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22 December 2024

Conceptual model for breaking ripple effect and cycles within supply chain resilience

Giulio Marcucci, Giovanni Mazzuto, Maurizio Bevilacqua, Filippo Emanuele Ciarapica & Luca Urciuoli

1 Abstract

Business world has reached a complexity tipping point, increasing the risk of disruption consequences not to remain localised in a single company but to reverberate on the entire Supply Chain. Literature now pays great attention to studying this ripple effect, which can critically undermine resilience of the entire Supply Chain. This work further investigates ripple effect by analysing the presence of cycles among these chain reactions using Fuzzy Cognitive Maps. This methodology allows to link multidimensional and multidisciplinary concepts: by unveiling this information, managers and policymakers are provided with more details about the system behaviour. The research method exemplified uncovers the causal relationships among factors influencing Supply Chain Resilience, providing necessary insight to break or reinforce such connections. A case study of an automotive industry Supply Chain is presented to show the application of the proposed methodology into an operating context: 15 different cycles have been enumerated, explaining how connections among these factors ultimately impact Supply Chain Resilience.

2 Introduction

The last decades have been characterised by significant changes in Supply Chains (SCs) due to an increasing level of globalisation: the turbulent and rapidly changing nature of the global business economy affects SCs in terms of vulnerability, uncertainty and complexity (Yao and Fabbe-Costes 2018; Saenz et al. 2015; Kochan and Nowicki 2018; Villena et al. 2018).

Moreover, this growing role of global SCs has been associated with greater interconnectedness between suppliers and producers, leading to greater interdependency and complexity among SC businesses (Prajogo, Mena, and Nair 2017). Due to this trend, the research activity of many authors (Liberatore, Scaparra, and Daskin 2012; Ivanov 2018; Scheibe and Blackhurst 2018) is focusing towards the circumstances where a singulardisruption becomes the cause of further disturbances along the SC: literature addresses this phenomenon as the ripple effect. Sometimes this disruption cannot be localised and cascades downstream and upstream, affecting all SC performances. It is therefore fundamental to define a method to identify these factors' chain among disruption events and assess the impacts on the performance of the system as a whole, thus having a significant added value on the system's ability to continue in full operation during and after this destructive event. To this regard, the concept of Resilience, intended as 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 2004), has made its way into the research and general approach to the above-mentioned issue. Other researches enriched the definition of Supply Chain Resilience (SCR). Many other studies have contributed to study the definition of SCR from different point of view.

Gaonkar and Viswanadham (2007) define SCR as the ability to maintain, resume and restore operations after a disruption. Instead, Töyli et al. (2013) understand SCR as the ability to cope with change: in their work, they affirm that an SC can be resilient if its original stable situation is sustained or if a new stable situation is achieved.

Therefore, by developing SCR strategies, enterprises are able to predict and prevent any trigger events that could affect the performance of the system, as well as prepare the appropriate responses to oppose a ripple effect (Hosseini and Ivanov 2021; Lorenc, Czuba, and Szarata 2021). Indeed, different SCs present sequences of factors that repeat cyclically and can trigger SC disruptions. This work further investigates the ripple effect and investigates the presence of cycles among factors' connections, as a subsequent analysis to previous research work (Bevilacqua et al. 2018). In particular, the proposed research method aims at addressing the following research gap: the development of a conceptual model able to unveil the presence of ripple effects among SC factors and to highlight the presence of cycles among these factors. A cycle is a course or series of factors or concepts that recur regularly in the SC. The presence of a cycle indicates recursive ripple effects, which can bring positive or negative effects to the SC. These cycles can be connected to each other and the activation of a cycle can trigger another one. The definition of links among those cycles can break the negative ones or enforce the positive ones. Figure 1 shows this situation.

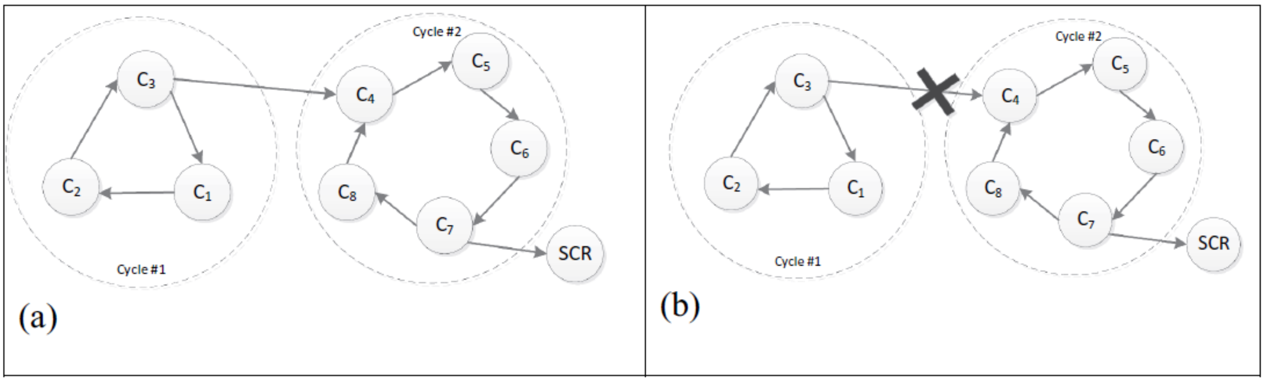

Figure 1. (a) example of concept cycles; (b) link between cycles

As Figure 1(a) shows, Cycle #2 is directly connected to SCR. This cycle must be analysed in order to understand if it has a positive or negative effect on SCR. Moreover, Cycle #1 is connected to Cycle #2 through the connection C3-C4. Therefore, it is important to analyse if Cycle #1 carries a negative or positive influence to Cycle #2. In fact, Cycle #1 can strengthen or weaken the Cycle #2 and, as a consequence, it has an impact on SCR. The methodology proposed in this work aims at identifying these cycles and their links in order to understand what measures have to be carried out. If the consequences of connections are negative for SCR, corrective actions should be aimed at disrupting these links (Figure 1(b)). On the contrary, if the consequences are positive, managers should try to enforce these connections. An example of a ripple effect between concept cycles is shown in Figure 2.

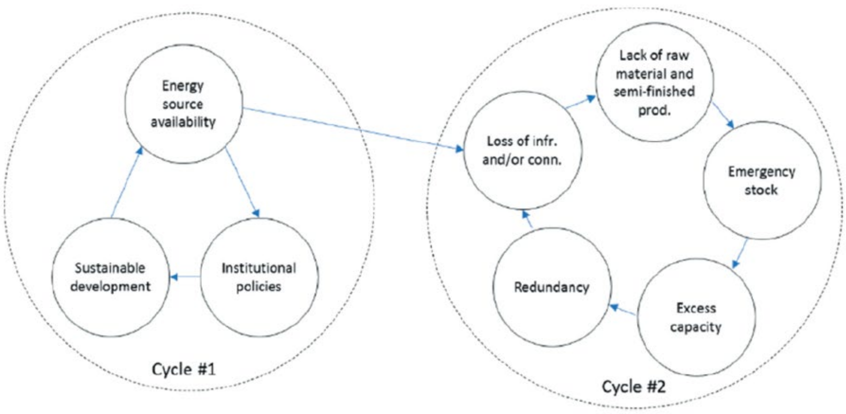

Figure 2. Example of concept cycles and link between cycles.

In cycle#1 we see the concept 'Sustainable development' connected to 'Institutional policies'. This means that the choices of 'Sustainable development' of a Country influence the 'Institutional policies' of that Country. The latter can influence the degree of 'Energy source availability' (for example, a Country may decide not to produce electricity through nuclear power plants). Finally, the type of energy used will have an impact on 'Sustainable development' in future years. The cycle#1 concepts are linked to cycle#2 concepts because the 'Energy source availability' can be linked to the concept of 'Loss of infrastructure and/or connections' of an SC. In turn, this concept triggers the other concepts reported in cycle#2. In general, SCs can be affected by many factors and present many cycles between these factors. Identifying these cycles and understanding their connections is the starting point for disabling unwanted cycles and increasing the resilience of an SC.

This work proposes a method based on Fuzzy Cognitive Maps (FCM) in order to develop the connection network and identify the main factors' chain. Kosko (1986) introduced FCMs as a powerful tool for connecting multidimensional and multidisciplinary concepts in the presence of unsupervised data. FCMs allow analysing data by directed graphs and connection matrixes in order to evaluate critical paths starting from an initial concept and to a top-event, identified as the main concept. Moreover, FCMs point out cognitive mechanisms that influence human decisions for the complex systems management.

