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Development of a quantitative decision-making tool to evaluate and improve supply chain agility

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Sommario

L'agilità delle catene di distribuzione è considerata una proprietà cruciale per la sopravvivenza di organizzazioni operanti in ambienti economici competitivi, dinamici ed incerti. A causa delle turbolenze che hanno caratterizzato la realtà industriale degli ultimi anni, questo tema ha acquisito rilevanza sia tra ricercatori che professionisti.
Questa ricerca ha lo scopo di sviluppare un modello quantitativo per valutare e migliorare l'agilità di tali sistemi. A questo proposito, sono stati analizzati i suoi elementi costitutivi, indagando anche le metodologie e i parametri usati in letteratura per calcolarla. È emerso che gli autori hanno identificato diversi eventi che influenzano l'agilità delle catene di distribuzione, nonché varie azioni tecniche e manageriali che possono essere implementate per migliorarne il livello.
La maggior parte degli articoli analizzati utilizza metodi qualitativi basati su valutazioni soggettive di esperti per stimare l'agilità dei sistemi, mentre i modelli quantitativi esistenti presentano limitazioni e non considerano l'eterogeneità di situazioni e leve che possono influenzarne le prestazioni. Pertanto, è stato sviluppato un nuovo modello matematico basato su equazioni dinamiche atte a rappresentare i flussi di informazioni e materiali caratteristici delle catene di distribuzione, simulando l'impatto di tali elementi sulle prestazioni del sistema. Questo consente una valutazione del livello di agilità dei sistemi, e l'indagine di leve che possono migliorarlo. L'applicazione di una leva rispetto ad un'altra può generare scenari diversi in termini di agilità, e per confrontarle è sviluppato un modello di simulazione ad eventi discreti. In aggiunta, un modello di costi è costruito per valutare l'impatto economico generato dall' attivazione di queste leve, mentre uno studio teorico permette di considerarne la sostenibilità ambientale e sociale. Un caso studio illustrativo ed uno reale sono svolti per mostrare il funzionamento di tale modello e la sua applicabilità nella realtà industriale.

Parole chiave: Agilità; Equazioni dinamiche; Controllo di flussi e scorte; Simulazione; Catene di distribuzione; Sostenibilità; Incertezza

Abstract

Supply Chain Agility is considered crucial for organizations to survive in dynamic, competitive, and uncertain business environments. Due to the unexpected events that have characterized the industrial reality of recent years, this topic has gained relevance both among researchers and practitioners. This research is aimed to develop a quantitative model to evaluate and improve the agility of end-to-end supply chains. In order to do so, its constitutive elements are investigated, inquiring also the methodologies and metrics presented in the literature for its calculation. It emerged that authors identified several events that can disrupt supply chain activities, as well as technical and managerial actions that can be deployed to face them by enhancing the agility level of networks. Most of the articles analysed exploit qualitative methods based on experts' subjective evaluations to assess this level, while existing quantitative models suffer from limitations and do not consider the heterogeneity of situations and levers that may affect the agility of organizations. Therefore, it is developed a novel mathematical model based on dynamic equations that represent the information and material flows of generic supply chain configurations, simulating the impact of these elements on the performance of the system. This allows an evaluation of the agility level of networks with respect to the disruption impacting the system, as well as the investigation of levers that can enhance it. The application of one lever with respect to another may generate different scenarios in terms of agile performance, and a discrete-event simulation model is developed to compare them. In addition, a quantitative cost model is used to evaluate the costs incurred to activate these levers, while a theoretical framework permits to consider their environmental and social sustainability. An illustrative case study is presented to show the mechanism of the mathematical model, while a real case study is performed to show its applicability in industrial reality.

Keywords: Agility; Dynamic Equations; Flow & Inventory Control; Simulation; Supply Chain; Sustainability; Uncertainty

Extended Abstract

Overview

This thesis addresses the topic of Supply Chain Agility, defined as the ability of supply chains to respond quickly and effectively to internal and external disturbances, either proactively or reactively (Boubaker, Jemai, et al., 2019b).
A supply chain is a set of three or more entities directly involved in the upstream and downstream flows of products, services, finances, and information from source to customer (Mentzer et al., 2001). Due to the unexpected and catastrophic events that have characterized the economic and industrial reality of recent years, agility has gained attention both among researchers and practitioners. Indeed, disruptions have negative consequences on productivity, cost of working, brand image, employment levels (Elliott et al., 2019), and agility represents a mitigation tactic that can help organizations to face them (Braunscheidel and Suresh, 2009).
Agility has been pointed out as the business paradigm of the 21st century (D. Gligor, Holcomb, and Stank, 2013), and scholars have investigated its constitutive elements, characteristics, drivers and enablers, proposing models to enhance it.
Despite various researches have shown the positive effects of agile capabilities on economic performance (Tseng and Lin, 2011; Tse et al., 2016; Al-Refaie et al., 2020) and some of them highlighted also the positive impact of agility on environmental and social sustainability (Ciccullo et al., 2018; Yusuf et al., 2020), the performed systemic literature review has shown that only a few articles related to the assessment and improvement of networks' agility were published, and most of them exploit qualitative-based techniques.
In this work it is presented a tool that permits to quantitatively evaluate and improve supply chain agility. The research has been developed through a collaboration between Politecnico di Milano and the Supply Chain Chair of CentraleSupélec.
Several aspects have been investigated. First of all, a bibliographical research regarding the situations that push networks to develop agile capabilities has been performed. Global sourcing, longer networks and often unpredictable customer behaviours have grown together with the need of shorter delivery time and larger assortments, shortening products' life-cycles (Boubaker, Jemai, et al., 2019a). Any internal and external disruption or sudden event can have severe consequences if it not faced rapidly and effectively (Al-Refaie et al., 2020). Therefore, a series of events that require agile capabilities to be faced as well as technical and managerial means that can help enhancing the agility level of networks have been investigated.
This literature research permitted to create the theoretical basis for the mathematical model that represents the core of the thesis. Indeed, it highlighted the heterogeneity

of risks that can put pressure on supply chain activities and the different techniques that can be deployed to improve agile performance. The development of a quantitative model able to consider this heterogeneity represents a novelty in this research field, as most of the analysed articles consider demand variations as unique potential disruptions and most of them focus on the selection of suppliers as agility levers.
The proposed model is based on the definition of dynamic equations that can represent the information and material flows characterizing supply chains. It allowed the implementation of a discrete-event simulation model, where the state of the system is defined at the beginning of each period t considering its state at the previous time $t-1$ and the impact of events that occur at time t, changing it.
Its objective is to determine the agility level of networks when disruptions occur. The assessment of the agility degree serves as an indicator of their strategic position (Patel, Samuel, et al., 2020). Indeed, to foster proactive and reactive capabilities networks should be aware of their agility level with respect to potential disruptions, and then decide which agility levers to implement.
The activation of one lever with respect to another can give different results in terms of agile performance, but it can also affect the economic, environmental and social sustainability of a supply chain. For this reason, the agility model has been integrated with a cost model that allows the evaluation of the trade-off between agile and economic performance. In this way it is possible to select the most suitable actions that can guarantee adequate agility under a constraining budget or the ones that maximize it at the minimum cost. Besides, a theoretical framework based on a literature review is presented, in order to keep into account also environmental and social aspects in the decision-making process.
To permit the exploitation of this mathematical model, it has been translated in the Visual Basic for Application coding language, which allowed the creation of an interface with Microsoft Excel and the development of a simulation tool.
Across the thesis, the following research questions have been addressed.

1. Which are the constitutive elements of supply chain agility, its drivers and enablers?

2. How supply chain agility is evaluated in literature and which metrics are adopted?

3. How to develop a set of dynamic equations that represent the behaviour of supply chain under various configurations?

4. How to develop an algorithm to evaluate the agility of supply chains based on this set of equations?

5. Which decision-making tools can be used to evaluate and improve the supply chain agility level of an organization?

In the next section, the organization of the dissertation and the content of each chapter are presented.

Dissertation organization

The present work is composed of 5 interrelated chapters. Each one exploited a research methodology to address the research questions proposed. Table 1 below reports its organization and the outcomes of each chapter.

