Analysis of ripple effect and its impact on supply chain resilience: a general framework and a case study on agri-food supply chain during the COVID-19 pandemic

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Abstract

Vulnerabilities and disruptions that are localized in a specific company can lead to consequences along with the entire supply chain, snowballing in magnitude and causing a resilience loss. This study proposes a methodology to unveil the causal relationships that occur among different factors as a result of a disruption and how these causal relationships strengthen or weaken supply chain resilience. This methodology is based on fuzzy cognitive maps capability to link multidimensional and multidisciplinary factors together, providing supply chain managers with a graph structure for understanding the system behaviour. The proposed methodology is applied to a case study in order to explain the research approach and show how the implementation of the fuzzy cognitive maps can provide valuable support in defining casual reactions that generate resilience variations. In particular, an agri-food supply chain is analysed taking into consideration as a disruption the COVID-19 pandemic. A total of 60 principal paths (ripple effects) and 6 cycles influencing agri-food supply chain resilience have been exemplified, highlighting how “Long shelf-life food demand”, “Closure of the Ho.Re.Ca. channel” factors are critical into influencing supply chain resilience. Other results reveal how “panic buying” can instead strengthen agri-food Supply Chain Resilience. The proposed methodology has shown its generality as a holistic approach in the analysis of all type of disruptions in a supply chain.

Keywords: supply chain resilience; COVID-19 pandemic; agri-food sector; ripple effect; fuzzy cognitive maps

1 Introduction

Today, interruptions are difficult to anticipate and control due to the inherent complexity of supply networks and the combined impacts of dynamic propagation (Li and Zobel 2020; Marcucci et al. 2021; Piprani et al. 2022). When a supply chain (SC) disruption occurs, this disruption can have beneficial or negative effects on several elements (companies flexibility, visibility, velocity, etc.). Moreover, these factors may have a positive or negative impact on other SC factors, creating the ripple effect (Bevilacqua et al. 2018; Ivanov 2017; Marcucci et al. 2022). Such vulnerabilities and disruptions which are localized in a specific company can in fact reach a tipping point, leading to consequences along with the entire SC, snowballing in magnitude, resulting in a high impact effect on SC performance. This phenomenon has been named “ripple effect” (Ivanov, Dolgui and Sokolov 2019) and it is the idea that a small change or event may have a large influence that spreads and causes a chain reaction, comparable to how a pebble put into calm water causes ripples to spread outward. Many authors focus their attention on this phenomenon, since it can amplify the unwanted negative effects that disruption can bring to a SC (Dolgui, Ivanov and Sokolov 2018; Ivanov 2017). In literature, models have been developed, with the purpose of analysing the disruption propagation effect (Baghersad and Zobel 2021; Ivanov and Dolgui 2022), also from ripple effect point of view (Li et al. 2021; Li and Zobel 2020; Lohmer et al. 2020). Although the existing research is valuable, quantitative methods to structurally analyse the connection among factors that affect every player of a SC and the causal reactions behind the negative or positive variation of the overall SC performance, according to the authors' best knowledge, are not present in the literature. Moreover, most of the proposed models analyse the disruption effect only on one or two factors. For example, Yu et al. (2019) analysed the disruption effect on SC Dynamism, Alfarsi et al. (2019) the effect on firm reputation while Durowoju et al. (2021) the impact on information security breach.

The fuzzy cognitive mapping (FCMs) technique suggested in this paper tries to overcome this deficiency by bringing a unique decision-making tool in this essential task. In particular, a methodology is developed to analyse this chain of effects, by unveiling the causal path among multidimensional and multidisciplinary factors that can affect every SC player and the overall SC. The suggested study approach is based on FCMs because to their crucial role in connecting multidimensional and multidisciplinary elements, especially when the studied data are unsupervised. FCMs are graph topologies capable of conveying graphically causal reasoning while modelling dynamics of qualitative systems (Carvalho 2013). Their vagueness facilitates hazy degrees of causality between hazy causal objects. i.e., factors: this feature represents the key added value of the research approach exemplified in this study. Indeed, FCMs are used in this paper as tools to generate metaknowledge and explore hidden implications of expert experience. Morevoer, FCMs have been extensively used in modelling and decision-making within systems risk analysis (Bakhtavar et al.

2020). Among these studies, Ravasan and Mansouri (2015) used FCM to examine important ERP system failure factors and to predict the interrelationships of risks in ERP deployment initiatives, while Mital et al. (2018) used FCM to build a mental model for decision-makers and to develop a SC risk framework.

The ripple effect generated by a disruption can have an impact on many SC performance measures (revenues, delivery delays, product quality, etc.). However, as stated recently by several authors, one of the main key capabilities required to a SC is its resilience (Al-Hakimi et al. 2021; M. H. Ali et al. 2021; Sabouhi et al. 2018), i.e., 'the ability of a system to return to its original state or move to a new, more desirable state after being disturbed.' (Christopher and Peck 2003). Various definitions of Supply Chain Resilience (SCR) exist in the literature (Tukamuhabwa et al. 2015). Some authors define it as the SC as the ability to avoid/reduce the probability of disruptions and to respond and recover quickly (Hohenstein et al. 2015), while other definitions are more comprehensive, defining SCR as the adaptive capability of the SC to prepare for unexpected events, respond to disruption and recover from them by maintaining continuity of operations at the desired level of connectedness and control over structure and function (Ponomarov and Holcomb 2009).

Although the methodology exemplified in this paper can be used to assess any type of performance measure, the resilience capability is strategic for every SC and it deserves to be studied and analyzed as it allows companies to survive in the long term (Andres and Marcucci 2020; Blackhurst et al. 2018) and maintaining agility and flexibility within their SC (Wen and Liao 2021). Therefore, in this work we have considered the loss of SCR as the impact measure of the ripple effect generated by a disruption.

Regardless of its definition though, it is commonly acknowledged that SCR is a multidimensional notion that includes the ability to absorb shocks, the speed of recovery, the degree of adaptation to changes, and the robustness to disruptions (Gligor et al. 2020). Hence its multidimensional characteristics, to our knowledge, scientific literature has a research gap about quantitative methods to structurally analyse and predict the connection among multidimensional and multidisciplinary factors that can affect a SC and unveil the causal reactions behind the negative or positive variation of the SC performance.

Overall, the purpose of this paper is to fill this gap in the growing body of literature on SCR by proposing a methodology based on the above mentioned FCMs that can assist researchers and practitioners in better comprehending the complex and dynamic nature of SCR and identifying strategies to improve it. The proposed methodology is applied to a case study to illustrate the research approach and demonstrate how the adoption of FCMs can provide considerable assistance in distinguishing casual reactions that cause variations in resilience.

In particular, an agri-food SC is analysed, taking into consideration as a disruption the COVID-19 pandemic. This choice is based on the fact that the COVID-19 pandemic has been labelled as a black swan event (Badhotiya et al. 2022; Carissimi et al. 2022; Das et al. 2021; Mazzoleni et al. 2020; Yarovaya et al. 2020), since its characteristics are high-impact and low-probability disruption. Moreover, the agri-food sector is among the most affected by such disruption (Altieri and Nicholls 2020; Sharma et al. 2020; Majumdar et al. 2022; Ghafour and Aljanabi 2022). Nevertheless, the achievement of a resilient SC within the agri-food system is an imperative goal, since population food security relies upon this system (Irani et al. 2018). Ahmed et al. (2020) directs such emphasis to the vulnerability of the agri-food system and how its resilience should be imperative in order to limit consequences that could affect food security and even health-related outcomes. Although the proposed methodology was applied to a specific SC and disruption the aim is to develop a method for analysing of all type of disruptions in a supply chain using a holistic approach. In the examination of this case study, a total of 60 ripple effects were illustrated: ten paths characterizing each actor of the considered SC and ten paths describing the aggregate SC. This type of research was undertaken to enable an analysis highlighting the dynamics of each SC actors and the ones of the SC as a whole: elements such as "Long shelf-life food demand" were discovered to be as dominating for the majority of individual actors as for the SC as a whole. Regarding the entire SC, 6 cycles have been shown, highlighting the importance of "Long shelf-life food demand" and "Ho.Re.Ca. channel closure" in influencing SCR. Other findings indicate, contrary to many research findings, that "panic buying" may actually improve agri-food SCR. The present article is structured as follows, to exemplify the research method: the literature is reviewed in Section 2, while the study methodology is explained in Section 3. In Section 4, an illustration of the analysis of an agri-food SC using FCMs is provided, followed by a summary of the obtained results and a pertinent discussion (Section 5). Section 6 concludes the investigation by presenting its findings.

2 Literature Review: disruption propagation and ripple effect

There are a number of studies examining disruption propagation from various aspects. Ivanov (2017), Lohmer et al. (2020) and Li et al. (2021) addressed directly the ripple effect, analyzing how a small disruption can spread forward and downward via the material flow and ultimately affect the SC as a whole. Scheibe and Blackhurst (2018) provided theoretical insights on the propagation of disruptions, revealing how some factors are beyond the control of SC managers, and that entities within SC can reduce disruption propagation by implementing a systemic perspective, within an holistic approach strategy toward risk. There is also numerous empirical research in this area. Baghersad and Zobel (2021) developed a novel quantitative measure of a disruption's impact for examining both the operating performance and the stock market reaction of over 300 companies that experienced a SC disruption between 2005 and 2014.

Świerczek (2014) investigated the connection between intensity and span of SC integration with the snowball effect within disruption propagation: their result suggests that the strength of interruptions in forward and backward transmission in both material and information flow, and the breadth of supply chain structure, have a strong but unfavourable association.

In regard to this context, we propose a methodology to analyse the disruption propagation modes within a SC and the relationships among SC factors affected by this disruption. In this context, this literature review is focused on two issues: the analysis of methods proposed in literature to assess a disruption propagation mode in a SC (section 2.1) and the typology of factors affecting SCR when a disruption occurs (section 2.2).