In order to explain the methodology developed in this work, a case study in the automotive sector will be proposed. Many authors agree that automotive SCs are especially affected by the ripple effect phenomenon (Bentley, Bailey, and Braithwaite 2017; Ivanov 2018; Stoean 2019). An interesting case study regarded the consequences following the 11 September 2011 terrorist attack, after which the United States decided to immediately close its border. This decision triggered the following chains of events: Ford Motor Co. had to run their assembly lines empty, since the arrival of components was delayed from Canada and Mexico. Toyota Motors Corp. Indiana Plant arrived within hours of production stoppage, waiting for steering sensors that usually arrived by air from Germany (Sheffi 2005). Since that event, many other authors focused on researching this issue from the automotive SC perspective (Azevedo et al. 2013; Simchi-Levi et al. 2015).

The present research paper is organised as follows: Section 2 reviews the extant literature about SCR and the ripple effect. Section 3 exemplifies the FCM theory and in Section 4 the research method is illustrated. The following Sections, 5 and 6, present the application of the proposed method in an operating context: an automotive case study. The final Section 7 displays the research conclusion.

3 Literature review

In the modern business world, Supply Chain RiskManagement (SCRM) is an integral function of the SC. SCRM is utilised in the food industry (Abadi and Darestani 2021), cyber security (Gomes Filho, Rego & Claro, 2021), fashion business (Hernandez and Haddud 2018) and in the context of the ongoing COVID-19 pandemic (Dohale et al. 2021; Woong & Goh, 2021). A canonical view of the traditional risk management process foresees a continuous cycle of identification of hazards, assessment of risks, analysis of controls, choosing controls, implementing controls, and review. In this process, risk assessment phase is a critical step: it is based on assessing the probability and severity on the occurring of a certain event. Therefore, SC risk management techniques can be inadequate to characterise lowprobability, high-consequence events and cannot deal with unforeseeable events. This degree of uncertainty influenced the use of the classic SCRM techniques, since they can lead to critical imprecision and bias in the decision-making process, caused by unmeasured, incomplete, and unattainable information. To this regard, SCR can fill these gaps and supplement existing risk management programmes, thus enabling companies along the SC to survive unforeseen disruptions and create competitive advantage (Pettit, Fiksel, and Croxton 2010).

Several researches have been conducted with the purpose of defining a strategy for increasing the SCR (Andres and Marcucci 2020; Bevilacqua et al. 2019; Akkermans and Van Wassenhove 2018; Donadoni, Caniato, and Cagliano 2018; Khan, Haleem, and Khan 2020; Marcucci et al. 2021). Kamalahmadi and Parast (2016) studied and deepened the development of SCR, conducting a survey to examine the literature related to this topic. They summarised their conclusions in various areas, including definitions of SCRs, the principles of SCR, and strategies to improve the resilience of an SC. Christopher and Peck (2004) reported on an empirical study on SCR in various sectors, including food, oil and petrochemicals, pharmaceuticals, packaging, electronics, transport services and automotive parts distribution retail. Their study focused on the development of a conceptual framework for the management strategy of SC risk, with several recommendations for improving SCR.

Many authors tried to identify the factors that influence the SCR. Ponis and Koronis (2012) defined the concept of SCR and identified the SC capabilities that can best counteract the consequences of given disruption.

In this research, authors performed a critical analysis of the existing conceptual frameworks, to understand the relationships between the various factors that affect the SCR. Brusset and Teller (2017) developed research in order to map the relationship over all the processes and resources on which SC managers had control. Throughout this methodology, the researcher studied the relationship between SC capabilities and resilience, as well as the role of SC risks into influencing the dynamics of these relationships. Jain et al. (2017), through an extensive literature review, identified the enablers of SCR and used Interpretive Structural Modelling (ISM) to analyse the levels of relationships among those enablers. The authors then identified 13 key enablers of resilient SC and then described the relationship among them, using ISM. Recently, Dolgui, Ivanov, and Sokolov (2018) pointed out the ripple or domino effect phenomenon in an SC.

This effect describes the propagation of the impact of a disruption within the nodes that make up an SC. This phenomenon occurs when any disruption or interruption of services propagates in cascade influencing the performance of the entire SC, instead of remaining localised or being contained. Many authors agree on the presence of this phenomenon (Kinzig et al. 2006; Zhao et al. 2011; Scheffer et al. 2012) and they have tried to analyse how this propagation can amplificate the negative effects that such disruption can lead to a SC. Another research work which drew attention to this phenomenon was the analysis of Scheffer et al. (2012), in which the authors studied how the domino/ripple effect can be found both in ecological networks and other complex structures, such as financial systems.

Ivanov, Sokolov, and Dolgui (2014), in their research work, structured and classified existing studies on the ripple effect, identifying research gaps and suggested future research paths. Ivanov et al. (2016) also exemplify the ripple effect within a real-life case study: in this research work, Australia dairy industry SCs are shown, by further analysing the recovery policies in the presence of the above-mentioned ripple effect.

The present study is part of this context, aiming at developing the study of the connections not only between the factors and the SCR but also between the factors themselves, in order to further analyse what many researchers call the ripple or domino effect.

This research paper aims to define a methodology for identifying cycles among the factors' connections that affect the SCR.

4 Materials and methods: fuzzy cognitive maps

FCM has been used as a modelling instrument in many fields: for example medicine (Amirkhani et al. 2017), environmental sciences (Falcone, Lopolito, and Sica 2018), economics (Azevedo and Ferreira 2019) or decision science (Salmeron and Froelich 2016).

Through a graphical representation, the FCMs model the behaviour of a dynamic system. In this graph, nodes represent the concepts, while the links between these nodes are represented by weighted arcs. These arcs connect the nodes, and thus represent the causal relationships that exist between the concepts: the concepts that represent the cause or the means to reach the goal are located at the tail of the arrow, while those that represent the end are located at the arrow's end. Figure 3 shows the structure of an FCM: the concept Cj has a state value, and the arrow indicates quantitatively the influence of this cause concept Ci to the effect concept Cj: eij can assume a fuzzy value within [−1, 1].

The FCM shown in Figure 2 is represented as an adjacent matrix in Table 1.

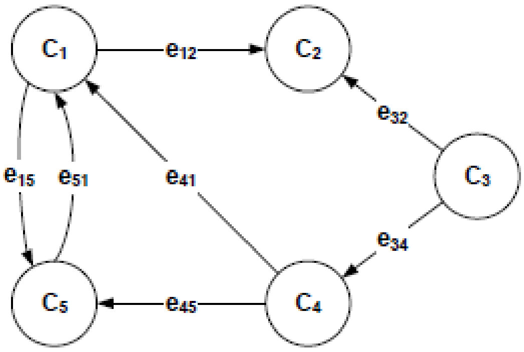

Figure 3: The structure of a FCM.

	C_1	C_2	C_3	C_4	C_5
C_1	0	e_{12}	0	0	e_{15}
C_2	0	0	0	0	0
C_3	0	e_{32}	0	e_{34}	0
C_4	e_{41}	0	0	0	e_{45}
C_5	e_{51}	0	0	0	0

Table 1: Adjacency matrix

The negative, the null and the positive eij values identify the possible types of causal relationships between the involved concepts:

- eij = 0 stands for no causality relationship between concepts Ci and Cj;
- eij>0 stands for positive causality between Ci and Cj. In particular, an increase (decrease) in the value of Ci leads to an increase (decrease) in Cj value;
- in the same way, eij<0 stands for negative causality between concepts Ci and Cj, and it means that an increase (decrease) Ci leads to a decrease (increase) in the value of Cj.

In order to identify the FCM concepts and the degree of influence between them, the input of human experiences and knowledge on the system is fundamental: input can be obtained through semistructured interviews (Eden 1988; Laukkanen 1998) or from documents and historical data (Axelrod 2015).

In this work, the interconnections of concepts are defined through expert opinions. These interconnections are evaluated through linguistic values and aggregated using the t-conorm fuzzy inference method for the union of triangular fuzzy sets (Figure 4) in order to produce the final linguistic weight.

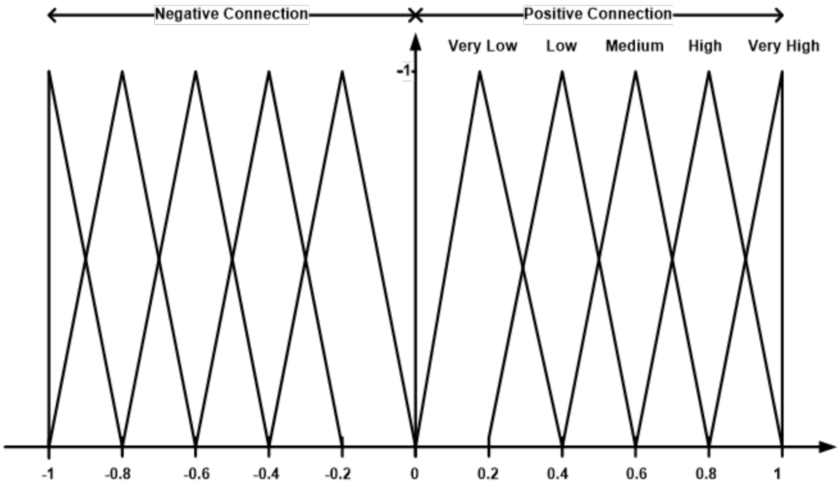

Figure 4: Membership function for the fuzzy weights.