Table 1. Organization of the dissertation

Chapter	Research Questions	Research Method	Outcome
1	1	Bibliographical research	Definition of a conceptual model embedding the elements that have been recognised in literature as drivers, levers and barriers of supply chain agility
2	2	Systemic literature review	Definition of the state of the art regarding qualitative and quantitative supply chain agility assessment methods
3	3,4	Theoretical model, illustrative case study	Development of a mathematical and simulation model to quantitatively evaluate and improve supply chain agility. Explanation of its mechanism through an illustrative case study
4	5	Theoretical model, literature review	Development of a quantitative cost model and a theoretical framework to evaluate the impact of agility levers on economic, environmental, social sustainability
5	5	Real case study	Validation of the model proposed through an explanatory real case study performed in collaboration with a company

The content of each chapter is presented below.

Chapter 1: Supply Chain Agility

This chapter provides a framework of Supply Chain Agility, inserting its concept among other paradigms and investigating its elements. Researchers have widely investigated this topic, providing a body of knowledge that offers insights about to the importance of agility in supply networks and on the variety and heterogeneity of situations that need agile capabilities to be answered.
Agility is defined as the ability of the supply chain to respond quickly and effectively to changes proactively or reactively, therefore either before or after their occurrence (Boubaker, Jemai, et al., 2019b). It is addressed as an "externally-focused capability" (Braunscheidel and Suresh, 2009) that has both cognitive and physical dimensions. The former are related to information sharing and decision capabilities, the latter to their implementation (D. Gligor, Holcomb, and Stank, 2013).
It is considered an antecedent of supply chain resiliency (D. Gligor, N. Gligor, et al., 2019) and a strategic feature to match product's demand and supply with the network design (D. M. Gligor, 2016).
The need of agility in organizations derives from the uncertainties and pressures that the business environment puts on their activities (Sharifi and Z. Zhang, 1999). In

(Boubaker, Jemai, et al., 2019b) these elements are defined *agility drivers*, as drive networks towards the adoption of agile practices. Thirteen drivers have been identified, related to uncertainties in customer and markets, the direct external and internal environment of companies, exogenous factors related to the context in which the company evolves.
Specific events requiring agility can be associated to each driver, therefore defined *situations needing agility* (Boubaker, Jemai, et al., 2019a). As instance, some situations related to the uncertainties on customer needs are the introduction of new products/services, forecast errors, changes in product's design or price.
To mitigate the impact of situations requiring agility, a set of managerial and technical means can be deployed. They are addressed *agility enablers* (Boubaker, Jemai, et al., 2019b), and according to (Al Humdan et al., 2020) they can be categorized in proactive, reactive, both proactive and reactive. Specific actions that can be used to improve the agility level of a network are associated to each enabler, and are defined *agility levers* (Boubaker, Jemai, et al., 2019b).
Also barriers towards the achievement of agile capabilities are investigated, and the relationship between agility and supply chain performance is considered. It emerged that top management support and information sharing technologies are addressed as recurring elements required to reach agility (Sindhwani et al., 2019; Zhukov et al., 2019; Centobelli et al., 2020).

Chapter 2: State of the art

This chapter is aimed to define the state of the art regarding the methodologies and metrics adopted to assess the agility level of organizations. It is performed a systemic literature review based on articles made available by the database SCOPUS and published between January 2019 and April 2021, as no other reviews considering this time range were found in literature. Therefore, it contributes to update the state of the art in this research field, and its integration with previous bibliographical reviews has allowed to observe how authors addressed the calculation of supply chain agility. Among the analysed studies it emerged that mainly theoretical, empirical and real studies have been considered in the literature of the past two years. Some authors presented theoretical models and approaches to assess specific performance metrics related to the agility of networks, while others focused on the determination of their efficacy through empirical demonstrations.
These models allow to understand how close networks are to become agile by aligning and integrating agility capabilities and drivers to gain competitive advantage. Several metrics where employed to this aim, most of which related to customer satisfaction (order fulfilment rate, responsiveness, etc.) and costs.
Although a considerable number of models and methodologies have been identified, a tool able to deal with the heterogeneity of situations that can impact supply chains and the levers that can be exploited to enhance agility has not been found. Besides, the analyses of the literature highlighted that most of authors exploited qualitative-based methods, where the agility degree of a network is assessed through expert's subjective evaluations.

Chapter 3: Supply chain agility evaluation model

This chapter is dedicated to the presentation of the mathematical model developed to quantitatively evaluate and improve the agility of supply chains. It is based on a framework proposed by the Supply Chain Chair of CentraleSupélec, defined Supply Chain Agility Evaluation Model. Differently from methodologies presented in Chapter 2 it does not need qualitative evaluations, but it simulates the physical and informational flows characterizing networks in order to measure the impact of changes on them through appropriate performance indicators.
This framework requires five inputs, i.e. the configuration of the supply chain and the parameters that characterize each activity across it (lead times, frozen periods, production and logistics capacity), the inventory and flow management policy adopted, parameters related to situations needing agility and levers, the metrics used to assess the agile performance.
In order to represent the configuration of generic end-to-end networks, seven operations that can take place in real organizations are modelled. They address both mono and multi-product activities, and their combination allows to address open-loop supply chains without a limited number of levels or agents.
To manage the movement of materials it is adopted a demand-dependent, future-requirement flow policy. According to it, the actors in the most downstream level of the supply chain receive the external exogenous demand and share information to upstream levels related to the net required quantities. This backward mechanism is performed by each stock point composing the chain, until the most upstream raw-materials level. Therefore, only actors in the final level directly observe variations in demand and perform estimations for upcoming periods, while all the others receive a derived information. It is considered that information is updated simultaneously among all the agents of the network.
While the information flow is modelled through a backward algorithm, the material flow is addressed using a forward one from the raw-material level to end-customers. These flows are designed as separated flows.
The agility level of networks is measured through three metrics related to the time needed to re-acquire nominal performances after the disrupting impact of a situation needing agility. They are defined Supply Chain Agility Response Metric, the time needed for the supply chain to respond unforeseen events and re-achieve previous performance levels; Supply Chain Agility Preparation Metric, the time required to anticipate the occurrence of a disruption so that it does not impact service levels; Supply Chain Resiliency Evaluation Metrics, the time needed for re-achieving targeted inventory levels after a disruption has happened.
The outcome of this model is a discrete-event simulation tool that allows to estimate supply chains' agility levels with respect to disrupting events, and to compare the impact of proactive or reactive levers on agile performance. Indeed, the application of one lever rather than others may provide different scenarios, and their comparison permits to select the most appropriate actions to enhance agility.
The tool has been developed with the Visual Basic for Application coding language, which allowed to create an interface with Microsoft Excel to simplify the decision-making process. An illustrative case study is performed in order to show its potentiality.

Chapter 4: Comparison instruments

The mathematical model presented in Chapter 3 allows to evaluate the level of agility of a supply chain configuration and compare the effects of the application of levers in terms of agile performance. Nonetheless, managers may be interest in compare the different scenarios obtained also under a sustainability point of view.
Supply chains' management decisions are generally based on the economic performance of the involved parties, and these evaluations influence the adoption of strategies to manage flows across them (Rosič and Jammernegg, 2013). However, in recent years supply chains have been facing pressures from stakeholders for sustainable business development, therefore for including social and environmental performance measures into the conventional metrics (V. Sharma et al., 2021). As a result, companies should be committed to sustainability, safeguarding also the environment and the welfare of people (Golini et al., 2014).
In order to account these aspects, in Chapter 4 it is presented a quantitative cost model to evaluate the economic impact derived from the activation of agility levers, as well as a framework to provide indications related to their positive or negative effects on environmental and social sustainability.
The cost model considers the fixed and variable costs related to agility levers, therefore the expenses incurred to activate them and the operational ones required for their running. These latter depends on the duration of the activation of a lever. Besides, costs of product outsourcing are considered by accounting the quantity purchased and their unitary price.
On the other hand, the theoretical framework allows a qualitative comparison of levers, and it is based on elements found in a bibliographical review. It represents a contribution to the current literature on supply chains, as only a few articles dealt with the relationship between agility and sustainability (Ciccullo et al., 2018).

Chapter 5: Case study

The concepts presented in chapters 3 and 4 are then exploited to perform a real case study in BCS, a leader company in the production of agricultural machines.
It is analysed the supply chain of an innovative product the company is introducing to the market, in order to investigate whether a targeted level of agility could be reached when facing a situation needing agility related to a demand increase.
The case study follows a framework based on six steps: definition of the supply chain configuration, identification of situations needing agility, choice of agility metrics and targets, application of the simulation model, identification of agility levers and estimation of their impact. Once completed this process the level of agility is evaluated and if acceptable the process finishes, otherwise other levers are investigated.
The necessary data to apply the simulation model are gathered using a questionnaire, proposed to professional figures inside the company belonging to different departments. Several scenarios were simulated using these data and investigating levers. Their comparison allowed to identify the most suitable solution to reach a targeted agility level while respecting the constraints imposed by the company.
This case study shows the applicability of the developed model in the industrial reality. Besides, it highlights also some of its limitations, such as that the simulation of a large number of scenarios is a time-consuming process.