2.1 Proposed models for analysing a disruption propagation mode in a supply chain

There is an increasing desire to comprehend the phenomena of disruption spread, often known as the ripple effect (Dolgui et al. 2018; Hosseini et al. 2020; Ivanov et al. 2014), and numerous methodologies have been proposed to analyse disruption propagation modes. Simulation (Ivanov 2017; Ivanov and Dolgui 2020; Macdonald et al. 2018; Pavlov et al. 2019; Zhao et al. 2019) and agent-based simulation methods (Basole and Bellamy 2014; Li et al. 2021; Zhao et al. 2019) are frequently used to delineate the SC disruption propagation behaviour. Dolgui et al. (2020) conducted a simulation-based investigation on the interrelationships between the ripple effect and bullwhip effect. Their findings expanded the understanding of these dynamics by demonstrating that the ripple effect may be a bullwhip-effect driver, whereas the latter can be initiated by a severe disruption in both the upstream and downstream directions. A similar conclusion has been evinced by Strommer and Földesi (2020), who asserts that the ripple effect alone may cause the bullwhip effect. Missing control during a disturbance has been proved to generate bullwhip effect. Probabilistic graphical models like Bayesian network approaches; Hosseini and Ivanov 2019; Ojha et al. 2018) are commonly used to simulate dependencies in complex networks, such as the forward and backward propagation (inference) of disturbances. Through this methodology, Garvey and Carnovale (2020) revealed that the propagation of local exogenous risk should be monitored more closely than non-local exogenous risk, while Hosseini and Ivanov (2019) created an approach that explicitly permits the identification of latent, high-risk providers in order to assist the development of suggestions to manage the ripple effect, such as the identification of important suppliers with poor resilience.

Despite the fact that, as stated previously, several research have analyzed the transmission of disruptions, less attention has been dedicated to studying the hidden consequences of expert knowledge. Frequently, it is the perception or experience of SC operators that can intuit the connections of factors that occur after a disruption. The suggested method

also enables us to produce a graphical and mathematical depiction of a manager's beliefs of the causal links between elements that improve or decrease SCR.

2.2 Supply chain factors affecting resilience when a disruption occurs

Different researchers have analysed the main factors that influence SCR when a disruption occurs. The most used factors are SC collaboration, flexibility, visibility, and information accuracy (Li et al. 2017; Pettit et al.; Sheffi and Rice Jr 2005; Xia and Tang 2011), supplier selection (Hosseini et al.; Hosseini and Barker 2016), network structure and design (Falasca et al. 2008; Habermann et al. 2015; Nair and Vidal 2011; Zhao et al. 2011) reverse logistics channels (Pettit et al. 2019) and risk management culture (Christopher and Peck 2004).

Some authors tried to classify these factors. Ali et al. (2021) identified four disruption factor categories including natural, humanmade, system accidents, and financials with a total of sixteen disruption factors.

Other authors have identified antecedent factors affecting SCR such as: SC visibility (Brandon-Jones et al. 2014), risk-taking disposition and SC security measures (Park et al. 2016), infrastructure for resource reconfiguration and risk management (Ambulkar et al. 2015), SC collaboration (Scholten and Schilder 2015), SC mitigating capabilities and SC design features (Craighead et al. 2007), uncertainty, regulatory focus, level of risk (Cantor et al. 2014), and firm innovativeness (Golgeci and Ponomarov 2013).

Different studies analysed factors connected to the network structure. Nuss et al. (2016) explore factors such as product complexity, supplier diversity, and SC length. When studying network resilience under circumstances of risk propagation, Li and Zobel (2020) show that network characteristics are typically more revealing than network type or average degree. Alikhani et al. (2023) developed a study to examine the criticality of nodes and the vulnerability of the network at various levels, noting how the ripple effect can be activated by various disruption, e.g., pandemic, cyber-attacks, since a disruption affecting one node can activate other dynamics and compromise the whole network. In general, though, it can be affirmed that a disruption can have a positive or negative impact on n different factors in a SC (see figure 1). In turn, these n factors will have a positive or negative impact on other factors.

According to the FCMs used in this work, a positive impact is intended if an increase in one factor causes an increase in the next, and a negative impact if an increase in one factor causes a decrease in the next. This sequence can continue for several layers. In addition, the state variation of some factors of successive layers may have an impact on factors of previous layers (red arrows in Figure 1), creating cycles within the network. Finally, the state variation of some factors may have a positive or negative impact on several SC performance measures.

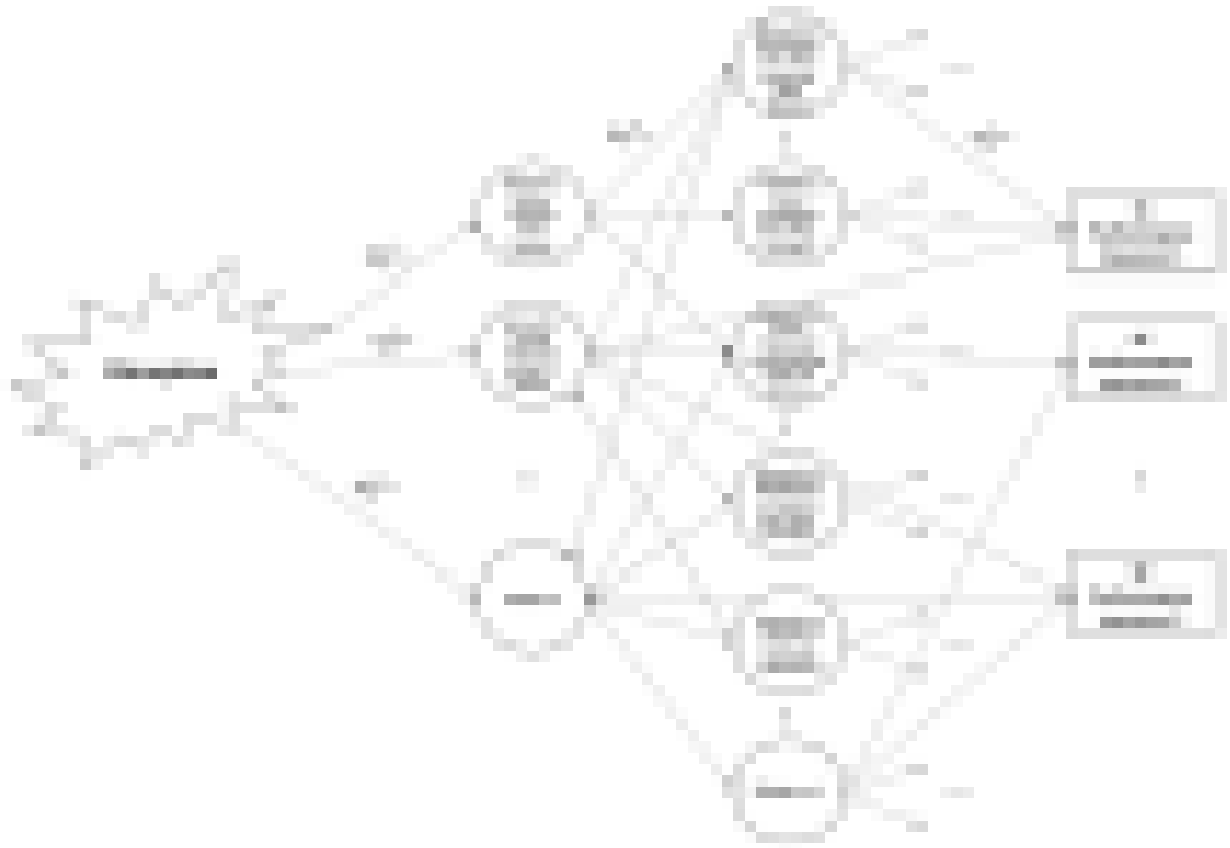

Figure 1: Causal relationships among Disruption-Factors-SC performance

The nature of the factors influencing a network can vary, since they can address different aspects and dimension of the SC characteristics, and many of the existing SCR studies discussed above take often a one-dimensional or one-aspect approach.

Hence, the suggested technique, based on FCMs, present a turnkey methodology that takes into account multidimensional and interdisciplinary aspects that pertain to sectors that are often remote from one another, such as risk sources (e.g., Border Closures, Preventive and safety measures for workers, etc.), resilience conceptualizations (e.g., Resilience of food-processing companies, Resilience of distribution companies, Resilience of retail companies, etc.), other SC factors (e.g., Availability of agricultural inputs, Cost of transport, Home Delivered Food Demand, Closure of the Ho.Re.Ca. channel, etc.) and other aspects (e.g., Panic buying, Food Security, etc.).

3 Research Approach

The research approach proposed in this work is shown in Figure 2.

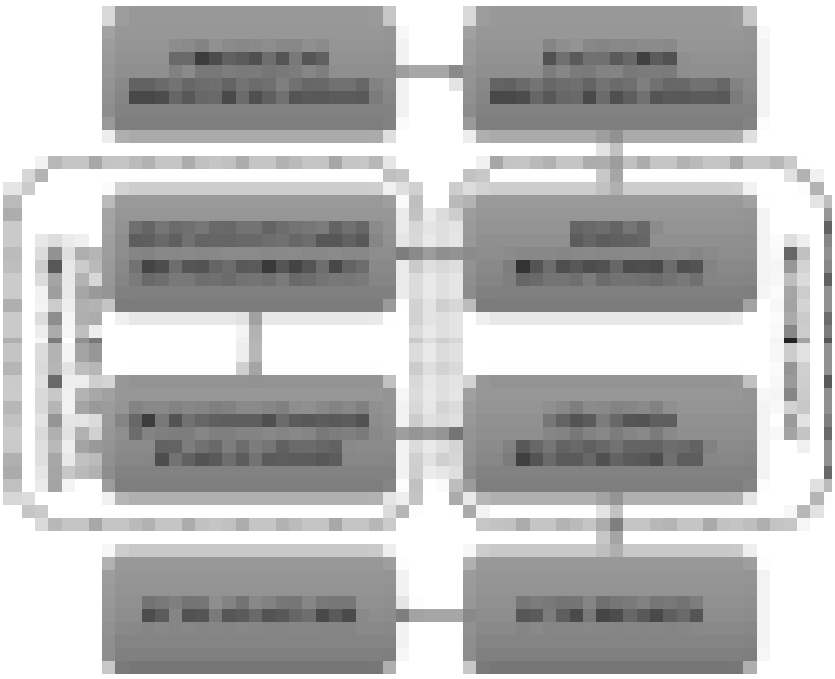

Figure 2: Research approach

This research approach consists of 8 phases, starting from ‘Problem Identification’ that aims at defining the goal of the study and ending with the FCM analysis that is focused on the identification of several paths (ripple effects) that are a concatenation between factors towards the top event. An overview of these 8 phases is given in the following sections.