Subsequently, the defuzzification method of the centre of gravity (COG) (Lin 1996) is used to transform the final linguistic weight into numerical terms.

4.1 Research approach

The research approach proposed in this work consists of two macro phases (see Figure 5). The first phase, the 'Development of a cognitive modelling group', aims at defining the general framework for subsequent analysis.

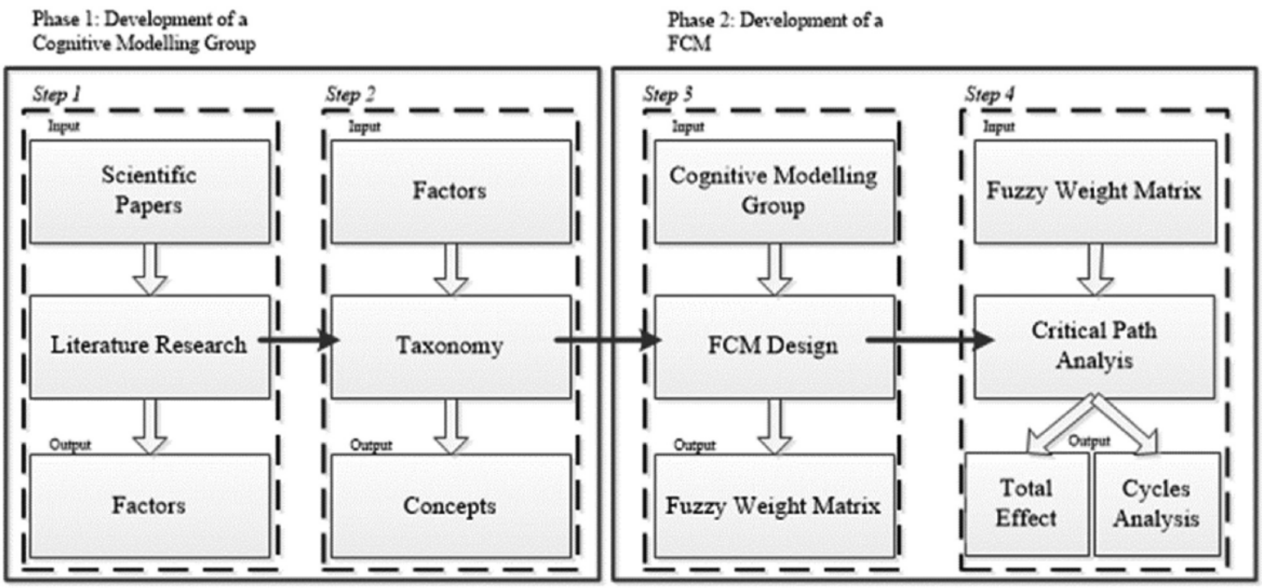

Figure 5: Research approach

The first phase is structured in two sub-steps: in thefirst step, 'Literature research', research of the factors that influence the SCR and how these factors impact on it is carried out. During the second step,

'Taxonomy', such factors are grouped in concepts in order to achieve an optimal trade-off between extensiveness of information and comprehensiveness of the following questionnaire. The meaning of the word ‘factor’ in this work aims to remain as general as possible since in a real context every SC is influenced by multidimensional and multidisciplinary aspects. In this work, factors are summarised as SC characteristics (e.g. SC vertical integration degree), sources of risk (e.g. natural disasters, conflicts or political troubles), conceptualisations of SCR (e.g. flexibility, agility,), and other aspects (e.g. organisational relationships, sustainable development).

Also, the second phase consists of two sub-steps: in the ‘FCM Design’ step, a panel of expert traces the links among the concepts outlined in the taxonomy step and define the weight of these links, in order to build the adjacent matrix and the cognitive map. The weight of the previously drawn links is evaluated through interviews and questionnaires addressed to the panel of experts. The last step, ‘Critical Path Analysis’, allows researchers to highlight the domino effect among the concepts. This analysis will also show the presence of cycles and the connection among them, as previously explained in Figure 1.

4.1.1 Phase 1: development of a cognitive modelling group

In order to exemplify this research method in a real context, a case study on the automotive sector has been chosen, so as to provide additional discoveries, not possible with other methods (McCutcheon and Meredith 1993). Table 2 provides a description of the players analysed in this research. These companies are the main players of the automotive SC in terms of turnover.

SC players	Typology	Location	Description
Tier two supplier	Semi-finished electrical products supplier	Germany	This player produces and assembles the basic materials needed from the tier one supplier.
Tier one supplier	Finished electrical products supplier	Italy	Tier one supplier operates the assembling from many semi-finished products, which they send to the main manufacturer
Manufacturer	Automotive producer	Sweden	Swedish company producing industrial vehicles: trucks, road tractors, buses and diesel engines.
Shipper company	Global transportation and logistics company	Switzerland	The shipping company provides specialised services for the import/export and international handling of goods, guaranteeing capillary operation and logistics for the SC products.
Marketing BU	Marketing BU	Italy	Develops market intelligence, identifies opportunities and leverages key stakeholder partnerships.

In the present research case study, the group is composed of 16 people: one academic whose research focuses on SC management and SCR, and three managers from each player in the SC considered for this case study. To take into consideration the horizontal and interdisciplinary capabilities required to develop the above-mentioned cognitive map, the managers are chosen from different business units: SC management, logistic, and administrative functions.

4.1.1.1 Literature research: factor affecting supply chain resilience.

Present research envisaged a literature review to discover the main factors affecting the resilience of automotive SCs. The analysis has been carried out on the most relevant databases, including Emerald, Metapress, Science Direct, Scopus, and Web of Science, using the following set of keywords (1):

Supply Chain AND Automotive AND (Resilience OR Risk OR Disruptions OR Uncertainties)

The keywords ‘Supply Chain’ and ‘Automotive’ have been included in order to ensure that the results were addressing the automotive SC, as the goal of this research case study. Consequently, filters were applied to individualise the core set of studies for selecting the main concepts. The filters were defined as follows:

- Ensuring an adequate level of relevance by effectively capturing the phenomenon under consideration: this criterion has been ensured by requiring that articles contain these keywords in the title, in the abstract or in the predefined paper keywords;
- Consider only English language articles;
- Remaining abstracts should be read for substantive relevance;
- Remaining full articles should be read for substantive relevance;

Through the application of the first two filters, 90 papers were identified, of which 22 were defined as relevant. Considering these 22 selected articles, we listed all the factors mentioned in them (see Table 3).

The present literature review allows the highlighting of the trend of some factors to be cited more than others. Risk management has been cited more than ten times, in various forms: ‘risk management culture’, ‘contingency plans’, ‘business continuity’ and so on. Weather-related risks were also cited among the mentioned papers, like ‘tsunamis’, ‘flood’ or ‘extreme weather conditions’. ‘Flexible’ attributes were also cited in many ways: ‘flexible transportation systems’ or flexibility as the capability of ‘adding supplier and/or ensure multisourcing’. Another important factor mentioned many times in the analysed papers is ‘visibility’: very often, the ability to trace raw materials/semi-finished products/finished products and the ability to make data readily available to all interested parties, including the end customer, are mentioned as indispensable attributes for an SC.

Finally, the most recent papers inevitably cite the COVID-19 pandemic as a central factor affecting the automotive industry during the 2020s, along with some of the direct consequences, such as ‘consumers reduced income’ and ‘production shutdowns’.