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Chapter 1

Supply Chain Agility

1.1 Introduction

Over the last two decades, increasing attention has been given to Supply Chain (SC) turbulences. Global sourcing, longer networks and often unpredictable customer behaviours have grown together with the need of shorter delivery time and larger assortments, shortening products' life-cycles (Boubaker, Jemai, et al., 2019a).
Moreover, firms have experienced an increasing trend of unexpected and catastrophic events in recent years. These events are known as disruptions, and have negative consequences on productivity, cost of working, product release delay, brand image, employment levels, and overall SC performance (Elliott et al., 2019).
Disruptions may be specific of the network, causing the unavailability of one or more components of its supply chain, or the result of unpredictable events such as natural calamities, epidemics and pandemics (Paul and Chowdhury, 2020). For example, (Linton and Vakil, 2020) shows that the world's largest 1000 companies have been negatively affected by the spread of COVID-19 because multiple facilities of their chain were located in quarantine zones.
The impact of disruptions may have different features: short or long-lasting effects, propagation on other activities, sudden demand and supply variations that may threaten the survival of companies. Considering the COVID-19's outbreak, some products' supply chains (gel sanitizer, face masks, etc.) faced raw material shortages due to a sharp demand increase, while others risked bankruptcy because of a drastic demand drop (Ivanov and Dolgui, 2020).
Firms have adopted different approaches to mitigate supply chains' disruption risks, such as increase safety stocks to safeguard production lines or prepare backup sourcing to ensure material flows. However, these methods increase the redundancy in a supply system and require resources for risk mitigation (Tse et al., 2016).
On the other hand, Braunscheidel and Suresh (2009) state that disruption risks can be effectively mitigated by developing Supply Chain Agility (SCA). This latter is considered a critical element that enables firms to face potential and actual disruptions, affecting their competitiveness at a strategic level.
It represents both a mitigation and response tactic, which provides proactive and reactive measures to counteract potential threats and respond in the occurrence of expected or unforeseen events (Braunscheidel and Suresh, 2009).

In volatile and unpredictable marketplaces, firms need to react quickly to challenges as well as to exploit their operations to remain competitive. For these reasons, agility has been considered a fundamental property of supply chains to endure, thrive and create business value by managing disruption risks (Aslam, Blome, et al., 2018).
X. Li et al. (2008) affirm that the beneficial impact of agility on organizations is well acknowledged nowadays, and they address it as a feature proper of best supply chains. Indeed, agility has emerged as a competitive vehicle for organizations operating in uncertain and dynamic environments, and has been pointed as the business paradigm of the 21st century (D. Gligor, Holcomb, and Stank, 2013).
Although it offers solutions to SC's issues such as excess inventory and potential shortages (Centobelli et al., 2020) the concept of SCA is fragmented, without a well-defined structure. Several definitions have been proposed in literature and researchers addressed it in various research fields, preventing its recognition with specific features. This fragmentation has brought to the adoption of different metrics to assess the level of networks' agility, and most of authors address this calculation through qualitative-based research methods.
The target of the present work is to provide a mathematical and simulation tool to assess quantitatively the level of agility of a SC. It has been developed in collaboration with the Supply Chain Chair of CentraleSupélec, which proposed an agility evaluation model based on the assessment of specific key performance indicators (KPIs).
The following Chapter is aimed to present an overview of the SCA concept. First, a brief review of definitions is presented, explaining which are the most recurring elements through which agility is defined. Then, it is studied in relationship with other organizational features to investigate the attributes that allow networks to become agile and its role in enhancing other organizational paradigms. In the end, a conceptual framework of SCA is presented to explain its constitutive elements and provide a theoretical basis for the mathematical model developed.
Eventually, Chapter 2 focuses on a systematic literature review on the metrics and methodologies adopted by scholars to determine the agility level of networks, defining and updating the state of the art. The analysis indicates that most of authors exploit qualitative-based methods to assess this level and to identify proper actions to enhance it. Therefore, a model able to embed the heterogeneity of SC networks and to measure quantitatively the impact of disruptions or opportunities can represent a contribution to existing literature.
This model is presented in Chapter 3, together with an illustrative case study aimed to show its functioning and potentiality. It allows to calculate the agility level of a network through specific metrics, observing the impact of levers that can be deployed to enhance it.
The application of a lever with respect to another can have different effects on the economic, environmental and social sustainability of a SC. Therefore, Chapter 4 presents a cost model to allow the economic comparison of levers, and a theoretical framework is built to take into consideration the other two sustainable aspects.
In the end, Chapter 5 describes an application of the model on a real SC network developed in collaboration with BCS, a leader company in the production of agricultural machinery.

1.2 Definition

Supply Chain Agility is a concept in continuous evolution, without a rigorous and globally-accepted definition (Al Humdan et al., 2020). It has its origins in manufacturing: an industry-led programme published by Nagel and Dove (1991) theorized that the era dominated by mass production was close to an end, stating that American industry had to focus on agility to re-acquire its leadership.
By enriching customer satisfaction, mastering changes and improving communication networks, agile manufacturers would have been able to gain competitive advantage.
Since the publication of this report, agility has become a popular topic in the manufacturing context appearing in the form of books, trade magazines, and academic journals (X. Li et al., 2008). These principles were then extended to other aspects of the business economy, making SCA an emerging research field in the late 20th century (Sharifi and Z. Zhang, 1999).
Several authors tried to formulate a formal definition (Al Humdan et al., 2020). Some of them defined it in operational terms, some as a management philosophy, others in terms of strategy. However, agility is a multi-dimensional concept that crosses many disciplines, making uncommon for researchers to adopt a single definition (D. Gligor, Holcomb, and Stank, 2013). In its broadest sense, it is the capability of a system to easily vary one or more of its operative parameters (Treccani, 2021).
Early researchers defined SCA as a reactive feature that enables firms to prosper in an evolving environment. For example, Sharifi and Z. Zhang (1999, p. 9) defined agility as "the ability to cope with unexpected challenges, to survive unprecedented threats of business environment, and to take advantage of changes as opportunities". Nonetheless, the construct of SCA evolved over time and scholars extended its concept embedding other features.
Al Humdan et al. (2020) noticed that authors based their definitions mainly on four elements of agility: speed, scope (reactive, proactive ability), mode (demand, supply) and outcomes. They show that most of definitions report terms such as "in real-time", "quickly" and "timely manners", related both to the detection of changes and their recovery. Indeed, time is considered a constitutive element of agility, and timeliness has been commonly recognised fundamental to achieve competitive advantage.
Regarding the scope of agility, the ability to react demand variations has been commonly associated to agile networks. However, in the first decade of 21st century authors started considering also supply as scope of agility (Al Humdan et al., 2020). For example, Mason et al. (2002, p. 611) defined it as a key element "to inventory reduction, adapting to market variations more efficiently, enabling enterprises to respond to consumer demand more quickly, and integrating with suppliers more effectively".
Despite reactivity is considered the dominant mode, some definitions highlight that agile organizations should be able not only to react against disruptions, but also to proactively anticipate threats or opportunities. As instance, X. Li et al. (2008, p. 421) state that "agility is the result of integrating an alertness to changes – both internal and environmental – with a capability to use resources in responding (proactively/reactively) to such changes, all in a timely, and flexible manner".
Some scholars defined agility through its targets, considering it the ability to effectively reach customers and employers satisfaction, successfully fulfil end customers' requirements or effectively achieve competitive advantage (Al Humdan et al., 2020).

In the present work it is adopted the definition proposed by Boubaker (2019, p. 20), which embeds the four agility features presented and is one of the most recent, formally-stated definitions appeared in literature: SCA is "the ability of the supply chain to respond quickly and effectively to internal and external sudden situations, proactively or reactively, by making the appropriate internal decisions and changes". The suddenness of a situation is associated to the quickness of its occurring. It can be either unexpected or anticipated, but it is considered that it would happen without a smooth transitional phase.
Starting from these considerations, in the next sections dimensions and features of SCA are investigated in order to understand its role in reaching competitive advantage.