3.1 Problem identification

The problem identification phase consists of defining the disruption to be analysed and the SC performance indicators to be monitored. The proposed framework is general and can be used for any disruption and for any performance indicator. In the case study analysed in the next sections, the goal is to assess the causal relationships that occur in an agri-food SCs as a result of the Covid-19 disruption and how these causal relationships impact on the SCR. The analysis focuses on resilience variation of distributors, manufacturers and retailers, and finally of the overall SC.

In the problem identification phase, different professionals are taken from the specific SCs to be analysed in order to create a panel of experts. A heterogeneous panel of experts is formed for carrying out a holistic approach to the problem and for taking multidimensional and multidisciplinary factors. This way, an overall and collective judgment is ensured within every SC player and from the whole SC point of view.

3.2 Factors identification and first refinement

During this step, all potential contributing elements and parameters are identified. In this study, the term 'factors' is used

in a broad sense, with the intent of analyzing relationships between diverse features such as risk factors (e.g., export limit, import limit), direct impacts from the disruption on economy and society (e.g., limits on the people mobility, border closures) and other aspects (e.g., product traceability; sales processes; etc.). In order to create a baseline of potential factors, a systematic literature review is used. Starting from this baseline, the SC experts can then decide to accept, group or include new factors. The literature search is set according to the research protocol: to identify and collect the published research, a number of major databases can be used and keywords as (type of disruption*) AND ((resilience) OR (risk)) AND (supply chain) can be applied. Subsequently, all factors of a SC that are affected by that disruption are extracted from the selected papers. Relevant factors and variables will compose the initial FCM structure.

The First Refinement phase follows the Factor Identification phase. In this step, all of the identified factors composing the initial FCM are fully examined by the experts to point out potential conflicts among them by assessing the presence of possible differences in their involvement. The complete procedure for factors identification and refinement has been exemplified in the next section 4.1 for an agri-food SC.

3.3 Questionnaire evaluation and second refinement

This macro phase is divided into different steps. Questionnaire Development and Evaluation: in this step, the relationships among factors are identified by the panel of experts in order to create the Adjacency matrix and an initial Cognitive Map. The panel of experts has also to evaluate the weight of the relationships among factors.

The questionnaire processing step yields a weighted matrix representing an expert's personal cognitive map. Specifically, the associations were rated by experts using fuzzy labels ranging from ‘very low’ to ‘very high’ for Negative and Positive links. To obtain the final linguistic weight, these linkages are evaluated using linguistic values and aggregated using the t-conorm fuzzy inference technique for the union of triangular fuzzy sets (Figure 3). In the section 4.2 that follows, a sample questionnaire has been included.

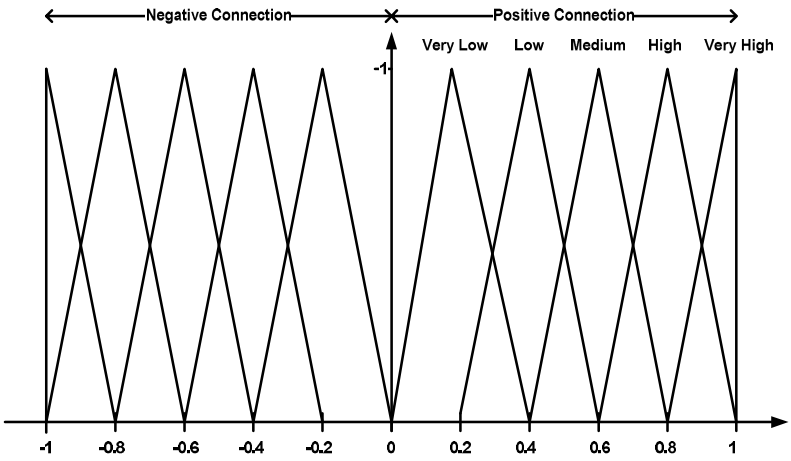

Figure 3: Fuzzy weights membership function

The Second Refinement phase follows the Questionnaire Analysis phase. In this step, the obtained relationships among factors are evaluated and refined according to the factors list, defined as a result of the first refinement, and, potentially, it is understood if the initial identified factors and relationships need to be adjusted. Indeed, all of the new proposed factors and relationships are fully examined by the experts to point out potential conflicts, possible errors or inconsistencies. Using a two-step validation process consisting of a literature study and the review of a panel of experts, these two modifications aim to ensure the consistency of outcomes.

3.4 FCM design

All info collected through the questionnaires will be successively converted into a graphical representation (the Fuzzy Cognitive Map). In this graph, nodes indicate the factors, and weighted arcs reflect the connections between these nodes. These arcs connect the nodes and so highlight the causal linkages between the components: the elements that represent the cause or the means to attain the goal are at the arrow's tail, while those that represent the goal are at its tip. Figure 4 is an illustration of an FCM graph. The component C_j has a state value, and the arrow quantifies the effect of the cause factor C_i on the effect factor C_j: e_{ij} can adopt a fuzzy value between -1 and 1. Figure 4's FCM is represented in Table 1 as an adjacent matrix. Negative, null, and positive e_{ij} values indicate the sorts of probable causal links between the included elements.

- $e_{ij}=0$ stands for no causality relationship between factors C_i and C_j;
- $e_{ij}>0$ indicates a directly proportional causal relationship between C_i and C_j. Specifically, a rise or decrease in the value of C_i causes an increase or decrease in the value of C_j;

- Similarly, $e_{ij}<0$ denotes negative causality between components C_i and C_j, signifying that an increase/decrease in C_i causes a decrease/increase in C_j's value.

Fundamental to identifying the FCM components and the degree of impact between them is the contribution of human experiences and system knowledge (Eden 1988; Laukkanen 1998).

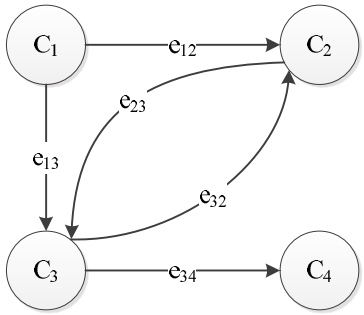

Figure 4: The structure of an FCM

	C_1	C_2	C_3	C_4
C_1		e_{12}	e_{13}	
C_2			e_{23}	
C_3		e_{32}		e_{34}
C_4				

Table 1: Adjacency matrix

The different experts' experience provides a different cognitive map regarding identified factors and relationships. FCMs have been selected, as a methodology to unveil the causal relationships that occur among multidimensional and multidisciplinary factors as a result of a disruption. COVID-19 pandemic disruption, for instance, has triggered ‘factors’ connected to the sources of risk (e.g. export limit, import limit), factors connected to the economy and society (e.g. limits on the people mobility, border closures) and other general aspects (e.g. product traceability; sales processes; etc.) (Asokan et al. 2022).

The procedures for combining all the FCMs obtained from experts belonging to the same SC is described by Lin and Lee (Kosko 1986) approach in which all the weights, referred to a specific relationship, are grouped using the defuzzification method Centre of Gravity (COG). According to Lin and Lee (1996), the defuzzification method centre of gravity (COG) is therefore used to group values and render numerical application creating the last FCM.

3.5 FCM analysis

To comprehend the importance of the causal influence of one FCM concept to another, all potential causal paths ending at the specified top-event have to be identified: '$C_1 \rightarrow C_{k1} \rightarrow \ldots \rightarrow C_{kn} \rightarrow C_j$'. Once it has been done, a complete map analysis can indeed be performed, and the FCM created in the preceding stage will now be studied using two concepts: Indirect Effect (IE) and Total Effect (TE) (Axelrod 1976). The IE is computed using the formula (1):

$$I_k(C_i, C_j) = \min\{e(C_p, C_{p+1})\} \quad (1)$$

where (C_p, C_{p+1}) indicates the concatenation route of the components beginning at C_p and finishing at C_{p+1}. Kosko (1986) adopts the Indirect Effect (IE) from C_i to C_j to determine the effects of the causality C_i on C_j. It is necessary to designate the sequence of factors as a chain, where the weight e(C_i, C_j) denotes the robustness of each ring (pair of factors) in the chain. In order to best exemplify the meaning of IE the following metaphor can be used: 'a chain is only as strong as its weakest link' (Bevilacqua et al. 2013). If there is a weak ring in the chain in fact, the total hardness of the chain may be determined by utilizing the hardness of the weakest ring. The IE evaluates this tenacity. Total Effect (TE) is the second notion utilized in this investigation. When there are several concatenations between a source node and an effect node, it is important to define the overall impact, i.e. the total effect T(x,y). In fact, according to Axelrod (1976) and equation (2), in the presence of many pathways beginning at the same initial node and terminating at the same top-even idea, the overall impact is the maximum of all indirect effects of the paths.