Source	Factors	#
Wicher et al. (2015)	Natural disasters, extreme weather changes, conflicts and political troubles, terrorism, sudden radical changes of demand	5
Vujović et al. (2017)	Demand and supply uncertainty, volatility of price and cost, market share reduction risk, reputation loss or brand damage risk, coordination complexity, natural disasters, demand and supply uncertainty, selection of proper suppliers, poor quality or process yield at supply, inflexibility of supply source, lack of sustainable knowledge/ technology, environmental pollution, hazardous waste	13
Carvalho, Azevedo, and Cruz-Machado (2013)	To make use of flexible supply base/flexible sourcing, to constitute strategic stock, to reduce lead time, to create total supply chain visibility, to use flexible transportation systems	6
Marasova, Andrejiova, and Grincova (2017)	Unstable exchange rate, increased tax rates, deterioration of economic situation in the country, limited financial resources in the company, errors in prognostics, theft, sabotage, natural disasters, lack of raw materials and semi-finished products, strikes, changes in international trade conditions, foreign policy risks, changes in social policy, change of government	14
Hudin, Hamid, and Chin (2015)	Imperfect communication, lack of trust and open communication	2
Mohammaddust et al. (2017)	Bankruptcy of suppliers, inaccurate demand forecast, poor supplier knowledge, terrorism, war, natural disasters, fire, a production failure,	15

	system breakdown, strikes, a supplier's inability to respond quickly to a change in demand, supplier development, substitute supplier or facility, emergency stock, excess capacity	
Lotfi and Saghiri (2018)	Business continuity teams, contingency plans made, detection systems in place to detect any supply chain disruption, security against deliberate intrusion, establishing communication lines in case of a disruption in the supply chain, visibility, collaboration, redundant supplier for the same part with these suppliers being capable to substitute each other, alternative modes of transportation, excess capacity, decentralisation of physical assets in multiple locations of assets	12
Jiantong, Zhuoqi, and Xiaodong (2016)	Unstable exchange rate, inflation, financial crisis, bankruptcy of suppliers, inaccuracy, demand forecast, changed customer preference, price increase of oil, unqualified products from suppliers	8
Pandey and Sharma (2017)	Inventory risk (forecasting error, uncertainty in supply, uncertainty in demand, issue with warehouse space, excess inventory, excess inventory cost) Forecasting error (inventory issues, supply and demand uncertainty) Scarcity of raw material (delayed supply, high cost) Logistic risk (delays in delivery, more logistics cost accidents, longer lead time) System failure (delay in production, loss of orders) Labour unrest (increase in labour cost, loss of work, accidents) Outsourcing risk (supplier failure, delay in supply, high cost) Imperfect order fulfilment (order shortage bullwhip effect, excess inventory issues)	8
Arto, Andreoni, and Rueda Cantuche (2015)	Earthquake	1
Haefele and Westkämper (2014)	Customer expectation, product recall	2
Matsuo (2015)	Risk management, creating SC risk management culture, supply chain collaboration, fire, earthquake flexibility (ensure multisourcing), agility, redundancy (add resources)	9
MacKenzie, Barker, and Santos (2014)	Earthquake, tsunami, globalised supply chain	3
Yoon et al.(2018)	Supplier failure or bankruptcy, supplier's financial stress	2
Sampaio et al. (2016)	Supplier selection	1
Hsieh, Wee, and Chen (2016)	Lean manufacturing, unstable exchange rate, financial crisis, economic uncertainty, forecasting error, promotion, customer incentive, educated customer, contingency plans made, creating SC risk management culture, proactive planning team, mitigation plan, increase responsiveness, recovery plan, build up decision management support, SC information flow risk-accuracy, security and disruption, terrorism, man-made disaster, natural disasters, extreme weather changes, earthquake, tsunami, material flow interruption, strikes, substitute supplier or facility, agility, flexibility	32

Wang and Wells (2020)	COVID-19 pandemic, economic uncertainty, sales loss, consumers reduced income	5
Blackhurst, Scheibe, and Johnson (2008)	Unstable exchange rate, supplier failure or bankruptcy, inaccurate demand forecast, financial strength of customers, ability to share information with suppliers, vertical, integration of supply chain, conflicts and political troubles, terrorism, theft, war, cyberattack, natural disasters, extreme weather changes, fire, earthquake, flood, labour dispute, labour availability, border crossing and customs regulations	19
Blos et al. (2009)	Unstable exchange rate, economic uncertainty, credit default, theft, sabotage Natural disasters, extreme weather changes, fire, flood, loss of key facility, logistics route or mode disruptions, logistics provider failures, utilities failures: communications, electricity, water, power, etc, union relations: labour disagreements & contract frustrations, fuel prices, geopolitical risks, adverse changes in industry regulation, land, water, atmospheric pollution	18
Araujo, Tessaro, and Sardim (2016)	Bankruptcy of suppliers, inflexibility to attend changes on production demand, have more customer access, increase responsiveness, terrorism, natural disasters, transportation issues, labour dispute, border crossing and customs regulations, geopolitical risks, redundant supplier, flexibility, excess capacity, add inventory	15
Ceryno, Scavarda, and Klingebiel (2015)	Unstable exchange rate, inflation, fiscal and monetary reforms, changes in consumer tastes, availability of substitute goods, scarcity of complementary goods, rivalry among existing firms, potential entrants into the industry, joint efforts to share risk related information, risk sharing, efforts to prepare supply chain continuity plans, visibility, transparency, information transmission/sharing, outsourcing, vertical integration, conflicts and political troubles, terrorism, war, natural disasters, extreme weather changes, earthquake, flood, IT system uncertainties, lack of raw materials and semi-finished products, strikes, labour unrest, change of government, government regulation, trade restrictions, flexibility, maintaining excess capacity in productions, storage, handling and/or transport, globalised supply chain, centralised distribution, centralised production, global sourcing product liability environmental pollution	40
Sharma and Bhat (2014)	Economic uncertainty, supplier's financial stress, forecasting error (inventory issues, supply and demand uncertainty), market share reduction risk, geopolitical risks	5
Xu et al. (2020)	COVID-19 Pandemic, Production shutdowns	2
Ishida (2020)	COVID-19 Pandemic	1
Barroso, Machado, and Machado (2011)	Visibility, economic supply incentives, flexible transportation systems, flexibility (adding supplier and/or ensure multisourcing), strategic stock	6

Table 3: Factors affecting SCR

4.1.1.2 Taxonomy

Literature research has generated a massive amount of data and more than 180 factors (Table 3) have been identified. In the 'Taxonomy' step, all these factors are clustered into few concepts. In this research, the taxonomy of factors that affect SCR has been developed by the Cognitive Modelling Group according to the Delphi method criteria. The taxonomy analysis is used to identify concepts to be included in the cognitive map. The factors list (Table 3) has been given to the Cognitive Modelling Group. The instructions were to regroup the factors into a few concepts in an efficient way. The optimal breakdown point should have been a number big enough to maintain the detail level, but small enough to make the results analysis simple. Consensus has been reached after three iterations of Delphi analysis with the identification of 24 concepts (Table 4). A 'top event' is described as a single event that is influenced by all other events. Since the goal of the research is to unveil the ripple effect influencing 'SC Resilience' (C24), this concept has been chosen as top event.

Code	Concept	Description	Factors
C1	Operation management strategy	All practices connected to Agile and Lean Production	Reduce lead time, lean manufacturing, agility, agile supply chain-
C2	External Financial Risk (outside supply chain)	Risks linked to the financial sector in which the SC operates	Unstable exchange rate, increased tax rates, deterioration of country economic situation in the country, inflation, financial crisis, economic uncertainty, fiscal and monetary reforms, price controls, changes in relative prices
C3	Internal Financial Risk (inside supply chain)	Risks linked to the financial situation of the enterprises.	Limited financial resources in the company, bankruptcy of suppliers, supplier failure or bankruptcy, supplier's financial stress, credit default, bankruptcy of suppliers
C4	Market Volatility	Uncertainties linked to market developments	Sudden radical changes of demand, demand and supply uncertainty, volatility of price and cost, errors in prognostics, inaccurate demand forecast, changed customer preference, inventory risk (forecasting error, uncertainty in supply, uncertainty in demand, issue with warehouse space, excess inventory, excess inventory cost), forecasting error (inventory issues, supply and demand uncertainty), customer expectation, financial strength of customers, new or foreign competitors, inflexibility to attend changes on production demand, changes in consumer tastes, availability of substitute goods, scarcity of complementary goods, sales loss, rivalry among existing firms, potential entrants into the industry, volatile demand, customers reduced income
C5	Market Position	Place that the brand occupies in the mind of the customer and how it is distinguished from competitors' products	Market share reduction risk, reputation loss or brand damage risk, promotion, customer incentive, educated customer, have more customer access, gain market power

