Kumar, A., & Siswanto, N. (2021). A supply chain resilience capability framework and process for mitigating the COVID-19 pandemic disruption. In *IEEE Transactions on Engineering Management*. https://doi.org/10.1109/TEM.2021.3116068

Vitorino, L., Costa, I. P., Terra, A. V., Medina, A. C., Gomes, C. F., & Santos, M. (2022). Analysis of food distribution network using Anylogistix computational tool. *IFAC-Papersonline*, *55*(10), 2018–2023. https://doi.org/10.1016/j.ifacol.2022.10.004

Vitorino, L., Silva, F. C., Gomes, C. F., Medina, A. C., & Santos, M. (2022). Simulation of the grape distribution network in the São Francisco Valley region: Anylogistix. *Procedia Computer Science*, *214*, 1015–1022. https://doi.org/10.1016/j.procs.2022.11.272

Xu, Z., Elomri, A., Kerbache, L., & El Omri, A. (2020). Impacts of COVID-19 on global supply chains: Facts and perspectives. *IEEE Engineering Management Review*, *48*(3), 153–166. https://doi.org/10.1109/EMR.2020.3018420

Xu, M., Wang, X., & Zhao, L. (2014). Predicted supply chain resilience based on structural evolution against random supply disruptions. *International Journal of Systems Science: Operations & Logistics*, *1*(2), 105–117. https://doi.org/10.1080/23302674.2014.934748

Zhu, Z., Chu, F., Dolgui, A., Chu, C., Zhou, W., & Piramuthu, S. (2018). Recent advances and opportunities in sustainable food supply chain: A model-oriented review. *International Journal of Production Research*, *56*(17), 5700–5722. https://doi.org/10.1080/00207543.2018.1425014

Zhu, Q., & Krikke, H. (2020). Managing a sustainable and resilient Perishable Food Supply Chain (PFSC) after an outbreak. *Sustainability (Switzerland)*, *12*(12), 5004. https://doi.org/10.3390/su12125004

Zhu, H., Liu, S., Li, X., Zhang, W., Osgood, N., & Jia, P. (2023). Using a hybrid simulation model to assess the impacts of combined COVID-19 containment measures in a high-speed train station. *Journal of Simulation*, 1–25. https://doi.org/10.1080/17477778.2023.2189027

Appendix

Table A1. Meaning of the twelve capitals defined in Longo et al. (2018).

Capital	Meaning
Material capital	It refers to non-living physical objects (e.g., raw materials, processed resources)
Financial capital	It concerns the financial well-being of the organisation, expressed in terms of economic resources, that are necessary to start and/or maintain the business
Stakeholders-related capital	It takes into consideration the needs and cultural values of each of the stakeholders (e.g., customers, suppliers), which are crucial for the success of the business. In the modern concept of sustainability, the advantages of all actors must be maximised, according to a win-win logic
Shareholders-related capital	It refers not only to the shares owned by the shareholders, but also to the expectations they have about the long-term increase in the value of the assets
Internal social capital	It is based on the benefits for each individual within the organisation. Such a capital must necessarily be taken into account because the performance of each individual influences the performance of the entire organisation
External social capital	It is linked to the context in which the organisation falls. It concerns the importance of the surrounding social communities (e.g., associations, environmental groups, political parties), which must be properly managed in order to have tangible, but above all intangible, benefits
Relation capital	It concerns the relations between the company and other companies, institutions, people (e.g., market agreements)
Image capital	It refers to the perception that people have about the organisation, whenever it is mentioned. It can grow through appropriate communication strategies, brand promotion, etc.
Natural capital	It is linked to the use of natural resources, the excessive exploitation of which leads to negative impacts on ecosystems
Identity and ethical capital	It concerns the ethical and moral principles of the organisation and is typically conditioned by the values "owned" by the workers
Intellectual capital	It is about the know-how of the organisation
Human capital	It is a set of "lessons learned" accumulated by the organisation over the years (e.g., well-practiced skills, routines, acquired knowledge).