$$TE(C_i, C_j) = \max\{I_k(C_i, C_j)\} \quad (2)$$

Therefore, the total effect within an FCM is the overall impact of a particular concept on the rest of the system. It considers both the indirect effects that are spread through the network of relationships in the map as well as the direct relationships between that concept and other concepts in the FCM. It takes into account both the direct relationships between that concept and other concepts in the FCM as well as the direct effects that are spread out across the network of relationships in the map. In this work, $I_k(C_i, C_j)$ and $TE(C_i, C_j)$ are interpreted according to fuzzy mathematics and $e(C_p, C_{p+1})$, which determines the weighting relationship between factors Cp and Cp+1, can be exemplified using fuzzy values. Indeed, Kosko (1986) calculated $I_k(C_i, C_j)$ and $TE(C_i, C_j)$ as t-norm (triangular-norm) and t-conorm (triangular conorm) and Alsina, Trillas, and Valverde (1983) introduced them into fuzzy set theory. Specifically, they claimed that the t-norm and t-conorm may be applied to the intersection and union of fuzzy sets. Consider, for example, the three distinct pathways between variables C1 and C5 outlined below:

$$I_1(C_1, C_5) = \min\{e_{13}, e_{35}\} = \min\{much, lot\} = much$$

$$I_2(C_1, C_5) = some$$

$$I_3(C_1, C_5) = some$$

The appearance of three distinct pathways linking the identical nodes (C1 and C5) signifies that the component C1 can influence the final node (C5) in a variety of ways with varying consequences. Consequently, the TE calculus enables one to determine the greatest impact of C1 on C5:

$$TE(C_1, C_5) = \max\{I_1(C_1, C_5), I_2(C_1, C_5), I_3(C_1, C_5)\} = \max\{much, some, some\} = much$$

This method enables the panel of experts to determine the most significant causal chain among the elements, the presence of cycles, and the relationship between them.

4 Agri-food case study

As stated earlier, the COVID-19 pandemic and the corresponding lockdown of social and business activities have had a very strong impact on many industrial sectors. In this paper we aim at analysing this impact on a specific SC in the agri-food sector. The main problem is to understand the level of impact the pandemic has had on the SCR, what ripple effects occur during the pandemic, and the most important factors in these ripple effects.

In order to explain the research approach and to analyse how the various factors at stake have affected the resilience of an agri-food SCs, this approach has been applied to a SC for producing canned food: i.e., canned legumes and vegetables. The main characteristics of this SC are exemplified in the Table 2.

SC Players	Typology	Location	Size (as of 2021)	Description
Supplier	Food raw material	Europe	More than 5.000 employees and over €2 billion turnover	Supplier of raw materials located throughout Europe
Production	Food Processing Company	Italy	More than 2.000 employees and over €1 billion turnover	Receives the raw material, checks its state of preservation, and proceeds with final processing to finished product.
Packaging	Manufacturer of metal food cans	U.S.A.	More than 25.000 employees and over €10 billion turnover	Produces and supplies aluminium cans and lids
Shipper	Global transportation and logistics company	Germany	More than 300,000 employees and over €4 billion turnover	Provides sea transport and overland services.
Distributor	Large-scale distributor	Italy	More than 4,000 employees and over €5 billion turnover	It manages a retail system network of supermarkets throughout the national territory

Table 2: Canned Food SC

A panel of experts involved in this specific SC is established to analyse in-depth the specific issues. Three professionals from each SC tier are chosen, with a total of 15 experts in order to implement a holistic approach to the problem and collect information from the whole SC. In addition, experts with different skills were involved (from logistics to corporate finance, from operations to marketing, ...) to collect information from players that have a different point of view on the SC system. Table 3 shows in detail the composition of the panels.

SC player	Panel of experts	Expert background
Supplier	Marketing manager	Degree in marketing, he performs field research to analyze market trends and competition.
	Operation manager	Degree in management engineering, prior experience working in related industries.
	Technical manager	This professional figure has deep understanding of the types of products the company offers, since he is responsible of the two main production lines
Production	Commercial manager	Degree in economics, with both sales and marketing expertise from prior experience in sector-related industries
	Financial manager	Degree in finance, he is appointed to analyze financial and management data so that the company can make informed decisions.
	Operation manager	Degree in mechanical engineering, he is one of the responsible of the main business process of the company.
Packaging	Technical manager	Degree in industrial engineering, this professional figure has deep understanding of the packaging processes in the company
	1st commercial manager	Degree in economics, he is in charge of creating and implementing successful domestic business strategies.
	2nd commercial manager	Degree in economics, he is in charge of creating and implementing successful international business strategies.
Shipper	1st logistic manager	In charge of maintaining and recording warehouse inventory, while organizing transportation, customer service, and logistics.
	2nd logistic manager	In charge of guaranteeing the effectiveness of each process, communicating with suppliers, producers, and clients. He is also responsible of quality control and customer satisfaction.
	Financial manager	Degree in finance. He controls all financial activities, ensure timely and accurate financial closing, and create financial and management reports.
Distributor	Logistic manager;	Degree in logistic engineering. He is in charge of management of customers and suppliers' logistic networks and he has supervision of branch departures and transports
	1 marketing manager	Degree in marketing. He is responsible of the events strategy to achieve B2B commercial sales objectives. Moreover, he plans, oversees, and manage the development, administration, and execution of the company meetings and events.
	2nd marketing manager	Degree in financial marketing. He studies and analyses company KPIs and report findings to the top management, while maintaining, updating, and analyzing measurement tools.

Table 3: Compositions of the panel of experts

As mentioned in the research approach, forming the expert group is one of the critical steps in the process. Indeed, they

identify the fundamental factors describing the questioned system dynamic according to their experience and approach to the topic. This means that to create a collective mental model that is as in-depth as possible, the group of experts must be as heterogeneous as possible in terms of the professions involved; obviously with knowledge of the subject matter.

4.1 Factors identification and first refinement

Present research entails a literature review to identify the most influential parameters influencing the resilience of agri-food SCs. The literature search is conducted using the following keywords: 'Supply Chain,' 'Resilience,' 'Risk,' 'Disruptions,' 'Supply Uncertainties,' 'Agri-food,' 'Food,' 'Agriculture,' and 'COVID-19' in the following databases: Emerald, Metapress, Science Direct, Scopus, and Web of Science. As a result, filters were used to individualize the core set of research in order to choose the most important aspects. The following describes the filters:

- Ensure substantive relevance, which is defined as the sufficiency of the articles in addressing and capturing the investigated phenomena, by mandating that they include the keyword search in their title, abstract, or keywords;
- Consider only publications written in English;
- The remaining abstracts should be reviewed for relation to content;
- The remaining entire papers should be reviewed for relevance;

By applying the first two filters, 63 papers were discovered, of which 38 were determined to be pertinent. Table 4 contains a listing of all factors addressed in the 38 selected papers.

Factors	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
COVID-19 pandemic	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Limits on the mobility of people	x	x		x		x		x	x	x		x	x	x	x	x	x	x	x	x			x	x	x	x		x		x	x	x	x	x	x		x
Border closures	x	x		x		x		x		x		x	x	x	x		x			x					x	x				x				x				
Available workforce	x	x	x	x		x		x		x		x	x	x		x	x			x			x	x	x	x		x	x	x		x			x		x	
Limit of people at work	x	x	x			x																																x
Export limit	x		x		x	x		x		x		x				x				x			x	x		x			x					x				
Import limit	x		x		x			x		x		x		x		x							x						x									
Demand variation	x	x	x	x		x	x	x		x		x	x			x				x		x	x			x		x	x	x	x		x	x	x		x	x
Reduction of consumer income	x	x	x		x					x		x	x	x	x	x				x			x	x		x												
Increased costs of pesticides		x										x																										
Increased seed costs												x																										
Increased fertilizer costs												x																										

Lack of pesticides		x	x																																		x	x
Lack of agricultural inputs		x	x			x		x				x											x	x		x		x										x
Preference for staple foods		x		x		x														x						x												
Preference for food with a longer shelf life		x		x		x																				x		x										
Eating habits change		x	x	x		x		x	x				x	x									x	x		x		x	x		x	x						
Food home-delivery	x			x		x		x	x	x							x											x	x									
Consumption of home-cooked food		x	x	x		x	x	x	x				x				x																					
Increased e-commerce of food				x		x		x		x																					x							
Relationship between farmers and market/restaurant/seller		x																												x						x		
Closing restaurants, hotels, bars, school canteens		x	x	x		x		x	x			x		x			x				x	x		x	x	x		x	x		x							
Preventive and safety measures for workers	x	x	x	x		x	x	x																x														
Food security	x	x	x	x				x	x	x		x		x	x									x		x		x	x			x	x				x	x
Safety and prevention	x	x	x	x		x	x	x					x						x					x		x		x	x	x	x	x			x		x	
Higher transportation cost		x						x																					x	x								
More time for forms and customs clearance	x	x																																			x	
Transport restrictions	x	x		x		x	x	x				x	x	x			x			x			x	x		x		x		x								x
Decrease in GDP due to Covid	x															x	x																					
Oil price drop	x	x		x																				x			x											
Panic buying		x	x	x		x		x	x				x							x	x		x			x			x	x	x	x						
Reduced distribution company capacity			x				x	x					x		x																							
Reduced processing of company capacity			x				x	x					x		x																							
Reduced reseller capacity			x				x	x					x																x									
Digitalization																															x						x	
Use of alternative marketing channels and buyers																													x									
Bottlenecks in transport and logistic																														x	x		x	x			x	x

Table 4: Factors affecting agri-food SCR

1. Barichello (2020), 2. OECD (2020), 3. Larue (2020), 4. Nicola et al. (2020), 5. UNCTAD (2020), 6. Jámbor et al. (2020), 7. Brewin (2020), 8. Hossain (2020), 9. Aldaco et al. (2020), 10. Siche (2020), 11. Pomarici and Sardone (2020), 12. FAO (2020), 13. Henry (2020), 14. Altieri and Nicholls (2020), 15. Fontan Sers and Mughal (2020), 16. Dente and Hashimoto (2020), 17. Gray (2020), 18. Meine (2020), 19. Villulla (2020), 20. Kerr (2020), 21. Shanks et al.