1.3 Agility dimensions and other paradigms

The absence of a formally-recognised definition led researchers to investigate the dimensions of SCA, as well as its relationship with other organizational features.
X. Li et al. (2008) defined *alertness* and *responsive capabilities* to changes the two main dimensions of agility. Alertness represents the capability to seek for changes both externally (by anticipating threats and opportunities) and internally the SC environment, exploiting interconnections between market and organization's resources. On the other hand, response capabilities enable changes in organizational processes by selecting relevant actions to reach competitive advantage, managing dependencies among activities and resources.
D. Gligor, Holcomb, and Stank (2013) classified SCA's dimensions in cognitive and physical. Cognitive dimensions are the ones related to information sharing, which allows organizations to decide when and which actions to take. They recognized that a SC to be agile needs *decisiveness*, defined as the ability to make decisions resolutely, *accessibility*, the ability to access relevant data, and *alertness*, to quickly detect threats and opportunities. Physical dimensions instead are related to the implementation of actions that can help organizations to reach the desired level of agility. Therefore, an agile organization should have also *swiftness*, the ability to implement decision quickly, and *flexibility*.
The relationship between agility and flexibility has been widely investigated in literature, as sometimes these terms have been used interchangeably (X. Li et al., 2008). Swafford et al. (2006) explain that SC flexibility is related to firms' internal functions such as purchasing or manufacturing, while agility is related to organizational-level abilities, like market responsiveness and product delivery.
Therefore, SCA can be considered an "externally focused capability", while flexibility an "internally focused competency" that influences the level of agility of a firm (Braunscheidel and Suresh, 2009, p. 120). Accordingly, SCA and SC-flexibility are different concepts, and flexibility is an antecedent of agility: a system can be flexible without being agile, but an agile system is also flexible (Swafford et al., 2006).
In order to determine the organizational features that allow to reach SCA, several constructs have been investigated in literature as agility antecedents.
Braunscheidel and Suresh (2009) claim that SC integration, intended as connectedness among firms of the chain, contributes positively to reach SCA by enabling coordinated tactics to mitigate disruptions.

Connectivity has been addressed as antecedent of agility also in (Dubey, Altay, et al., 2018), where information sharing capabilities are regarded as necessary elements to develop visibility. High speed knowledge transfer allows to establish relationships between partners, obtaining a shared understanding and access to information without distortions and allowing the whole network to point toward the common objective.
Even if agility has been recognised a characteristic proper of most successful companies (Abdallah and Ayoub, 2020), the fragmentation of its concept might blur the distinction with other organizational paradigms.
For example, Shekarian et al. (2020) specify that the concepts of SCA and SC-responsiveness are not equivalent, despite scholars address time and responsive capabilities as major dimensions of agility. They argue that the former is a capability that allows firms to operate in an efficient and responsive manner, while the latter indicates the ability of a network to promptly respond in a target time frame to customer requests.
Another construct that has been investigated in its relationship with SCA is SC-resilience. Due to the multidimensionality of these two concepts, literature has not always offered a clear distinction between them (D. Gligor, N. Gligor, et al., 2019). D. Gligor, N. Gligor, et al. (2019) show that even if the constructs have unique characteristics, they also share common themes.
Agility is considered the ability of organizations to change, customize and integrate processes to overcome threats and exploit opportunities. On the other hand, resilience is about surviving disruptions, resist shocks and return to original performance after severe damages. Nonetheless, both concepts present anticipation features, exploit flexibility and are based on speed (D. Gligor, N. Gligor, et al., 2019).
According to (Aslam, Khan, et al., 2020), resilience is the ability of an organization to rebound after major and long-lasting shocks, while agility deals mainly with short-term or one-time threats. They argue that agility is an antecedent of resilience and that ambidexterity, defined as the ability to adapt according to the market changes while aligning the targets of SC partners, allows organizations to reach agility. Indeed, alignment and adaptability enhance SCA, which requires cooperation between the SC partners to minimize the overall cost of receptiveness and the response time to customer requirements (Dubey, Altay, et al., 2018).
D. M. Gligor (2016) investigated the relationship between agility and SC-fit. This latter is considered the strategic ability to match products' supply and demand characteristics (demand predictability, product variety, lead times, etc.) with the SC design characteristics (supplier selection strategy, inventory management, etc.).
The author argues that the more the level of environmental uncertainty increases, the more difficult is to match demand with supply. However, the introduction or improvement of SCA positively mitigates the relationship between fit and environments of high dynamism and uncertainty.
The reason of this positive impact can be found in the dimensions of agility. Indeed, alertness allows firms to quickly access information about changes in demand and supply and accessibility facilitates access to relevant data about these changes. Decisiveness helps firms determining what actions are necessary to achieve the fit, while flexibility and swiftness can facilitate their implementation (D. M. Gligor, 2016).
Despite agility has been addressed as a mean to reach competitive advantage, in (D. M. Gligor, 2016) it is specified that at low levels of environmental uncertainty or

dynamism its impact on the performance of organizations may be marginal. Therefore, managers should be aware of the potential positive outcomes in adopting SCA, but also of the implementation costs of agile solutions and their possible contribution, investigating the need of agility of their networks.
In order to clarify when supply chains may need agile capabilities, the next section is dedicated to the presentation of a conceptual framework of SCA that can help understanding which are the circumstances that need agile responses and which actions can be implemented to counteract them.

1.4 Supply chain agility conceptual framework

In previous sections it has been presented a definition of agility and the dimensions of an agile organization, as well as the role of SCA with respect to other organizational features. However, it has not been presented yet how scholars and practitioners addressed the issue of reaching agility and which are the events that lead organizations to become agile.
The aim of this section is to show and explain the factors that push supply chains towards agility, the technical means that can be applied to counteract such factors and some possible barriers that could prevent agility to be reached.
Through a literature research, it is presented first a series of situations that require agile capabilities to be faced. Next, a series of actions that enable and lever the enhancement of SCA is introduced. In the end, disturbing elements in reaching agility and the impact of SCA on organizational performance are explored. Figure 1.1 shows a conceptual model that embeds the elements influencing SCA found in literature.

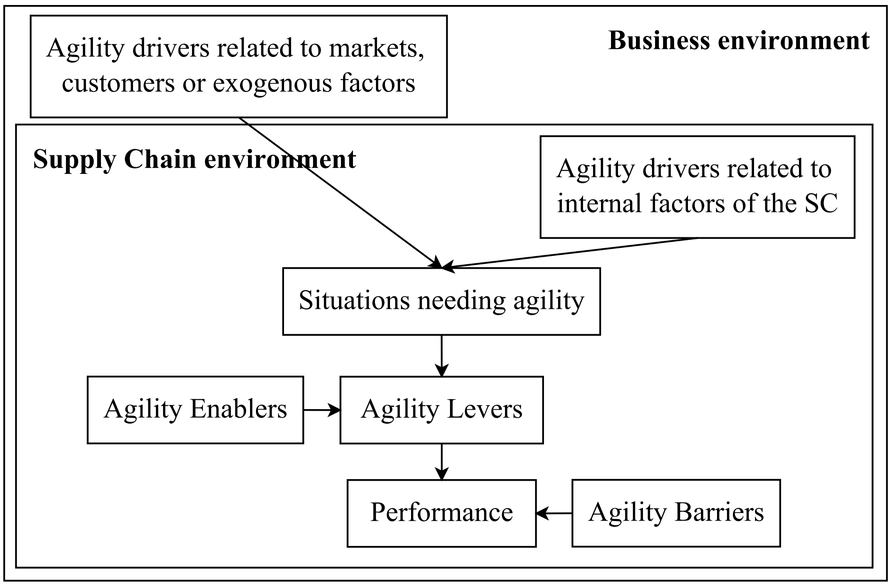

Figure 1.1. Supply chain agility conceptual model

1.4.1 Agility drivers and situations needing agility

The term driver indicates a factor that causes a particular phenomenon to happen or develop (Boubaker, Jemai, et al., 2019a).
The need of agility derives from changes and depends on the nature of the change in the business environment of the firm (Sharifi and Z. Zhang, 1999). Lin et al. (2006, p. 287) stated that "the driver of agility is change", recognising that the business environment of organizations acts as a source of uncertainties and imposes pressure on their activities, driving them to improve their competitiveness.
Since different companies might face different threats or opportunities, also agility drivers could vary depending on their contexts, competencies, characteristics (Sharifi and Z. Zhang, 1999). For this reason, several authors in multiple research fields have focused on the study of situations that push companies towards agility, providing a wide body of literature (Boubaker, Jemai, et al., 2019a).
Through a literature research based on SCA and risk management, Boubaker, Jemai, et al. (2019b) identified and classified a list of drivers then completed and validated by SC managers and specialists.
They recognised that the word driver was used by most of scholars to describe the sources of change (competition, technological development, etc.) and not the specific events that supply chains have to face. Therefore, they introduced the term *situation* to indicate the set of things and conditions caused by an agility driver in a specific time and place, and the expression Situations Needing Agility (SNA) to define "the external and internal sudden disturbances and changes that lower supply chain performances, temporary or sustainably, and consequently, require an agile response" (Boubaker, Jemai, et al., 2019a, p. 270).
According to their research, agility drivers can be classified in four major groups: drivers related to customers and markets, to SC's partners, to external exogenous factors and to the internal environment of enterprises.
Table 1.1 reports this classification, and the factors associated to each category.