C6	Risk Management culture	All of the risk management branches developed by the company: prevention techniques, risk evaluation, reduction of action plans to face sudden disturbances	Business continuity teams, contingency plans made, detection systems in place to detect any supply chain disruption, security against deliberate intrusion, risk management, creating SC risk management culture, proactive planning team, mitigation plan, increase responsiveness, recovery plan, build up a decision management supports for disaster relief supply chain, joint efforts to share risk-related information, risk sharing, efforts to prepare supply chain continuity plans
C7	SC Visibility	The ability of parts, components or products in transit to be tracked from the manufacturer to their destination	Coordination complexity, total supply chain visibility, imperfect communication, lack of trust and open communication, visibility to a clear view of downstream inventories and demand conditions, poor supplier knowledge, establishing communication lines in case of a disruption in the supply chain, visibility, collaboration, supply chain collaboration, information flow risk-accuracy, security and disruption, ability to share information with suppliers, have more customer access, transparency, information transmission/sharing, opportunistic behaviour because of asymmetric information
C8	Supply Chain Vertical Integration Degree	A SC is defined as completely vertically integrated when all activities are carried out by the same company.	Vertical integration of supply chain, outsourcing, vertical integration
C9	Deliberate attack	Intentional attacks aimed at disrupting operations or causing human or financial harm	Conflicts and political troubles, terrorism, theft, sabotage, war, human-made disaster, cyberattack.
C10	Natural Phenomena	An environmental danger to which risk of damage to people or things is associated	Natural disasters, extreme weather changes, fire, earthquake, tsunami, flood, lightning strikes, winddamage, COVID-19 pandemic
C11	Loss of infrastructure and/or connection	Physical loss of infrastructures: productive plants, physical connections (roads), telecommunications	Loss of key facility, logistics route or mode disruptions,

			logistics provider failures, utilities failures: communications, electricity, water, power, etc, transportation issues, IT system uncertainties
C12	Material flow interruption	Interruption of the normal flux of materials or final products	Lack of raw materials and semi-finished products, a production failure, production shutdowns, system breakdown, scarcity of raw material (delayed supply, high cost), logistic risk (delays in delivery, more logistics cost accidents, longer lead time), system failure (delay in production, loss of orders), material flow interruption
C13	Manpower availability	Availability of human resources to carry on normal activities inside the SC	Strike, labour unrest (increase in labour cost, loss of work, accidents), labour dispute, labour availability, union relations: labour disagreements & contract frustrations, loss of key personnel, HR risks – key shortage, personnel turnovers
C14	Energy sources availability	Availability of energy sources to carry out SC activities	Price increase of oil, fuel prices
C15	Political Economy	Relationships between production and trade with law, customs, and government	Changes in international trade conditions, foreign policy risks, changes in social policy, change of government, border crossing and customs regulations, geopolitical risks, government regulation, trade restrictions, nationalisation, economic supply incentives
C16	Institutional Policies	Formal restrictions regarding automotive sector products	Adverse changes in industry regulation
C17	Suppliers Reliability	Refers to the level of interest of the press regarding events related to the SC	Demand and supply uncertainty, the selection of proper suppliers, a poor quality or process yield at supply, supplier's inability to respond quickly to a change in demand, supplier development, redundant suppliers capable of substituting each other, unqualified products from suppliers, outsourcing risk (supplier failure, delay in supply, high cost), supplier selection, loss of key suppliers

C18	Flexibility in outsourcing	Ability to quickly change inputs or the mode of receiving inputs	Inflexibility of supply source, redundant supplier, to make use of flexible supply base/flexible sourcing, flexible transportation systems, substitute supplier or facility (multi-supplier strategy), alternative modes of transportation, flexibility (adding suppliers and/or ensure multi-sourcing), flexibility, flexibility strategies – shift order and production quantities
C19	Flexibility in order fulfilment	Ability to quickly change outputs or the mode of delivering outputs	Flexible transportation systems, alternative modes of transportation, imperfect order fulfilment (order shortage bullwhip effect), flexibility
C20	Redundancy	How much has been invested in resources compared to how much was needed	To constitute strategic stock, emergency stock, excess capacity, redundancy (add resources), add inventory, maintaining excess capability. In productions, storage or transport
C21	Degree of centralisation of asset and/or facilities	Degree of concentration of SC assets	Decentralisation of physical assets in multiple, globalised supply chain, centralised distribution, centralised production, global sourcing, urban systems and networkcentric organisations
C22	Product recall	Request of the return of a product after the discovery of technical or safety issues	Product recall, product hazard, product liability
C23	Sustainable development	Operational and business SC developments that meets the needs of the present without compromising the ability of future generations to meet their own needs	Lack of sustainable knowledge/technology, environmental pollution, hazardous waste, land, water, atmospheric pollution
C24	Supply Chain Resilience	Operational and business SC developments that meets the needs of the present without compromising the ability of future generations to meet their own needs	

4.1.2 Phase 2: development of a fuzzy cognitive map FCM design

In the 'FCM Design' step, the Cognitive Modelling Group identified the links existing among the concepts outlined during the taxonomy step to develop the Cognitive maps (see Appendix 1) and the adjacency matrix (Table 5). As explained in Section 3 the interconnections of concepts are evaluated through linguistic values and aggregated using the t-conorm fuzzy inference method. To transform the final linguistic weight into numerical terms the centre of gravity (COG) defuzzification method is used. The result is the Fuzzy Weight Matrix, which is shown in Appendix 2.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
C1	0	0	0	0	0	0	1	1	0	0	0	−1	0	0	0	0	0	1	1	−1	0	0	0	1
C2	0	0	1	1	0	1	0	0	0	0	0	0	0	−1	0	0	−1	0	0	0	0	0	0	−1
C3	1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	−1
C4	1	1	1	0	−1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1
C5	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	1
C6	0	0	0	0	0	0	1	1	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	1
C7	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1
C8	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	1
C9	0	1	1	1	0	0	0	0	0	0	1	1	0	−1	0	0	0	0	0	0	0	0	0	−1
C10	0	0	0	0	0	0	0	0	0	0	1	1	0	−1	0	−1	−1	0	0	0	0	0	1	−1
C11	0	0	1	0	0	1	0	−1	0	0	0	0	0	−1	0	0	−1	0	0	0	0	1	0	−1
C12	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−1
C13	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
C14	0	0	0	0	0	1	0	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0	1
C15	0	1	−1	0	0	0	0	0	0	0	0	0	0	−1	0	−1	0	0	0	0	0	0	0	1
C16	0	0	−1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	−1
C17	1	0	−1	0	0	0	1	1	0	0	−1	−1	1	0	0	0	0	1	0	0	0	−1	0	1
C18	0	0	−1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	−1	0	0	0	1
C19	0	0	−1	0	0	0	0	0	0	0	0	−1	0	0	0	0	0	0	0	−1	0	0	0	1
C20	0	0	1	0	0	0	0	0	0	0	−1	−1	1	1	0	0	0	−1	−1	0	0	0	0	1
C21	0	0	1	0	0	0	0	1	0	0	1	−1	1	0	0	0	0	0	0	0	0	0	0	1
C22	0	0	1	0	−1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	−1
C23	0	0	−1	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1
C24	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 5: Adjacency matrix

4.1.2.1 Critical path analysis

The FCM developed in the previous step can be analysed through the use of two notions: the Indirect Effect (IE) and the Total Effect (TE). The IE is calculated according to Equation (1).

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

where the symbol (C_p, C_{p+1}) represents the concepts concatenation path starting to form C_p and ending in C_{p+1}. It is essential to identify the sequence of concepts as a chain, in which the weight e(C_i, C_j) represents the hardiness of each ring (couple of concepts) forming the chain. The meaning of IE can be explained according to the metaphor ‘a chain is only as strong as its weakest link’ (Bevilacqua et al. 2013). If in the chain a weak ring exists, the total hardiness of the chain can be quantified with the hardiness of the weakest ring. The IE measures this hardiness. The second notion used within this research methodology is the Total Effect (TE). When there is more than one concatenation between a cause node and an effect node, it is useful to define the total effect T(x,y). Indeed, as asserted by Axelrod (2015) and according to Equation (2), in the presence of multiple paths starting from the same initial node and ending in the same topeven concept, the total effect is

$$TE(C_i, C_j) = max\{I_k(C_p, C_{p+1})\} \qquad (2)$$

In this work, $I_k(C_i, C_j)$ and $TE(C_i, C_j)$ are interpreted according to the fuzzy mathematics and $e(C_p, C_{p+1})$ which identifies the relationship weight between concepts C_p and C_{p+1}, can be expressed 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) while Alsina, Trillas, and Valverde (1983) introduced the t-norm and the t-conorm into fuzzy set theory. In particular, they suggested that the t-norm and the t-conorm can be used for the intersection and union of fuzzy sets. Consider, for instance, three different paths between concepts C1 and C5 as reported 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 presence of three different paths connectingthe same nodes (C1 and C5) means that the concept C1 can affect in many different ways the final node (C5) with different effects. Thus, the TE calculus allows to identify the maximum effect of C1 on C5:

$$TE(C_1, C_5) = max\{I_1(C_1, C_5), I_2(C_1, C_5), I_3(C_1, C_5)\} = max\{much, some, some\} = much \qquad (2)$$

This approach allowed the panel of experts to identify the domino effect among the concepts, the presence of cycles and the connection among them. The result of the critical path analysis has been presented in the next section.

5 Results analysis

According to the above-mentioned methodology, it is possible to analyse the results and to highlight the most relevant concepts within the route that leads to SCR by evaluating the TE (Total Effect) and IE (Indirect Effect) of every path. Thus, it is possible to highlight how a concept can affect the top event (SCR) through different concatenations.

The acyclical paths are sorted by Total Effect (TE) in Table 6. Only the TE of the concept 'Redundancy' and 'SC Vertical Integration Degree' present double paths, because the TE of such paths is the same.