(2020), 22. McDonald and Holtz 2020), 23. Zhang et al. (2020), 24. Laborde et al. (2020), 25. Seleiman et al. (2020), 26. Savary et al. (2020), 27. Wang et al. (2020), 28. Barcaccia et al. (2020), 29. Hobbs (2021), 30. Mishra et al. (2021), 31. Burgos and Ivanov, (2021), 32. Derossi et al. (2021), 33. Abu Hatab et al. (2021), 34. Alhawari et al. (2021), 35 Blessley and Mudambi (2022), 36. Sengupta et al. (2021), 37. Sridhar et al., (2022), 38. Nasereldin et al. (2021)

In order to achieve an appropriate balance between information detail and completeness, the aforementioned panel of experts regrouped the criteria to be included in the cognitive map. This is the first refinement step, and it aims at developing a coherent grouping in order to facilitate respondents' cognitive processing (Krosnick 2018). Indeed, although researchers and experts can address the same issue, their experience and approach to a specific issue may require a specific vocabulary. Thus, several different factors can have the same meaning. For this reason, in the first refinement, the mentioned evaluation is carried out on the literature review results through the application of the Delphi method, noting that a research group methodology is used because it can result in more in-depth knowledge through participatory discussion (Goldman 1962).

During the first iteration, a questionnaire is given to all the experts. Based on their comprehension of the literature review, the questionnaire asked participants to list the element that, in their opinion, has the greatest impact on SCR. Once all the questionnaires were completed, a summary was produced, in which the given list was regrouped in 42 factors. The report was then given back to the experts for their evaluation.

During the second iteration, a follow-up questionnaire was given to the expert, along with the first summary report. The experts were asked to re-evaluate their initial judgment in light of the suggestions made by their peers, and to share any updated facts or deductions from the literature review that they may have made since the initial round. Once all the questionnaires were completed, another report was created with the top factors identified by the experts – 31 factors – and the report was then sent back to the expert for review. During the third round, the process has been repeated, and the final report was completed with the consensus reached on 24 factors, including the 'Pandemic' factor (F1), which is the initial disruption, and the final 'top event'. Because the goal of this work is to assess the influence of different factors on SCR, it was decided to pose 'Supply Chain Resilience' as the 'top event' (F24). This means that all factors converge on this 'top event'.

This first refinement allows the panel to frame a context of the factors and the relationships between them, making them as balanced as possible (Krosnick 2018). For example, factors such as 'Limits on the mobility of people', 'Export limit', 'Import limit' are changed to 'Mobility of people', 'Export level' and 'Import level' factors, in order to provide the least influential background to a possible answer. The final factors list after the first refinement is shown in Table 5.

#	Factors	Description	Factors involved
F1	Pandemic	The COVID-19 pandemic currently underway, the so-called 'new coronavirus disease'.	COVID-19 Pandemic
F2	Mobility of people	The ability of people to move freely in the national territory.	Limits on the mobility of people
F3	Border closures	Impossibility of crossing national borders.	Border closures
F4	Available workforce	The availability of human resources to carry out routine production chain tasks.	Available workforce, Limit of people at work
F5	Export level	Quantity of goods exported.	Export limit
F6	Import level	Quantity of imported goods.	Import limit
F7	Consumer income	Level of monthly consumer income during the pandemic period.	Reduction of consumer income
F8	Cost of agricultural inputs	Cost of agricultural inputs, such as seeds, pesticides, fertilizers, food for animals, etc.	Increased costs of pesticides, increased seed costs, increased fertilizer costs
F9	Availability of agricultural inputs	Level of availability of agricultural inputs, such as seeds, pesticides, fertilizers, food for animals, etc.	Lack of pesticides, lack of agricultural inputs
F10	Staple food demand	Purchase of 'basic' food items such as bread, pasta, rice, canned food, etc.	Preference for staple foods, change of eating habits, demand variation
F11	Long shelf-life food demand	Buying food such as canned food, frozen food, etc.	Long term food preference, change of eating habits, demand variation
F12	Home delivered food demand	Purchase of food delivered directly to your home through orders placed via the internet, telephone, SMS, etc.	Increased e-commerce of food, change of eating habits, home delivery of food, demand variation, use of alternative marketing channels and buyers, Digitalization
F13	Consumption of home-cooked food	Consumers who buy products and then cook them and consume them at home.	Change of eating habits, consumption of home-cooked food
F14	Closure of the Ho.Re.Ca. channel	Forced closure of private and public foodservice industry.	Relationship between farmers and markets/restaurants/sellers, closing restaurants, hotels, bars, school canteens
F15	Preventive and safety measures for workers	Enforcement of safety regulations for worker protection such as shift work, spacing and use of guards, masks and gloves.	Preventive and safety measures for workers, Safety and prevention
F16	Food security	To guarantee the population access, both from an economic point of view and from the point of view of hygiene and health safety, to a sufficient quantity of food to have a healthy and active life.	Food security
F17	Cost of transport	Increased costs of food transport between two points in the SC.	Higher transportation cost, Bottlenecks in transport and logistic
F18	Customs clearance times	Increased customs clearance procedure.	More time for forms and customs clearance

F19	Transport restrictions between countries	Policies to limit public and private transportation of people.	Transport restrictions
F20	Panic buying	Consumers buy an unusually large amount of a product in anticipation of a perceived disaster or catastrophe.	Panic buying, Demand variation
F21	Resilience of distribution companies	The ability of the distribution company to return to its original state or a more desirable one after a destructive event.	Reduced distribution company capacity
F22	Resilience of food-processing companies	The ability of the distribution company to return to its original state or a more desirable one after a destructive event.	Reduced processing of company capacity
F23	Resilience of retail companies	The ability of the distribution company to return to its original state or a more desirable one after a destructive event.	Reduced reseller capacity
F24	Supply Chain Resilience (SCR)	The ability of the SC to return to its original state or a more desirable one after a destructive event.	Top event

Table 5: Factors definitions

4.2 Questionnaire Analysis and second refinement

Once the final factors are identified, the panel of experts defines if a relationship exists among them. An excerpt of the questionnaire created for this purpose is exemplified in Table 6. This excerpt concerns the relationships between 'Import level' and all other factors, but the same questions have been repeated for all factors.

According to the respondent, during the COVID pandemic, which of the factors listed below influence the 'Import level'?							
Panic buying	☐	Cost of agricultural inputs	☐	Closure of the Ho.Re.Ca. channel	☐	Resilience of retail companies	☐
Mobility of people	☐	Availability of agricultural inputs	☐	Preventive and safety measures for workers	☐	Resilience of distribution companies	☐
Border closures	☐	Staple food demand	☐	Food security	☐	Resilience of food-processing companies	☐
Available workforce	☐	Long shelf-life food demand	☐	Cost of transport	☐		
Export level	☐	Home delivered food demand	☐	Customs clearance times	☐		
Consumer income	☐	Consumption of home-cooked food	☐	Transport restrictions between countries	☐		

Table 6: Excerpt from the adjacency matrix questionnaire

The experts answered the various questionnaires during face-to-face sessions because this made the process of analysing them quicker and more immediate. Each expert proposed and discussed their answers with the others, giving immediate reasons. In this way, it was not necessary to investigate the validity of the various questionnaires and the

significance of the answers of each one was not questioned. In order to facilitate the procedure, a facilitator was introduced. By the foundations of cognitive theory, facilitator must be able, throughout the process, to raise awareness in the experts that their knowledge may be affected by bias and that they should therefore try to be curious, open to dialogue and ready to accept even the ideas of those who do not think the same way. During the process, discussion in the presence of one's observations allows one to identify possible evidence contrary to one's own beliefs that may in some way change one's judgement, and, possibly, accept them with humility (Hertel and Mathews 2011).

After the questionnaires were filled, the cognitive maps were obtained (see Figure 5). Adjacency matrix of this map is shown in Appendix 1 (see Table 15).