Table 1.1. Agility drivers (Boubaker, Jemai, et al., 2019b)

Uncertainties on customer and markets	Customer needs Competition Launch and end-of-life products Promotional or advertising events Entering / Closing a market or distribution channel
Uncertainties in the direct external environment of the company	Suppliers and outsourcing External logistics and transport
Uncertainties related to exogenous factors	Evolution of the external context of the company Price evolution Terrorism and natural calamities
Uncertainties in the internal environment of the company	Production and logistics Business context IT / IS / Technology

Each of these drivers presents specific characteristics and generates risks and situations that can push organizations towards agility.

Parast and Shekarian (2019) highlight that risks can be divided in two categories: internal and external. Internal risks are related to operational problems, supplier relationship management, demand variability, planning and financial uncertainty.
On the other hand, external risks include end-to-end risks (e.g. natural disasters, accidents, terrorism, technological trends), supplier risks (upstream supply risks, production problems, financial losses) and distribution risks (e.g. infrastructure and labour unavailability, warehouse and information and communication technology (ICT) inadequacies). These factors are source of uncertainties that can lead to disruptions, therefore potential situations needing agility.
As already seen in previous sections, some authors indicate as target of SCA the satisfaction and fulfilment of customer requirements. Demand uncertainty, given both by volatile environments or inaccurate forecasts, is often regarded as the most severe agility driver impacting supply chains (Fadaki et al., 2020).
Drivers and SNA related to changes in the market environment are recognized both as threats and opportunities that can lead companies to SC agility. For example, detecting emerging markets or the variation of existing goods' requirements may lead to the change of products' demand or the variation of a company's production mix.
Table 1.2 reports a classification of agility drivers and SNA related to market risks.

Table 1.2. Drivers and situations related to market risks (D. Z. Zhang, 2011)

Agility drivers	**Situations needing agility**
Customer needs	Change of products/services price, design Change of product volumes, complexity Introduction of innovative product/service Forecasts errors
Competition	Competitors' promotional campaigns End of patent protection Launch of products/services Change in competitors' schedules/ strategy
Launch and end-of-life products	Change in products assortment Product launch/shutdown schedule changes Variations of product life-cycle Changes in packaging solutions
Promotional or advertising events	Promotional campaigns Demand variations of existing products
Entering / Closing a market or distribution channel	Change in the demand distribution Change in strategy, impact on existing channels Customer loss and orders cancellation

Partner relationships represent another source of risk for organizations.
Fadaki et al. (2020) explain that in some cases supply uncertainties may impact SC performance more significantly than demand variations. Indeed, disruptions between suppliers, subcontractors or transportation activities can represent a threat for supply chains, involving changes both in quantities and time (delays or advances in production, changes in lead times, etc.). These uncertainties are related to the direct external environment of companies, composed by suppliers and outsourcing partners.
Any disruption caused by an external partner may lead to the disturbance of all the

SC activities (Boubaker, Jemai, et al., 2019b). For example, due to either internal (e.g. strikes, equipment breakdowns) or external factors (e.g. natural disasters, political decisions), it is possible that a buyer may only receive a portion of the quantity ordered from its supplier, or it may happen that an order cannot completely be delivered.
Minner (2003) claims that a series of risks should be kept into consideration when dealing with partner relationships. As instance, exchange rate fluctuations may determine variations in procurement costs or selling prices, affecting the profitability of firms. Companies can be bounded to their budget over the planning horizon, so the choice of suppliers may depend on the more convenient costs allocation that respects the budget limit rather than on agile solutions. Generally, the smaller the budget the higher the probability to adopt mono-sourcing solutions, decreasing the service level and incurring in supply capacity limitations (Minner, 2003).
Table 1.3 shows drivers and SNA related to partner relationships.

Table 1.3. Drivers and situations related to supply (Boubaker, Jemai, et al., 2019a)

Agility drivers	**Situations needing agility**
Suppliers and outsourcing risks	Supplier/outsourcer failure or disruptions Under/over capacity in production/logistics Material unavailability or quality issues Fraud/corruption Pricing change Lack of cooperation
Logistics and transports uncertainties	Change in transportation planning, lead times Transportation disruptions Anticipated/delayed deliveries Pricing change

Similarly, external factors of change associated to economical, geopolitical and social situations affect the activities of a SC. These drivers embed both opportunities (variations of exchange rates or energy price) and threats (cyber-attacks, natural calamities) related to the evolution of the external context of an enterprise (Boubaker, Jemai, et al., 2019a).
Fadaki et al. (2020, p. 5616) highlight that executive managers should be able to distinguish the "crude" and the "perceived" level of an external factor. The crude level refers to its intensity in a business environment, while the perceived level is the difference between the crude one and how effectively a company manages it. In order to satisfy customer requirements, agility may help to fill this gap.
In the end, drivers related to uncertainties into the internal environment of a firm are associated to managerial and coordination problems. As instance, the lack of cooperation between sales and operations may lead to shortages or quality issues.
Lee et al. (2020) state that the main target of manufacturer-supplier operations is to rapidly respond to uncertain demands from downstream customers and markets. To achieve this goal, companies need to analyse their operations and markets in order to take proper actions at the right time, by exploiting ICT, information systems (IS) and appropriate technologies to rapidly update and process data.
Technology has been identified as a fundamental factor affecting SCA (Centobelli et al., 2020). It is considered an essential component of agility as it enhances information

sharing. Indeed, real-time flows of data managed through big data analytics open opportunities for demand management and market sensitivity, driving organizations towards agile practices (Dubey, Gunasekaran, et al., 2019).
Table 1.4 resumes these concepts and provide a list of SNA related to the internal environment of enterprises.

Table 1.4. Drivers and situations related to the internal environment of firms (Boubaker, Jemai, et al., 2019a)

Agility drivers	**Situations needing agility**
Production uncertainties	Change in production mix or planning Product quality issues Under/over capacity in production Breakdowns Production lead-time changes Production cost variations Unavailability of workforce, resources
Logistics uncertainties	Breakdowns of tools or machines Change in planning or delivery times Under/over capacity in logistics Unavailability of workforce Inventory shortages
Business context uncertainties	Change in products assortment or priority Change of customers/markets priority Change of suppliers, holding costs
IT/IS/Technologies issues	Change in production/logistic schedule Physical and information flows incongruence Problems in record, monitor, process data Unavailability of IT systems

The lists of drivers and SNA presented indicate that supply chains are asked to deal with a considerable amount of sudden external and internal pressures. Thus, the ability of a system to respond effectively to unplanned situations become a competitive advantage and a strategic axis (Boubaker, Jemai, et al., 2019a).
The first step to improve the level of agility within supply chains is to recognise the source of uncertainty and the consequent potential disruption that requires agile capabilities. In Chapter 3 the identification of SNA will be considered the starting point to assess the agility level of networks. In particular, the focus will be given to situations that affect the physical parameters of supply chains, therefore:

- Demand variations: changes in total demand, production mix, market and distribution channels.
- Time or planning variations: changes in lead times, frozen planning periods.
- Production capacity variations: changes in quantities that can be produced or delivered by an upstream activity, production and logistic plans.

Once identified the situation that requires agility, proper actions have to be taken to counteract the disruption or exploit the opportunity. Indeed, supply chains have to respond quickly to unpredictable demand minimizing stock-outs, forced markdowns and obsolete inventory (Collin and Lorenzin, 2006). The next section describes a set of potential actions and means that could help improving the level of SCA.