#Path	Starting Node				TE
1	External Financial Risk				−0.775
2	SC Visibility				0.775
3	Sustainable development				0.75
4	Deliberate threats	SCR			−0.7375
5	Natural phenomena	SCR			−0.7375
6	Suppliers Reliability	Claims and Product recall	SCR		−0.7375
7	Claims and Product recall	SCR			−0.7375
8	Materials flow interruption	SCR			−0.7
9	Market Volatility	SCR			−0.6375
10	Flexibility in outsourcing	SCR			0.6375
11	Risk Mgmt. Culture	SCR			0.625
12	Flexibility in order fulfillm.	SCR			0.6125
13	Internal Financial Risk	SCR			−0.6
14	Loss of infr. and/or conn.	Claims and Product recall	SCR		0.5625
15	Oper. Mgmt. Strategies	SCR			0.5375
16	Institutional Policies	SCR			−0.5375
17	Manpower availability	SCR			0.5125
18	Degree of centralisation	Materials flow interruption	SCR		−0.5
19	Energy source availability	SCR			0.45
20	Redundancy	SCR			0.45
21	Redundancy	Energy source availability	SCR		0.45
22	SC Vertical Integr. Degree	Flexibility in order fulfillm.	SCR		0.4375
23	SC Vertical Integr. Degree	Flexibility in order fulfillm.	Materials flow interr.	SCR	0.4375
24	Political Economy	Internal Financial Risk	SCR		−0.4375

The second acyclical path mentioned in Table 6 is 'SC Visibility – SCR', with a positive TE of 0.775. This data emerges from the need, for each actor of the SC, to have a constant visibility regarding the flow of information and semi-finished products within the SC. SC Visibility has become more important as companies have outsourced parts of their SCs and lost control and visibility of what was once part of their operations. SC visibility technology promotes a rapid response to change, enabling privileged users to act and reshape demand or redirect supply. From the meetings held to weigh the maps, the importance of having information on the economic/ financial status of the companies belonging to the same SC emerged, so as to ensure a good continuity of the process. Sustainable Development is a concept that has had a very strong influence on the automotive industry, as demonstrated by the relevant publications (Kannegiesser and Günther 2014, 2014; Luthra, Garg, and Haleem 2014). After the Dieselgate, which officially began with the notification of the violation of the EPA of 18 September 2015 (United States Environmental Protection Agency 2015), the importance of Sustainable Development in the automotive sector, as confirmed by the result of our analysis, has risen: the third acyclical path is in fact 'Sustainable Development – SCR', with a positive TE of 0.75. All SC actors, according to our analysis, realise that this is a fundamental concept, for two reasons: the institutional one, as environmental policies are becoming increasingly strict, and the commercial one, as the end customer is increasingly sensitive to this type of issues.

Moreover, in order to better analyse how the SC concepts affect each other, concept cycles within the FCM have been studied. A total of 31 cycles have been founded and Table 7 shows the 15 cycles with highest IE value within the FCM.

The cycle with the highest IE is 'Internal Financial Risk – Risk Mgmt. culture – SC Visibility', with an IE of 0.4. This cycle can bring a positive effect to the SCR. In fact, the single path 'Internal Financial Risk – SCR' has a TE of −0.6 (see path #13, Table 6), but if the company managers are able to activate the virtu-ous cycle with 'Risk Mgmt. culture' and 'SC Visibility', the result is an increasing in SCR (Figure 6). Within the SC, an actor can be subjected to a high internal financial risk, due for example to a significant devia-tion between expected and actual profits.

In this case, a deep-rooted risk management culture can drive top management to intervene by applying adequate prevention plans in order to manage these situations at risk. A correct implementation of these plans provides an increase in the level of visibility within the SC (Christopher and Lee 2004), which in turn will decrease the internal financial risk of the overall SC, since it will raise the quality of information about the other actors and hence the knowledge about, among others, potential financial-based risks. Cycle #2 is 'External Financial Risk – Market Volatility', with an IE equal to −0.375. The greater the risk in the financial sector, the more the market will be volatile, and vice versa. Both these phenomena should be avoided since both concepts can negatively influence SCR, as can be seen from Table 6. Cycle #3 is 'Energy source availability – Institutional Policies – Sustainable development', with an IE of 0.3357, so this cycle can bring positive effects to the SC (Figure 7). The single path 'Institutional Policies – SCR' has a TE of −0.5375 (see Table 6). Formal restrictions regarding automotive products are a strong entry barrier in many potential markets, as our experts mentioned. Analysing the cycle, it can be stated that targeted policies can foster sustainable industry development, which in the medium-long term can increase the availability of energy resources which, in their turn, can drive for softer institu-tional policies. Thus, this cycle can indeed bring a positive effect to the above-mentioned acyclical path. Finally, this study has analysed how cycles are connected to each other in order to understand the type of link and how they affect the SCR.

#Cicle	Node												IE
1	Internal Financial Risk	Risk Mgmt. culture	SC Visibility										0.4
2	External Financial Risk	Market Volatility											-0.375
3	Energy source availability	Institutional Policies	Sustainable Development										0.3375
4	Oper. Mgmt. strategies	SC Visibility	Internal Fin. Risk	Risk Mgmt. culture	Vertical Integration	Market Position	Suppliers Reliability						0.3125
5	Internal Financial Risk	Risk Mgmt. culture	SC Visibility	Flex. In Outs.									0.3125
6	Internal Financial Risk	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Material flow interruption								0.3125
7	Internal Financial Risk	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Redundancy								0.3125
8	Internal Financial Risk	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Redundancy	Loss of infr.							0.3125
9	Oper. Mgmt. strategies	SC Visibility	Internal Fin. Risk										0.3125
10	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Material flow interruption									0.3125
11	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Redundancy	Loss of infr.								0.3125
12	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Redundancy	Loss of infr.	Energy source availability							0.3125
13	Market Position	Vertical Integration	SC Visibility	Flex. In Outs.	Material flow interruption	Risk Mgmt. culture	Energy source availability						-0.3
14	Market Position	Vertical Integration	SC Visibility	Flex. In Outs.	Material flow interruption	Risk Mgmt. culture	Energy source availability	Loss of infr.	Suppliers Reliability	Claims and product recall	Instit. Policies	Sust. Dev.	-0.3
15	Risk Mgmt. culture	SC Visibility	Flex. In Outs.	Redundancy	Loss of infr.	Suppliers Reliability	Manpower Availability						-0.3

Table 7: Cycles within the FCM

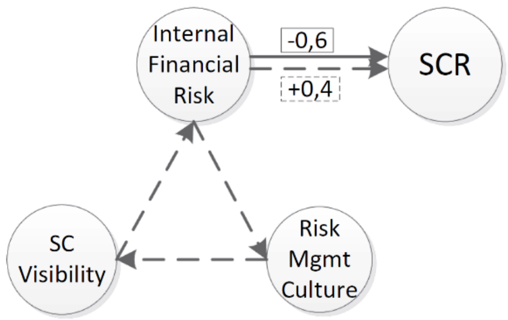

Figure 6: Analysis of cycle #1

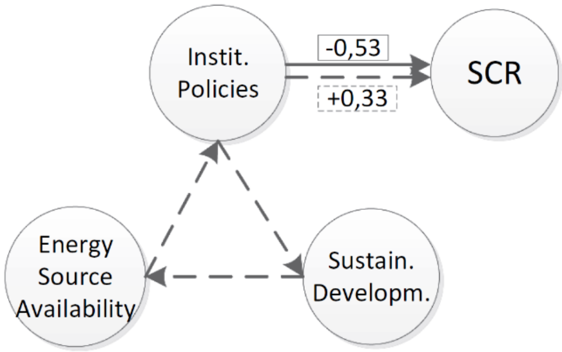

Figure 7: Analysis of cycle #3

Table 8 shows the main links connecting cycles to each other. The link with the most occurrences (87 times) is 'Loss of Infrastructures and/or connections – Suppliers Reliability', with an IE of −0.3. Supplier connections and infrastructure reliability are strongly associated with the reliability of the supplier itself (Yang et al. 2009; Tomlin 2009). A solid and reliable structure is crucial to maintain services, information and goods flow continuity. An iconic case has been the Tianjin Port Explosion which destroyed more than 10,000 cars and prevented the shipment of others from nearby factories in the short-medium term, seriously disrupting the China automotive market (Wang 2016). The links 'SC Visibility – Flexibility in outsourcing' and 'Operation Mgmt. strategies – SC Visibility' with both an IE of 0.3125 have, respectively, 7 and 4 occurrences. Visibility, as stated earlier, is indeed a cru-cial factor within the SC.