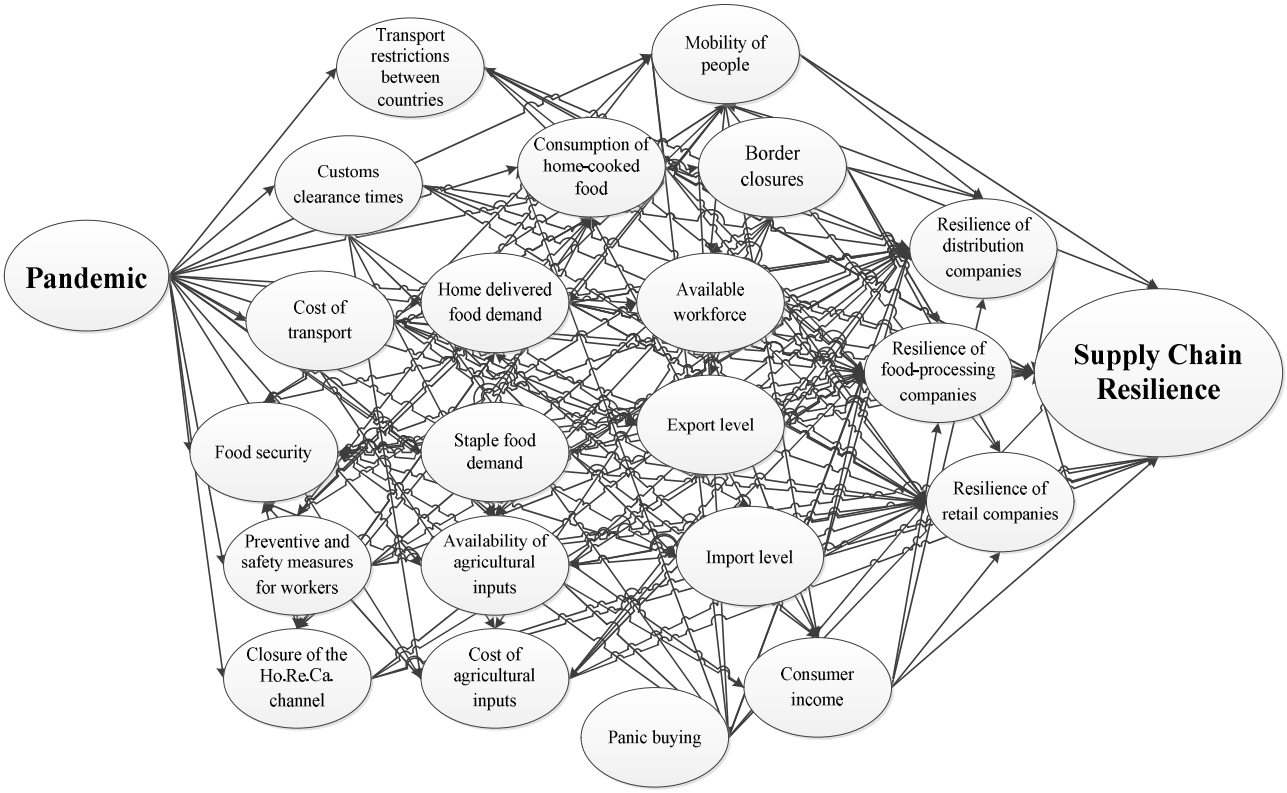

Figure 5: Canned SC Cognitive Map

The next step requires the panel of experts to define the weight of the relationships among factors previously identified, through the completion of interviews and questionnaires, following the same procedure of the previous step. An excerpt of the questionnaire used for this purpose is shown in Table 7. The connections' weights are defined using a Likert scale of 11 values that are associated with linguistic variables (positive and negative) and, also, a 'no connection' option (see Table 7). Linguistic variables are used in order to facilitate the decision-making process of the expert group. The obtained weights are the values of e_{ij} (see section 3.3).

According to the respondent, during the COVID pandemic, how did the factors listed below influence the 'Import level'?											
Factors	**Connection Weight**										
	Negative connection						Positive connection				
	Very High	High	Medium	Low	Very Low	No Connection	Very Low	Low	Medium	High	Very High
Border closures	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Cost of transport	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
Customs clearance times	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐
…	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Table 7: Excerpt from the questionnaire concerning the 'Import level' relationships

5 Discussion

The questionnaire analysis phase provides a cognitive map from each single expert and for each single SC players, in the form of a weighted matrix. Such cognitive maps are aggregated for every SC players and for the overall SC according to the methodology mentioned in section 3.4. The final weighted matrix about the overall SC is shown in Tables 16 (see appendix 2). Subsequently, for each SC player, the presence of principal paths within the FCM is studied. Tables 8 through 12 demonstrate the ripple impact of issues influencing every SC player, while principal paths for the overall SC is shown in Table 13. Principal paths represent all possible factors' chains that start from 'Pandemic' factor and end with 'SCR' factor. A total of 26,275 paths have been found. All paths are sorted in descending order by TE. In particular, the first 10 paths are shown, in order to find an optimal compromise between comprehensiveness and readability. TE defines the most important causal concatenation among the factors that bring from Pandemic to SCR when there are several possible paths. TE assumes positive value if the factors move in a concordant way, and a negative value if otherwise. Moreover, the last column of each table exemplifies the factors sequence which leads to SCR increase [↗] or decrease [↘] within the COVID-19 pandemic scenario.

#	***Supplier*** **- Principal Paths** - Starting Node: COVID pandemic							TE	SCR [↗.↘]
1	Preventive and safety measures for workers	SCR						-0.933	↘
2	Panic buying	SCR						-0.866	↘
3	Closure of the Ho.Re.Ca. channel	SCR						-0.866	↘
4	Mobility of people	Consumption of home-cooked food	Food security	Panic buying	Resilience of distr. companies	SCR		0.800	↗
5	Mobility of people	Consumption of home-cooked food	Food security	Panic buying	SCR			0.800	↗
6	Mobility of people	Consumption of home-cooked food	Resilience of distr. companies	SCR				0.800	↗
7	Mobility of people	Consumption of home-cooked food	SCR					0.800	↗
8	Border closures	Mobility of people	Consumption of home-cooked food	Food security	Panic buying	Resilience of distr. companies	SCR	0.800	↗
9	Border closures	Mobility of people	Consumption of home-cooked food	Food security	Panic buying	SCR		0.800	↗
10	Border closures	Mobility of people	Consumption of home-cooked food	Resilience of distr. companies	SCR			0.800	↘

Table 8: Supplier Principal paths

#	***Production*** - **Principal Paths** - Starting Node: COVID pandemic			TE	SCR [↗.↘]
1	Long shelf-life food demand	SCR		1.000	↗
2	Cost of agricultural inputs	SCR		-0.933	↘
3	Staple food demand	SCR		0.933	↗
4	Closure of the Ho.Re.Ca. channel	SCR		-0.933	↘
5	Border closures	SCR		-0.866	↘
6	Preventive and safety measures for workers	Mobility of people	SCR	0.800	↘
7	Mobility of people	SCR		0.800	↗
8	Available workforce	Resilience of food-processing companies	SCR	0.800	↘
9	Home delivered food demand	Resilience of food-processing companies	SCR	0.800	↘
10	Transport restrictions between countries	Resilience of food-processing companies	SCR	0.800	↘

Table 9: Production Principal paths

#	***Packaging*** - **Principal Paths** - Starting Node: COVID pandemic					TE	SCR [↗.↘]
1	Mobility of people	Consumption of home-cooked food	Food security	Panic buying	SCR	-0.866	↗
2	Border closures	SCR				-0.866	↘
3	Import level	Food security	Panic buying	SCR		0.866	↗
4	Consumption of home-cooked food	Food security	Panic buying	SCR		0.866	↘
5	Food security	Panic buying	SCR			-0.866	↘
6	Cost of transport	SCR				-0.866	↗
7	Customs clearance times	Import level	Food security	Panic buying	SCR	0.866	↗
8	Panic buying	SCR				-0.866	↘
9	Long shelf-life food demand	SCR				0.800	↘
10	Consumer income	Food security	Panic buying	SCR		0.800	↘

Table 10: Packaging Principal paths

#	***Shipper*** - **Principal Paths** - Starting Node: COVID pandemic				TE	SCR [↗.↘]
1	Cost of agricultural inputs	Resilience of food-processing companies	SCR		-0.933	↘
2	Availability of agricultural inputs	Resilience of food-processing companies	SCR		-0.933	↘
3	Availability of agricultural inputs	SCR			-0.933	↘
4	Resilience of food-processing companies	SCR			0.933	↘
5	Border closures	Import level	Resilience of food-processing companies	SCR	0.866	↘
6	Import level	Resilience of food-processing companies	SCR		0.866	↘
7	Cost of transport	SCR			-0.800	↘
8	Panic buying	SCR			-0.800	↘
9	Available workforce	Resilience of distribution companies	SCR		0.733	↘
10	Consumer income	Resilience of distribution companies	SCR		0.733	↗

Table 11: Shipper Principal paths

#	***Distributor*** - **Principal Paths** - Starting Node: COVID pandemic			TE	SCR [↗.↘]
1	Border closures	SCR		-0.933	↘
2	Staple food demand	SCR		0.933	↗
3	Long shelf-life food demand	SCR		0.933	↗
4	Consumption of home-cooked food	SCR		0.866	↗
5	Closure of the Ho.Re.Ca. channel	SCR		-0.866	↘
6	Panic buying	SCR		-0.866	↘
7	Import level	SCR		0.800	↗
8	Consumer income	SCR		0.800	↗
9	Mobility of people	Panic buying	SCR	-0.733	↘
10	Export level	SCR		0,733	↗

Table 12: Distributor Principal paths

#	***Overall SC*** - **Principal Paths** - Starting Node: COVID pandemic			TE	SCR [↗.↘]
1	Long shelf-life food demand	SCR		0.826	↗
2	Closure of the Ho.Re.Ca. channel	SCR		-0.800	↘
3	Panic buying	SCR		-0.786	↘
4	Border closures	SCR		-0.760	↘
5	Staple food demand	SCR		0.720	↗
6	Consumption of home-cooked food	SCR		0.706	↗
7	Cost of agricultural inputs	Resilience of food-processing companies	SCR	0.693	↘
8	Availability of agricultural inputs	Resilience of food-processing companies	SCR	0.693	↘
9	Preventive and safety measures for workers	Consumption of home-cooked food	SCR	0.693	↗
10	Resilience of food-processing companies	SCR		0.693	↘

Table 13: Principal paths of the Overall SC

5.1 Principal paths analysis

Looking at the principal paths regarding the SC players (Table 8-12) and the overall canned food SC (Table 13), several results can be highlighted. Looking at the Supplier principal paths (Table 8), the path 'Preventive and safety measures for workers – SCR' can be found at the top with a TE of -0.933. According to the experts involved, this factor has most negatively affected SC: many studies agree with this finding (Barichello 2020; OECD 2020), highlighting how this policy responses are a large treat to the day-to-day operations of a SC, e.g. the alteration of corporate environments in order to maintain social distance: international financial institutions also claim that containment measures had a significant negative impact on economic activity, resulting in a 15% drop in industrial production in the 30-day period after their introduction (Deb et al. 2021).