1.4.2 Agility enablers and levers

The Oxford dictionary defines the term enabler as "a person or thing that makes something possible" (OED, 2021). Agility enablers refer to the set of managerial, organizational and technological procedures that can be deployed to counteract a situation needing agility.
Lin et al. (2006) stated that networks require certain attributes to be agile, through which leaders can re-arrange plans, infrastructures, strategies and parameters.
These attributes have been widely investigated in literature (S. K. Sharma and Bhat, 2014), and likewise agility drivers authors have focused on their identification. Al Humdan et al. (2020, p. 298) affirm that SCA enablers can be distinguished according to their proactive and/or reactive features. They propose to classify them in three classes: "exclusively proactive", "exclusively reactive", and "both reactive and proactive". Through a bibliographical research they recognised that SCA enablers could be categorized in 11 groups, each one with reactive and/or proactive features. This classification is reported in Table 1.5.

Table 1.5. Categories of agility enablers (Al Humdan et al., 2020)

Proactive enablers	Market sensitivity Sourcing strategies Organizational change culture Strategic operational alignment
Reactive enablers	Strategic flexibility Demand management Contingency planning Strategic orientation
Proactive and reactive enablers	Supportive information technology Collaborative relationship Logistic and distribution capabilities

In order to identify the technical means provided by agility enablers that enhance the level of SCA, authors focused on the determination of organizational, technological and managerial practices that can be implemented by organizations.
Boubaker, Jemai, et al. (2019b) addressed these actions as *agility levers*, where the term lever stands for the ability to get advantage, "to change a situation in order to suit yourself" (Cambridge, 2021). Indeed, SCA levers represent the set of actions that allows a proactive or reactive enabler to counteract disruptions or exploit opportunities. Focusing on proactive enablers, they act as preventive mechanisms to reduce risks and concern supply, markets and operational capabilities (Al Humdan et al., 2020). Market sensitivity represents the ability to detect and anticipate sudden variations in demand and market. It is associated to sales activities, as supply chains should update frequently their forecasts and anticipate information (Boubaker, Jemai, et al., 2019b). It includes also the ability of detecting the evolution of the SC external environment

(government regulations, competitors moves, etc.), allowing organizations to rapidly adapt to constraints (Piya et al., 2020).
The adoption of proper sourcing strategies is another factor that helps organizations to be proactive. This enabler is related to the selection and involvement of key suppliers to maintain innovativeness (Al Humdan et al., 2020), the identification of changes in partners relationships and the adoption of sourcing techniques that enhance agility (Boubaker, Jemai, et al., 2019b). Erhun et al. (2020) stress also the importance of gaining visibility on upper-lever activities, in order to align the SC's objectives and increase the overall level of agility.
Strategic alignment is considered an enabler not only for supplying techniques, but also for production planning, process integration and inventory management (Al Humdan et al., 2020). By perceiving agility as a source of competitive advantage (Piya et al., 2020), partners of the supply chain can increase the flexibility and versatility of their activities by acquiring new machines, utilizing proper material planning and control methods or increasing the flexibility of human resources in production (Boubaker, 2019; Al-Zabidi et al., 2021).
The human impact has been related also to the culture of change, intended as the process that leads to continuous improvement through top management support and staff empowerment (Al Humdan et al., 2020).
Golgeci et al. (2019) highlight that organizations need the involvement of managers at all levels to become agile. They affirm that agility depends on the ability to show positive commitment toward the firm and make effective decisions in dynamic environments using the available information.
Table 1.6 shows a more detailed classification of proactive agility levers.

Table 1.6. Proactive agility enablers and levers

SCA enablers	**SCA levers**	**Reference**
Market sensitivity	Detect/anticipate demand evolution Forecasts and market trend analysis Customer-based performance measurement Review of health and safety regulations	(Al-Zabidi et al., 2021) (Boubaker, Jemai, et al., 2019b) (Patel, Tiwari, et al., 2020) (Piya et al., 2020)
Sourcing strategies	Detect/identify changes related to partners Select agile suppliers Adopt multi-sourcing techniques Adopt outsourcing solutions Enhance visibility on upper-tier activities	(Boubaker, Jemai, et al., 2019b) (Erhun et al., 2020) (Gunasekaran et al., 2019) (Minner, 2003)
Organizational change culture	Definition a target level of agility Transformational leadership Information sharing across organization Teamwork, involvement, commitment Employees individual empowerment	(Golgeci et al., 2019) (Gunasekaran et al., 2019) (Piya et al., 2020)
Strategic operational alignment	Flexibility/versatility of internal processes Size and position strategic over-capacity Optimize the layout of warehouses Position and size strategic inventory buffers Human resources' flexibility in production Manufacturing/warehouses automation	(Al-Zabidi et al., 2021) (Gunasekaran et al., 2019) (Piya et al., 2020)

While proactive levers and enablers are focused on mitigating the potential impacts of changes preventively, reactive enablers represent defensive mechanisms that enable the supply chain to respond disruptions after happened. They are effect-oriented, focused mainly on the demand side of the SC (Al Humdan et al., 2020).
Strategic flexibility refers to the set of technical means that allow the SC to adapt to changes with minimal penalty. It embeds operational, organizational and network flexibility, indicated respectively as the ability to reconfigure the SC, to cope with unexpected situation and to effectively manage resources (Patel, Tiwari, et al., 2020). Al-Zabidi et al. (2021) recognise that time compression is an important lever of agility, connected to a proper scheduling of core activities. Other levers are related to the adaption of production capacity to the situation needing agility, for example varying volume and mix of supply plans, outsourcing, increasing the flexibility and versatility of employees, schedules (Boubaker, Jemai, et al., 2019b; Lee et al., 2020).
Flexibility is correlated to the strategic orientation of a network, defined as the collective alignment of SC internal and externally-focused capabilities (Al Humdan et al., 2020). For example, Patel, Tiwari, et al. (2020) recognise that a single organization might be not able to respond rapidly to SNA, therefore it should form a virtual alliance with other companies to achieve a common target. In addition, it should cooperate with competitors and leverage core resources with partners (Piya et al., 2020).
In the end, an effective demand management allows to improve the level of SCA. Collin and Lorenzin (2006) explain that demand planning is the continuous process of turning customer and market forecasts into feasible volume demand plans. Over-planning leads to excess stock and decreased operational efficiency while under planning leads to reduced customer satisfaction and lost sales. The authors argue that an effective demand planning is essential to achieve the balance between satisfying customers and running an efficient and profitable business.
Reactive enablers and levers are reported in Table 1.7.

Table 1.7. Reactive agility enablers and levers

SCA enablers	SCA levers	Reference
Strategic flexibility	Increase/decrease production frequencies Reduce production lead time Prioritize production allocation Adapt the physical production capacity	(Boubaker, Jemai, et al., 2019b) (S. K. Sharma and Bhat, 2014) (Patel, Tiwari, et al., 2020) (Lee et al., 2020)
Strategic orientation	Virtual enterprising Alignment towards the objective Short-range planning, time compression	(Patel, Tiwari, et al., 2020) (Golgeci et al., 2019) (Al-Zabidi et al., 2021)
Demand management	Effective supply-demand plans Customer manipulation	(Collin and Lorenzin, 2006) (Al Humdan et al., 2020)

Despite enablers can be exclusively proactive or reactive, some of them might present both features depending on the timeliness of their application (Al Humdan et al., 2020). For example, a collaborative relationship can help to anticipate possible opportunities through proper information sharing, but also to reconfigure resources providing a response to disruptions (Al Humdan et al., 2020).
Collaboration refers to the bilateral and coordinated relationship of organisations

with their major business partners such as suppliers, manufacturers and distributors. Collaborative supply chains can share rules and ethical principles, achieving flexibility and competitive advantage by making required arrangements (Patel, Tiwari, et al., 2020). Boubaker, Jemai, et al. (2019b, p. 4) state that collaboration is a fundamental factor for agility and that SC firms should have an "optimization-oriented behaviour at the supply chain level, instead of the firm level".
In order to develop collaborative relationships, a proper system of information sharing must be adopted (Boubaker, Jemai, et al., 2019b). Abdallah and Ayoub (2020) affirm that information technology (IT) systems are the key for supply chains to be agile minimizing response time to customer needs, speeding up information flows, and enhancing collaboration and coordination. IT directly supports SCA enhancing companies' ability to sense and respond to market dynamics by improving accuracy, timeliness and accessibility of the information flow amongst members.
Moreover, Al Humdan et al. (2020) state that IT is required to activate most of reactive and proactive levers, recognising that enablers are interrelated. Indeed, it allows the early detection of internal and external variations improving reaction capabilities, but also the coordination and integration of procurement, manufacturing, logistics and distribution activities. An effective management of distribution channels allows to promptly adjust plans to substitute products, change priorities, satisfy clients' requirements (Boubaker, Jemai, et al., 2019b).
Independently from the type of operation, S. K. Sharma and Bhat (2014) affirm that the most important characteristic of an agile supply chain is the ability to reduce lead time, as it affects the SC dynamic response. Reducing decision, planning and information transfer horizons allow to make necessary actions both proactively and reactively (Boubaker, Jemai, et al., 2019b).
Enablers and levers that share proactive and reactive features are shown in Table 1.8.