C_i	C_j	IE	#
Loss of infr. and/or conn.	Suppliers Reliability	−0.3	87
SC Visibility	Flexibility in outsourcing	0.3125	7
Oper. Mgmt. strategies	SC Visibility	0.3125	4

Table 8: Main Cycle Links

This second analysis shows in fact that SC Visibility is a key trigger to achieve Flexibility in Outsourcing: SC Visibility appears more and more crucial in the distribution phases e.g. because a system from which more information can be obtained, greatly simplifies the management of the inventory and the logistics for the operations downstream of the SC.

Moreover, 'Operation Management Strategies', according to our analysis, is a key enabling concept for SC Visibility: the implementation of the above-mentioned strategies significantly implies fostering visibility within SC processes and activities. Technology application for input, output, time and costs tracking and analysis provides managers with the necessary information to apply, for example, Industry 4.0 production strategies. If production is out of demand or if there is any delay, business can pinpoint in a timely fashion where the problem is and take the necessary rectifications.

Furthermore, Figure 8 exemplifies connections among different cycles. For example, if the coordinates (1,10) are marked, it means that Cycle #10 is connected with Cycle #1. This is a many-to-many reading tool that can simplify the work analysis of the above-mentioned results. SC risk managers, resilience managers or business continuity managers can integrate this tool in the continuous monitoring operations, in order to unveil links among critical cycles: once identified, managers can improve SCR by breaking the undesirable chain of events leading to such cycles.

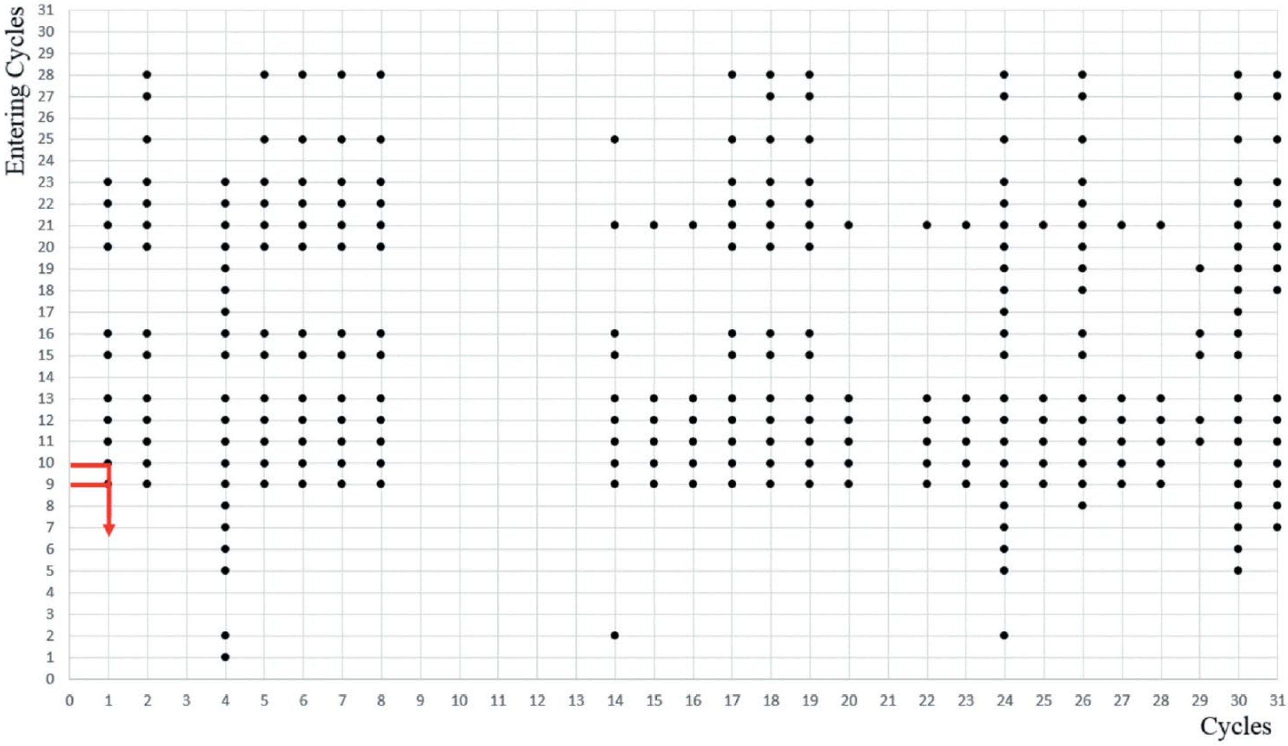

Figure 8. Connections among cycles: the arrow indicates the direction of the connection.

6 Discussion

The present study points out factors linked to SCR as well as improving understanding of their mutual relationships. An interesting finding of the study is the fact that the identified factors can be arranged in cyclical paths, in order to understand whether their mutual interaction intensifies their impact on SCR (IE>0) or the opposite regresses it (IE<0).

To our knowledge, the scope of this paper is indeed novel and therefore it may bring significant insights about factors affecting resilience and their inner relationships. Current research has investigated the topic of SCR from different multi-faceted aspects. However, the work is fragmented and published in various articles and journals. This study contributes in gathering all these investigations and putting them into a unique framework with logical links and explanations. The map can be further used by other researchers in order to identify new links to research upon.

Moreover, the research approach proposed in Figure 5 can be repeated systematically, to analyse the results from different SCs or different industrial sectors.

6.1 Research implications

The list of 24 concepts ranked on their Total Effect on SCR is well aligned with what found in previous research: for example, it is clear that economic crises affect sales of automotive vehicles due to the decreased purchasing power of consumers. Also, the financial crisis can lead to several entities of a SC to close, hence decreasing resilience capabilities, as outlined by other authors (Jüttner and Maklan 2011). Next, SC visibility has been recurrently mentioned by researchers as a significant factor that can improve resilience. Digital ecosystems and automation can be used to develop advanced risk management tools and enable faster detection and reaction to any disruptive event in SC (Urciuoli 2017). Blackhurst et al. (2005) interview several executives to find out that visibility is a key issue for dealing with disruptions. On the opposite, the implications of sustainable development and resilience show some contradictory results. Fahimnia and Jabbarzadeh (2016) warn that different levels of resilience can result in different states of economic, environmental and social sustainability.

Similarly, Ivanov (2018) using a simulation model shows that a typical sustainable single sourcing SC configuration worsens resilience by increasing impacts of potential disruptions. Hence, while these two factors are negatively correlated from an operational viewpoint, our study shows that from an institutional perspective, the opposite happens. This means when institutional pressure increases, in terms of compliance management to regulatory frameworks, the SC ultimately becomes more resilient to potential halts imposed by cross-border operations.

6.2 Implications for supply chain managers

The proposed method aims at involving SC managers in the conceptual model development. Indeed, a resilient approach must try to take an important step forward, not by adding or modifying existing vocabulary, but by creating other vocabulary that

contains ripple effect management from a different perspective, in particular involving companies' operators (Bevilacqua and Ciarapica 2018). People within an organisation should be cognisant of the possible failure events, and therefore ready to improve strategies to prevent these possibilities. Managers along the SC must continuously identify and manage risks in their area of responsibility. In this sense, the methodology presented in this paper offers a key added value: it exemplifies the causal relationships among factors, through which decision makers can examine step by step the ripple effect that from a trigger event 'A' can bring an undesirable event 'D', through intermediate events (for instance 'B' and 'C'). Knowing this chain of events can aid managers in providing targeted measures to prevent the happening of the undesirable event 'D'. Sometimes, in fact, if events 'A', 'B' or 'C' do not take place, the final event 'D' cannot begin at all, and therefore its negative effects cannot take place.

This study also presents substantial business implications, since it considers resilience from an operational behaviour viewpoint while associating it with strategic concepts that remain often abstract, and therefore difficult to implement as a managerial instrument.

Moreover, this study highlights the presence of chain reactions, identified in literature as ripple effects (Dolgui, Ivanov, and Sokolov 2018): to this regard, the development of a practical tool (Figure 8) to unveil the hidden ripple effect among concepts influencing SCR can be a crucial added value for decision makers.

In order to improve SCR, managers can use the map drawn in the present research to start identifying strategic areas for improvement or specific actions to work upon: moreover, multidimensional and multidisciplinary factors are taken into consideration, in order to provide a comprehensive approach and exemplifying the detailed behaviour of a system.

The analysis of cyclical paths, their mutual interaction and their impact on SCR allow SC managers to use this tool to identify further strategic areas for improvements.

Three cycles are highlighted: the first concerns the interaction between internal financial risk, risk management culture and SC visibility. This cycle is well in agreement with previous research. In the network of suppliers, it is fundamental to increase visibility to reduce financial risks and thereby avoid in extreme situations bankruptcy and SC disruption (Hallikas et al. 2004; Lai, Debo, and Sycara 2009). By improving these three factors in an SC, its resilience can be further improved. The second cycle relates to the interrelation between external financial risks and market volatility.