Subsequently, the paths 'Panic buying – SCR' and 'Closure of the Ho.Re.Ca Channel – SCR' can be both found with a TE of -0.866. Regarding the former, as a response to panic-buying, agri-food in general scrambled to meet increased demand by ramping up orders and production to try and keep shelves stocked. The whole food sector, in fact, has been put under strain as a result of people panic-buying and stockpiling food (Aldaco et al. 2020; Hossain 2020; Nicola et al. 2020): for example, large-scale distributors which are generally accustomed to just-in-time deliveries, encountered uncontrollable spikes in demand which were difficult to manage (Dulam et al. 2020; Jámbor et al. 2020). However, this reactive response had severe consequences to the downstream of the SC in terms of bullwhip effect, with the first tiers being the most afflicted. Thus, weakening [↘] the SCR as a whole, in line with results. Instead, the inversely proportional relation of the latter path is a direct consequence of the nationwide lockdowns imposed to 'flatten the curve' throughout the world, and many authors agree on this aspect (Gray 2020; McDonald and Holtz 2020). To this regard, Savary et al. 2020 highlight how these policies have sparked historically increased bottlenecks throughout local

and global food systems and decreased incomes and access to food for poor and more vulnerable households, who already had limited access to food, are disproportionately harmed by such policies.

Looking again at the supplier's paths table, we can also dwell on routes number 4 and 8, exemplified in detail in Figures 6 and 7.

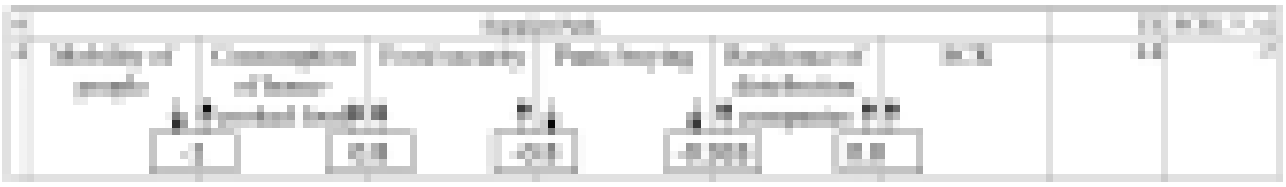

Figure 6: Exemplification of supplier path #4 in Table 8

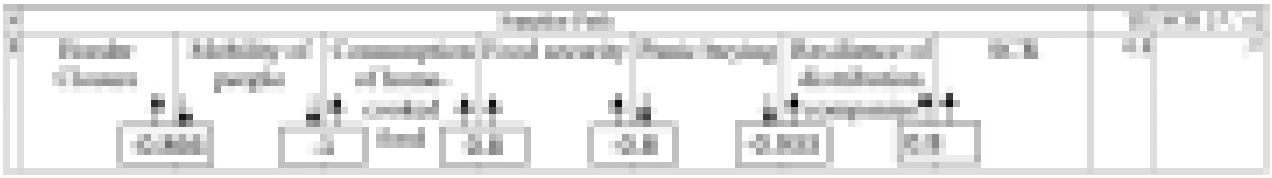

Figure 7: Exemplification of cycle #8 in Table 8

Although ‘Mobility of people’ and ‘Border closures’ factors respectively lower both the resilience of the entire SC and that of the individual supplier, in each case particular dynamics can be highlighted that tend instead to strengthen supplier resilience.

Indeed, analysing Fig. 6, we discover how the decrease in ‘Mobility of people,’ a phenomenon caused by the strengthening of the pandemic, changes the population's eating habits, which tends to prefer ‘Consumption of home-cooked food.’ The strengthening of this habit, in turn, increases the ‘Food security’ of the population itself, thereby decreasing the phenomenon of ‘Panic Buying,’ and thus increasing the ‘Resilience of distribution companies’ and thus SCR.

This is a peculiar result that is dissimilar to many works that has studied this dynamic, which points out that the decreasing of ‘mobility of people’ in one of the main factors behind the loss of resilience of SCs around the world. (Derossi et al. 2021; Mishra et al. 2021). In particular, Burgos and Ivanov (2021) highlight how the availability of seasonal workers for planting and harvesting has decreased in many countries due to restrictions on people's mobility, which brought a lack of labor, and resulted in significant food loss and waste.

Analysing Fig. 7, we find the same dynamic, which in this case is reinforced by the increase in the ‘Border closures’ factor, caused indeed by the intensification of the pandemic. This, in turn, severely limits the ‘Mobility of people,’ again triggering the above-mentioned dynamics.

The analysis carried out for the supplier can be repeated for every SC player. In the next part of this section, we highlight only some paths that characterize the supply chain. Regarding the Production company, an interesting

result can be seen with the first path ‘Long shelf-life food demand – SCR’, with a TE of 1. Long-life foods are in high demand as customers store up on necessities in anticipation of shortages and to reduce the need to go out for food. As more consumers move away from fresh meals in favour of stockpiling items with a longer shelf life, sales of processed, canned, and frozen foods are increasing. Long shelf-life goods, i.e., canned food, are, in fact, considered a ‘refuge food’ and therefore, in the event of a pandemic and prolonged lockdowns, consumers prefer to buy this type of product. Jámbor, et al. (2020) further emphasizes this point, stating that individuals have begun to store up on durable foods out of fear of being confined for an extended period.

It is also worthwhile to concentrate on evaluating the factors ‘Available workforce,’ ‘Home delivered food demand’, and ‘Transport constraints between nations’, all of which start path that led to ‘SCR’ with a TE of 0.800 after passing through ‘Resilience of food-processing enterprises’. This result makes clear that food processing companies are the key to the resilience of the whole SC: indeed, numerous research papers have been published on how and why food firms can adopt resilience to defend themselves from escalating business dangers, i.e., the COVID-19 pandemic. Food processing companies are willing to learn from their own and others' mistakes to minimize issues and seize opportunities. For example, when adapting to the available workforce or to the changing business environment, in terms of transport constraints between nations or change in the eating habits of the customers, i.e., home delivered food demand, as many authors also suggests (Barichello 2020; Mishra et al. 2021; Nasereldin et al. 2021; Sridhar et al. 2022).

Looking at results as whole, it can be seen that ‘Border closures’ is present in every player of this SC, and the path generated always weakens SCR [↘]: indeed, borders surrounding nations were restricted as the COVID-19 shutdown took effect across the globe, forcing vehicles to recalculate distribution routes. This is only one example of how important it is to maintain a balanced flow of items across our food supply chain to avoid empty grocery shelves. Other authors agree to this result: Pulighe and Lupia (2020) investigated how the combined effect of border closures and movement limitations increased food losses and export prices, especially for perishable products such as vegetables, and exposed nations lacking self-sufficiency.

It is possible to extract much info by analysing paths listed in tables 8-13. For instance, the path ‘Preventive and safety measures for workers – Consumption of home-cooked meals – SCR’ in Table 13 reveals an unusual dynamic observed during lockdown. In reality, many of the precautions put in place to protect personnel from the virus envisaged smart-working methods. This new normal changed the life-habits of working people, thus, changing their eating habits, with more and more approach to home-cooked food. In turn, this new habit augmented SCR, since the grow up demand of canned food.

5.2 FCM Cycles Analysis

The second analysis carried out with the FCM concerns the presence of cycles within the produced map. Table 14 exemplifies cycles within the whole canned food SC. A cycle is a process or set of reoccurring variables in the SC. The presence of a cycle shows the existence of recursive ripple effects that might have either good or negative consequences on the SC.

Regarding this analysis, a total of 6 cycles have been found within the whole SC FCM.

#	Cycles						TE	SCR [↗,↘]
1	Resilience of distribution companies	Resilience of food-processing companies	Resilience of retail companies	Resilience of distribution companies			0.440	↗
2	Resilience of food-processing companies	Resilience of retail companies	Resilience of food-processing companies				0.440	↗
3	Staple food demand	Consumption of home-cooked food	Food security	Panic buying	Staple food demand		-0.320	↗
4	Staple food demand	Consumption of home-cooked food	Food security	Panic buying	Long shelf-life food demand	Staple food demand	-0.320	↗
5	Long shelf-life food demand	Consumption of home-cooked food	Food security	Panic buying	Long shelf-life food demand		-0.320	↗
6	Consumption of home-cooked food	Food security	Panic buying	Consumption of home-cooked food			0.186	↗

Table 14: Cycles within the canned food SC FCM

In table 14 the common denominator consists in the cycles in which the resiliencies of individual actors are linked together: cycles #1 and #2, both with a TE of 0.440. This result is consistent with different studies (Bryce et al. 2020; Huang et al. 2020; Sanchis et al. 2020) underlining that enterprise resilience is a widely researched field within the COVID-19 pandemic context. Based on these results, it can be inferred that a given actor with an organizational resilience decrease, especially in the context of the COVID-19 pandemic, triggers a negative cycle that affects other companies in the same SC, negatively influencing organizational resilience, and, as a result, undermining the resilience of the whole SC.

Another interesting result can be observed in the third cycle of Table 14: ‘Staple food demand - Consumption of home-cooked food – Food security – Panic Buying – Staple food demand’ with the TE of –0.320 representing the critical connection between ‘Food security’ and ‘Panic Buying’.

Analysing in detail the nature of the linkages among the factors, it is possible to infer that the succession of these relationships reinforces the trend of ‘Staple food demand’. Figure 8 shows the detailed analysis of the relationship characterizing the third cycle within the SC FCM, describing the dynamics reinforcing the ‘Staple food demand’ factor. In particular, the ‘Staple food demand’ factor is directly proportional to the ‘Consumption of home-cooked food’ factor (the weight of this connection is equal to 0.44), while this last factor is inversely proportional to the ‘Food security’ factor (weight -0.72). Subsequently, an inversely proportional relationship has been identified between ‘Food security’

and ‘Panic buying’, with a weight of -0.32. Finally, also ‘Panic buying’ and ‘Staple food demand’ are connected with a inversely proportional relationship with a weight of -0.8.