Table 1.8. Proactive and reactive agility enablers and levers

SCA enablers	SCA levers	Reference
Collaborative relationship	Share risk information with partners Synchronize activities with partners Develop end-to-end visibility Integration of competencies with partners Selection of suppliers with agile capabilities	(Boubaker, Jemai, et al., 2019b) (Gunasekaran et al., 2019) (Patel, Tiwari, et al., 2020) (Piya et al., 2020)
Supporting information technology	Reduce information transmission time IT systems for decision support Early disturbances detection Digitalization of demand information Inter-organization information systems	(Erhun et al., 2020) (Gunasekaran et al., 2019) (Piya et al., 2020)
Logistics and distribution capabilities	Reduce planning horizons Vary supply and distribution frequencies Decrease distribution lead time Flexibility in logistics and transportation Change distribution allocation policies	(S. K. Sharma and Bhat, 2014) (Piya et al., 2020)

In the following chapters, levers related to the physical flow of the SC will be applied as proactive and reactive instruments to counteract situations needing agility.

Some authors have pointed out that the achievement of SCA might also be hindered by obstacles, defined barriers. The next section is dedicated to the description of these factors.

1.4.3 Agility barriers and performance implications

In previous sections it has been listed a series of situations that require the development of agile responses and a series of technical means that can help reaching agility targets. Nonetheless, the achievement of SCA may be hindered by different factors, commonly defined in literature as agility barriers. The identification of these obstacles helps improving the weaker areas of supply chains and the overall agility level.
Sindhwani et al. (2019) investigated barriers at an organizational level. They recognised that several factors deter the adoption of agile practices. For example, financial constraints, lack of managerial commitment or fear to change can prevent the development of proactive or reactive attitudes.
Commitment of top management is considered essential to adopt agile organizational policies and undertake internal changes. By investing in workforce training, appropriate tools, processes and technology that can enhance the communication with customers and suppliers, organizations can improve their agility. Oppositely, the inability to measure the cooperation quality with suppliers, the lack of collaborative relationships, technological inadequacies and the fear of financial, competitive losses in adopting SCA can obstacle such practices (Zhukov et al., 2019).
Technological and managerial orientations have been associated to information sharing capabilities. Centobelli et al. (2020) report that two major obstacles to gain agility are inappropriate technological systems and poor information flows. They affirm that technology issues are a consequence of managerial and leadership gaps, such as the lack of measures and methodologies to justify investments in advanced manufacturing technologies or poor partnership management.
The recent COVID-19's outbreak has highlighted the importance of adequate information sharing systems, and several authors have long recognised that agile supply chains must leverage data sharing to counteract supply-demand imbalances.
As instance, Bal et al. (1999) affirmed that organizations need to transmit value, demand, cost and supply information with sufficient detail and timeliness to avoid instability, which is intrinsic of the SC context. They state that the success of a SC depends on its ability to intercept and respond clearly and promptly to upstream and downstream information flows.
When members of a SC share information, no new information is created but only existing data move along the network (F. Chen, 2003). Therefore, managers should exploit and take advantage of technology to enhance collaboration, which requires on-time sharing of information between buyers and suppliers (Al Humdan et al., 2020). Sharing relevant, complete and confidential information contributes to enhance visibility in terms of inventory and demand, improving the overall level of SCA (Dubey, Altay, et al., 2018). The ability to share information across the SC minimises waste, and positively influences networks' performance (Yusuf et al., 2020).
The impact of agility on networks' performance has been widely investigated in literature. Scholars focused on the research of its effects on different performance indicators, from operational references (lead time reduction, service and quality improvement,

etc.) to strategic metrics, such as competitiveness and profitability.
Al Humdan et al. (2020) investigated how SCA have been associated to performance in a systemic literature review. They recognised that agility has often been positively or directly coupled with performance improvement.
In their study agility is addressed as a competitive mean that has a positive influence on cost, operational and business performance. The authors report that in literature the benefits of SCA have been mainly examined quantifying financial measures. For example, (Tse et al., 2016) analyses the impact of SCA on the financial performance of a Chinese electronic company, showing that it has a positive effect in terms of sales growth, return on investment, return on sales and profitability.
Similarly, Tseng and Lin (2011) argues that agile networks are cost-efficient, as the adoption of agile strategies has potential advantages for businesses including reacting rapidly and efficiently to satisfy market requirements.
By contrast, some authors have highlighted that SCA may also not influence organizational performance (Al Humdan et al., 2020). Gyarmathy et al. (2020) claims that agility does not fit with all the kind of product supply chains. They affirm that standardised products with long life-cycles, stable and predictable demand should be matched with lean management to achieve better SC results, while agile practices might be only marginally impacting. On the other hand, innovative products are usually subject to many variations, their life-cycle is short and demand is uncertain, therefore more suitable to agile management.
Nonetheless, they recognise that to sustain competitive advantage and higher profits companies should continuously innovate, investing in responsive and agile processes throughout the SC. Agile supply chains can respond quickly to unpredictable demand by deploying buffer stocks, reducing lead time and postponing product differentiation, increasing the overall performance (Gyarmathy et al., 2020).
In the end, SCA has been investigated also in its relationship with sustainable performance. Yusuf et al. (2020) argues that suppliers' decisions have an impact on environmental and social sustainability. The over-consumption of materials, energy and natural resources to protect against disruption and satisfy customer requirements influences the carbon footprint of the network, but also working conditions, fair treatment of customers, the social investment at communities where suppliers operate, the health and safety of workers.
Performing an investigation on the UK manufacturing industry SC, the authors show that there is a significant correlation between sustainability and agile practices. They argue that the higher the implementation of sustainable activities, the greater SCA is reached. In addition, their results show that agile capabilities have positive and significant effect on sustainability and operational performance.
The adoption of advanced technology can facilitate the reduction of social and environmental impacts, helping in identifying ways to eliminate waste and minimise resources consumption. Indeed, customer desires can be anticipated exploiting the market-sensing capabilities of an agile organisation, which can leverage on this understanding and on information technology to improve sustainability by creating ad hoc networks that maximize returns (Yusuf et al., 2020).

1.5 Conclusions

The aim of this chapter is to provide a framework of supply chain agility, inserting its concept among other SC-paradigms and giving a conceptualisation of its elements.
Researchers have provided a wide body of knowledge that offers insights about to the importance of agility in supply networks and on the variety and heterogeneity of situations that require agile attributes (Boubaker, Jemai, et al., 2019a).
In order to clarify its concept it is provided an indication of what is agility, which are its drivers and how an organization could improve it.
Authors have addressed it as a target-oriented feature, which can be developed to face the internal and external pressures that may affect a SC. Indeed, the need of agile capabilities derives from the changes in the business environment, and agility drivers represent the factors that push organizations towards their implementation. In order to mitigate the effects of changes that could lower the performance of the SC, a set of technical and managerial means can be deployed. They have been addressed as agility levers, and are classified in exclusively proactive, exclusively reactive, both proactive and reactive. Reactive levers can be deployed after the occurring of a situation needing agility, while proactive are aimed to anticipate a situation that is foreseen for upcoming periods (Al Humdan et al., 2020).
The investigation of barriers and performance implications has allowed to understand the role of information sharing in reaching agility, and the position of academics about the impact of SCA on financial performance. Even if this latter is considered the organizations' ultimate goal (Al Humdan et al., 2020), it is highlighted that agility is related also to non-financial issues such as flexibility, quality, partners' relations.
An agile SC can be considered as a supply/demand network that regards different business entities, which can cooperate into a competitive and dynamic market environment (Zhu et al., 2021). Agility allows to respond or anticipate internal or external changes by deploying a series of technologies, methods, tools, and techniques.
Some authors perceive it as a vehicle to gain competitive advantage, while others specify that the adoption of agile practices should depend on the operative and economic context of networks. Therefore, managers should analyse the business scenario of their supply chains and apply agility levers to improve performance if necessary.
The elements presented in this chapter constitute a theoretical basis for the agility evaluation model presented in chapters 3 and 4. It is aimed to calculate specific KPIs to determine SCA level of networks, giving indications of how close a network is to reach a targeted performance and which are the more suitable levers to face considered situations needing agility.
Different studies have attempted to assess an organization's agility in order to help decision makers better achieve sustainable agile supply chain (Al-Zabidi et al., 2021). Nonetheless, some authors argue that the existing literature on the maximization of agility is insufficient to address the complexity of this concept (Patel, Samuel, et al., 2020), and that the commonly implemented SCA measurements are fragmented (Al Humdan et al., 2020). For these reasons, the next chapter is dedicated to the investigation of methodologies and metrics adopted by scholars to measure agility levels, investigating the current state of the art.