The two factors are strongly tightened since if the financial sector in which the SC operates is undergoing a deep crisis, then demand of the products become volatile. This can be experienced in the automotive sector given the high price elasticity of cars or commercial vehicles (Bordley 1993). The FCM identifies a third cycle path consisting of energy source availability, institutional policies and sustainable development.

As explained previously, institutional pressure can affect compliance management to regulatory frameworks, and thereby, countries' sustainable goals.

Finally, this work pointed out connection between cycles, showing the links that can bridges different phenomena, as outlined in Table 8: this last analysis is fundamental in order to identify links and then break or reinforce the negative or the positive ones.

7 Conclusions

This study, by means of a literature review, identifies 180 different factors linked to SCR, and then clusters them in 24 concepts by means of taxonomy analysis. The 24 concepts are linked in a Fuzzy Cognitive Map (FCM) where main interrelations are drawn in order to understand impacts on SCR. By means of a case study, where managers from five different companies of an international automotive SC are interviewed, possible pathways linking the concepts towards SCR capabilities are examined, and then ranked in terms of Total Effects (TE). This allows the prioritisation of the concepts links that should be incentivised and those which hindered in order to improve SCR. The additional analysis of the interdependencies among the concepts enables the enumeration of 15 different cycles explaining how the Indirect Effects (IE) among the factors ultimately impact resilience.

The implementation of the developed methodology shows how important concepts related to risks and SCR correlate with each other and most of all how they ultimately contribute to improving or deteriorating resilience. However, it is still unknown what measures fit the pathways identified and most of all what impacts should be expected when applying these measures. Hence, future studies should aim to explore strategies for improving resilience in view of the cyclical paths and relationships identified in this study. An additional future challenge would be the quantification of the impacts of these measures.

Hence, future research should address the measurement of costs and benefits of the resilience strategies suggested by the FCM analysis.

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Appendix 1

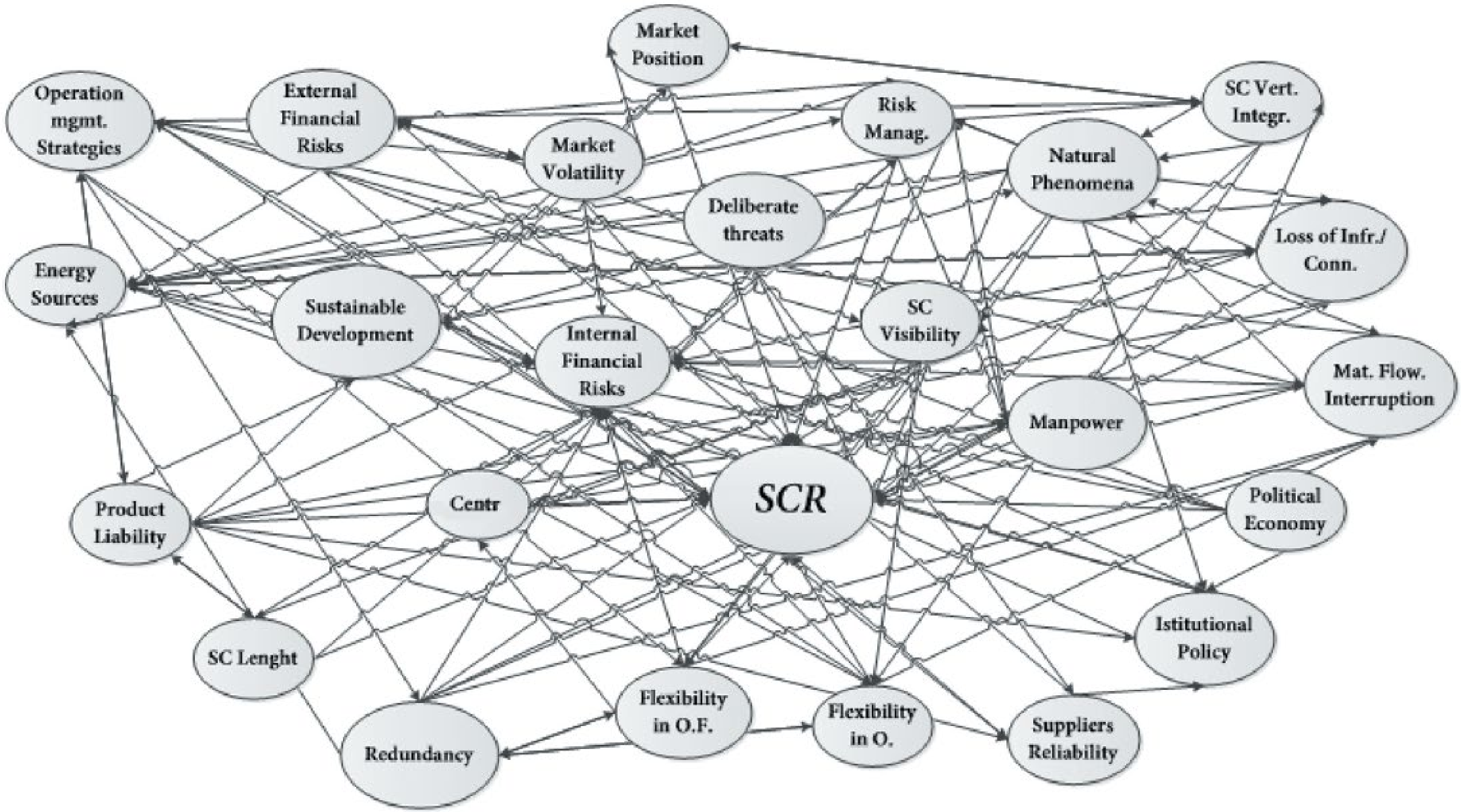

Figure A1: Cognitive Map

Appendix 2

0	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24
C1	0	0	0	0	0	0	0,313	0,438	0	0	0	-0,413	0	0	0	0	0	0,25	0,4	-0,463	0	0	0	0,538
C2	0	0	0,5	0,375	0	0,463	0	0	0	0	0	0	0	−0,438	0	0	−0,388	0	0	0	0	0	0	−0,775
C3	0,438	0	0	0	0	0,413	0	0	0	0	0	0	0	0	0	0	−0,263	0	0	0	0	0	0	−0,600
C4	0,525	0,4	0,475	0	0	0,35	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−0,638
C5	0	0	0	0	0	0	0	0,4	0	0	0	0	0	0	0	0	−0,363	0	0	0	0	0	0	0,513
C6	0	0	0	0	0	0	0,4	0,4	0	0	0	0	0,488	0,45	0	0	0,313	0	0	0	0	0	0	0,625
C7	0	0	−0,438	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,313	0,35	0	0	0	0	0,775
C8	0	0	0	0	0,388	0	0	0	0	0	0	0	0	0	0	0	0	0,375	0,438	0	0	0	0	0,388
C9	0	0,363	0,488	0,463	0	0	0	0	0	0	0,538	0,45	0	−0,375	0	0	0	0	0	0	0	0	0	−0,738
C10	0	0	0	0	0	0	0	0	0	0	0,488	0,413	0	−0,413	0	−0,375	−0,288	0	0	0	0	0	0,388	−0,738
C11	0	0	0,4	0	0	0,288	0	−0,238	0	0	0	0	0	−0,388	0	0	−0,300	0	0	0	0	0,563	0	−0,550
C12	0	0	0,425	0	0	0,475	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	−0,700
C13	0	0	0	0	0	0,4	0,425	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,513
C14	0	0	0	0	0	0,375	0	0	0	0	0,5	0	0	0	0	0,338	0	0	0	0	0	0	0	0,45
C15	0	0,375	−0,438	0	0	0	0	0	0	0	0	0	0	−0,325	0	−0,325	0	0	0	0	0	0	0	0,388
C16	0	0	−0,350	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0,425	−0,538
C17	0,513	0	−0,375	0	0	0	0,525	0,438	0	0	−0,600	−0,450	0,363	0	0	0	0	0,35	0	0	0	−0,738	0	0,6
C18	0	0	−0,363	0	0	0	0	0	0	0	0	−0,488	0	0	0	0	0	0	0	−0,463	0	0	0	0,638
C19	0	0	−0,438	0	0	0	0	0	0	0	0	−0,500	0	0	0	0	0	0	0	−0,425	0	0	0	0,613
C20	0	0	0,313	0	0	0	0	0	0	0	−0,425	−0,388	0,338	0,513	0	0	0	−0,325	−0,238	0	0	0	0	0,45
C21	0	0	0,4	0	0	0	0	0,475	0	0	0,488	−0,500	0,275	0	0	0	0	0	0	0	0	0	0	0,388
C22	0	0	0,8	0	−0,725	0	0	0	0	0	0	0	0	0	0	0,3	0	0	0	0	0	0	0	−0,738
C23	0	0	−0,775	0	0,738	0	0	0	0	0	0	0	0	0,5	0	0	0	0	0	0	0	0	0	0,75
C24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0