In addition, the ‘Staple food demand’ factor, in the context of the pandemic, reinforces the SCR of the whole SC (see the weighted matrix in Table 13) with a weight of 0.720, since the canned food product belongs to this category.

Figure 8: visual explanation of cycle #3 in Table 14

5.3 Theoretical contribution

In scientific literature, there is a lack of quantitative approaches to systematically analyze and anticipate the relationship between multidimensional and interdisciplinary elements that might impact a SC and the causal responses behind the negative or positive variance in SC performance. The proposed approach, which is based on FCM, allows researchers and business managers to consider multidimensional and interdisciplinary factors that belong to sectors that are often distant from one another and unveil the causal relationships that occur among such factors as a result of a disruption and how these causal relationships strengthen or weaken SCR.

The proposed research method analyzes the resilience of not only a single company, but also an entire SC. This creates a further research challenge, as each SC company may be affected by a unique set of factors that influence its own resilience. On the other hand, it is essential to recognize that the individual company's survival frequently depends on the survival of the whole SC. For this reason, it is essential to study the behaviour of every player and the entire SC. The FCM methodology addressed this research problem and combined the different SC players’ points of view throughout the experts' opinion, which have been then grouped using the Centre of Gravity (COG) defuzzification method. This methodology enabled SC managers to examine both the principal pathways of a single firm and the ripple impact for the whole SC. This technique provides a full comprehension of the system's behavior and enables us to explicitly examine the mental models of several SC players.

In addition, the inclusion of all players' perspectives can bring a fresh point of view to SC disruptions. We were able to obtain a graphical and mathematical representation of a manager's belief system thanks to the cognitive map. A manager's belief system (i.e., the collection of elements and linkages) is activated by circumstances that appear pertinent to the issue at hand. The map depicts the conscious sense of reality, or how a SC player perceives a particular disturbance. The FCM method enables analysts to model complicated systems that demonstrate causal relationships between key components and to handle inherent uncertainties.

6 Conclusions

The proposed study develops a general framework for analysing the disruption effects within a SC. Firstly, interconnections between factors related to the disruption are evaluated through linguistic values, allowing the SC experts to describe more efficiently the influence of one factor on others. Secondly, the application of FCM methodology gives the opportunity to expand the local view offered by each expert into a more comprehensive global view, which allows one to unveil otherwise hidden connections. These concatenations of factors influencing the SC, reveal the presence of paths and cycles that may strengthen or undermine their impact on SCR. In this case study, 60 paths are depicted, for highlighting the dynamics of individual SC actors as well as the dynamics of the SC as a whole. Moreover, 5 cycles are exemplified. SC, highlighting how factors that could compromise SCR could also activate cycles reinforcing agrifood SCR.

6.1 Implications for agri-food supply chain managers

Although the vaccination campaign has started at the end of 2020, many experts agree that the pandemic is far from over, and that the situation will not return to normal anytime soon. Secretary-General António Guterres, addressing the GAVI Vaccine Alliance, affirmed that the new COVID wave a reminder pandemic is ‘far from over’ (UN News 2022). This suggests that 2022 and 2023 may very likely feature other pandemic-related SC dynamics. Therefore, this research provides SC managers with both information and tools to face the 2022/2023 pandemic-related challenges. Firstly, this paper gives a glance into the inside mechanism behind the agri-food SCR dynamics in relation to the COVID pandemic. The analysis of the FCM provides company managers with the main ripple effects among factors and the impact of these factors on the SCR. Such information is a key insight into understanding what happens and to guarantee the safety condition of all operators and the continuity of the SC. People in their different roles within an organization must be aware of potential failure pathways, and therefore they will tend to develop failure-sensitive strategies to prevent these possibilities. When the principal path consists of a chain of factors that lead to a reduction in

SCR, managers can try to eliminate a link between these factors to break the chain, or to eliminate one of the factors in the chain.

Second, the provided technique has important consequences from a business perspective: it does not only examine the operational behavior of risks and resilience, but also attempts to correlate it with more abstract strategic variables that make it challenging to utilize as a management tool. This is a key added value in managing an agri-food SCR, especially within the COVID-19 pandemic scenario: SC Managers interested in enhancing agri-food SCR under uncertainty may begin by utilizing this study's map to identify critical areas for improvement or specific measures to implement. To give a complete approach, the suggested technique established Principal routes of multidimensional and multidisciplinary elements, illustrative of a system's behavior to SC management. The knowledge of these causal relationships can be crucial for company managers to handle impending vulnerabilities and potential disruptions. This aspect is worth analysing as resilience capability is becoming a success factor in the medium and long term.

6.2 Implications for theory and research

Current study on the issue of agri-food within the context of a pandemic scenario investigates SCR from several perspectives. This research contributes to the compilation of various findings into a unified framework with logical connections and explanations. The suggested technique seeks to establish a generic framework applicable to any SC. In this regard, the illustrative maps can be utilized by other academics to find new research-worthy linkages. The measurement of the ripple effect's influence on SCR's key performance measures would be an additional obstacle. Consequently, future study should focus on the assessment of the factor variation caused by the COVID-19 pandemic environment. The key restriction of the suggested framework relates to the necessity of incorporating a large number of managers from SC players in order to gain a holistic perspective of the disruption and to prevent overlooking any links between the various elements. In this approach, ongoing study focuses on determining how the area of expertise of each panel expert influences the identification of variables and the strength of their correlations. It will be crucial to design a tool for accurately assessing the impact of the experts' knowledge on the development of the FCM, taking into account a varying credibility value for each expert's opinion based on their familiarity with the issue.

6.3 Limitations and future research lines

The key restriction of the suggested framework relates to the necessity of incorporating a large number of managers from SC players in order to gain a holistic perspective of the disruption and to prevent overlooking any links between the various elements. In this approach, ongoing study focuses on determining how the area of expertise of each panel expert influences the identification of variables and the strength of their correlations.

As future line of research, it will be crucial to design a tool for accurately assessing the impact of the experts' knowledge on the development of the FCM, taking into account a varying credibility value for each expert's opinion based on their familiarity with the issue. Moreover, given the cyclical routes and interactions shown in this study, future research should focus on investigating methods for enhancing resilience. The quantification of the effects of these initiatives would be another issue in the future. Thus, future studies should focus on calculating the costs and advantages of the resilience solutions recommended by the FCM analysis.

7 Appendix 1 – Adjacency Matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24
F1	0	1	1	1	1	1	1	0	0	1	1	0	1	0	1	1	1	1	1	1	0	0	0	0
F2	0	0	0	1	0	0	1	0	0	0	0	0	1	0	0	1	0	0	0	1	1	1	1	1
F3	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
F4	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1
F5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1
F6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1
F7	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1
F8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F10	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1
F11	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	1	1	1	1
F12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	1	1	1	1
F14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
F15	0	1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1	1	1
F16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1
F17	0	1	0	0	1	0	1	0	0	0	0	0	1	0	0	1	0	0	0	0	1	1	1	1
F18	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
F20	0	0	0	0	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	1	1	1	1
F21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1
F22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1
F23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	1
F24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 15: Canned food SC Adjacency Matrix

8 Appendix 2 – Weighted Matrix

	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20	F21	F22	F23	F24
F1	0	-0,506	0,413	-0,52	-0,52	-0,506	-0,64	0	0	0,133	0,493	0	0,426	0	0,6	-0,466	0,306	0,546	0,68	0,56	0	0	0	0
F2	0	0	0	0,493	0	0	0,2	0	0	0	0	0	-0,2	0	0	0,093	0	0	0	-0,546	0,413	0,44	0,76	0,56
F3	0	-0,72	0	-0,146	-0,826	-0,773	0	0	0	0	0	0	0	0	0	0	0	0	0,4	0,573	-0,32	-0,653	-0,746	-0,76
F4	0	0	0	0	0	0	0,28	0	0	0	0	0	0	0	0	0	0	-0,133	0	0	0,52	0,493	0,666	0,6
F5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,186	0	0	0	0	0,4	0,36	0,333	0,426
F6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,773	0	0	0	0	0,64	0,64	0,586	0,546
F7	0	0	0	0	0	0	0	0	0	0	0	0	-0,28	0	0	0,68	0	0	0	0	0,533	0,28	0,24	0,64
F8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,213	0	0	0	0	-0,493	-0,746	-0,693	-0,64
F9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,693	0	0	0	0	-0,626	-0,813	-0,64	-0,613
F10	0	0	0	0	0	0	0	0	0	0	0	0	0,44	0	0	0,786	0	0	0	0	0,72	0,08	0,68	0,72
F11	0	0	0	0	0	0	0	0	0	0,48	0	0	0,666	0	0	0,773	0	0	0	0	0,68	0,733	0,573	0,826
F12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,36	0	0	0	0	0,106	0,28	0,426	0,293
F13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,72	0	0	0	0	0,666	0,4	0,666	0,706
F14	0	0	0	0	0	0	0	0	0	0	0	0,84	0,64	0	0	0,333	0	0	0	0	-0,4	-0,56	-0,693	-0,8
F15	0	-0,853	0	-0,106	0	0	0	0	0	0	0	0	0,693	0	0	0	0	0	0	0	-0,56	-0,226	-0,866	-0,48
F16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,32	0,173	0,56	0,12	0,12
F17	0	-0,32	0	0	-0,12	0	-0,28	0	0	0	0	0	0,266	0	0	-0,12	0	0	0	0	-0,666	-0,24	-0,253	-0,68
F18	0	0	0	0	-0,026	-0,04	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,186	-0,453	-0,026	-0,68
F19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-0,28	-0,653	-0,6	-0,546
F20	0	0	0	0	0	0	0	0	0	0,8	0,813	0	0,186	0	0	0	0	0	0	0	-0,853	-0,733	-0,706	-0,786
F21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,52	0,36	0,28
F22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,253	0	0,44	0,693
F23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,666	0,733	0	0,466
F24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 16: Canned food SC Weighted Matrix

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