Chapter 2

State of the art

2.1 Systemic literature review

In Chapter 1 it is presented a conceptualization of SCA, listing situations that push supply chains toward the adoption of agile practices and technical means that can help networks in reaching the desired level of agility. However, it has not been examined how scholars addressed the issue of measuring such level.
Researchers have proposed different models and approaches for assessing agility in supply chains. (AlKahtani et al., 2019; Boubaker, 2019; Galankashi et al., 2019; Hernández and Pedroza-Gutiérrez, 2019; Patel, Samuel, et al., 2020; Al-Zabidi et al., 2021) present literature reviews on SCA assessment methods, and all of them report that scholars have mainly focused on qualitative-based techniques. For example, in (Al-Zabidi et al., 2021) it is argued that several researchers evaluated SC's performance statistically by integrating questionnaire data and subjective approach, ranking agility enablers collected from business professionals.
In order to guarantee more objectivity, fuzzy-logic approaches have been exploited to transform linguistic valuation of attributes into numerical objects, then mathematically treated to obtain global assessments of SCA (Hernández and Pedroza-Gutiérrez, 2019). These methods are suitable for dealing with multidimensional concepts as SCA, even if the metric obtained is based on experts' subjective evaluations (Hernández and Pedroza-Gutiérrez, 2019). Indeed, they mainly measure conceptual elements related to agility such as enablers and attributes, dynamic capabilities.
On the other hand, a few quantitative techniques have been deployed to assess the agility level of networks, and they have been mainly related to the calculation of average supply path length and the total orders delay time (Hernández and Pedroza-Gutiérrez, 2019).
The aim of this chapter is to investigate how authors dealt with agility measurements in recent years, inquiring to methodologies and metrics.
Since no reviews on articles published between 2019 and 2021 have been found in literature, it represents a contribution to update the current state of the art.
In order to identify new proposed methods for the calculation of networks' agility, it has been chosen to execute a systemic literature review focused on articles published between the beginning of 2019 and April 2021, in English. Its integration with bibliographical reviews performed in past years permits to obtain the picture of agility

assessment methods appeared in literature.
It has been performed using SCOPUS, a database of peer-reviewed articles made available by Politecnico di Milano that allowed a research for relevant articles through keywords and keyword-search strings.
The research has been based on a basic string of keywords to which specific terms were added in order to focus on the objective. The basic research string has been developed accounting three issues (Al Humdan et al., 2020):

- Some scholars address SCA as "supply chain agility", others report "agile supply chain".
- Some articles investigate agile practices in relation with leanness, using the terms "leagility" and "leagile".
- Some articles use the term "chain", others "chains".

Therefore, in order to not miss relevant information the basic research string has been set to “supply chain agility” OR “agile supply chain*” OR “supply chain leagility” OR “leagile supply chain*”.
This string has been then oriented towards the objective of the review using specific terms related to the SCA assessment. Relevant keywords have been extracted by the empirical study (AlKahtani et al., 2019) on SCA assessment methods. They are "Framework", "Metric", "Assessment", "Measure*", "Model*" and "Method*".
As a result, a large number of articles coming from these six different searches were found and a three-level filtering process has been applied to each string in order to select the most suitable ones (Al Humdan et al., 2020):

1. First level filter: articles are assessed through the orientation of their titles towards the objective. If a title contains limited or ambiguous information to judge the article’s relevance, it is included.
2. Second level filter: articles are evaluated through the information in their abstracts, again with an inclusive orientation.
3. Third level filter: remaining articles are analysed to understand if their content is aligned with the aim of the research. If not, they are not considered in the review.

At the end, duplications were eliminated and a backward snowballing approach was conducted from reference lists to include relevant papers not covered by the database. A total of 479 articles was made available by the database and after the filtering process 50 of them resulted eligible to be considered. Figure 2.1 illustrates the search and selection process adopted to perform the systemic review.
Next sections focus on the investigation of qualitative and quantitative methodologies and metrics used to assess the SC agility level of a network, updating the current state of the art. First, it is presented an overview of these methods, explaining their characteristics and mechanism. Next, an analysis of the literature is provided, reporting the main results observed.

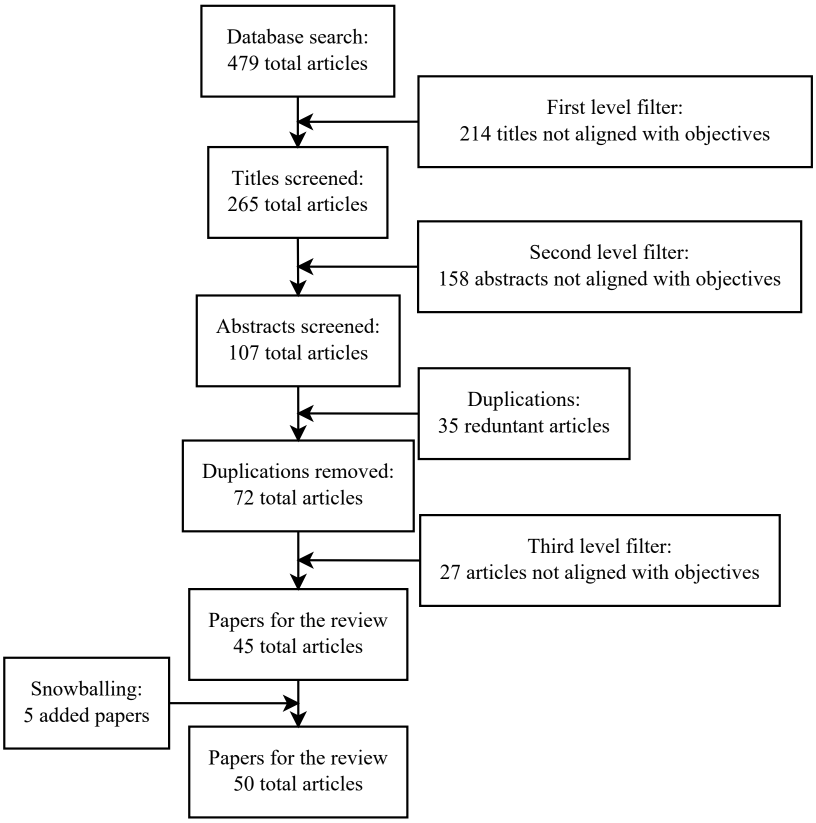

Figure 2.1. Systemic literature review process

2.2 Supply chain agility assessment methods

To assess the agility level of supply chains, researchers adopted multiple approaches. (Hernández and Pedroza-Gutiérrez, 2019) reports that three methodologies have been commonly exploited to assess SCA in literature: scale development processes, where a sample of items founded on theory are empirically validated by means of surveys; fuzzy logic methods, that transform linguistic valuation of certain attributes into numerical objects; mathematical models based on the evaluation of agile criteria.
In the following sections, assessment methods are grouped in two main categories. The first one regards qualitative techniques, which exploit experts' knowledge to measure the implementation's degree of agility capabilities. On the other hand, the second category includes quantitative methodologies based on mathematical models and the calculation of specific metrics related to agility.

2.2.1 Qualitative assessment methods

In the present literature review, 36% of the papers analysed evaluate SCA statistically through scale development processes based on questionnaire and interview data collection approaches. E-mail, telephonic and Google-forms interviews have been exploited to gather information from CEOs, presidents, directors, managers, supervisors or academics related to SC and operation management.
Their opinions are used in pre-processing phases to assess the content validity of

questionnaires and to define which SC attributes impact the agility level of samples under study. Indeed, these evaluation models have been mainly used to identify trends and factors of the SC that can have an impact on its agility.
They are theoretical studies based on large samples of analysis, focused on the individuation of actions that may enhance agility rather than on the measurement of its level. For example, Kareem and Kummitha (2020) investigated agile attributes of 235 manufacturing companies in Hungary, Irfan et al. (2019) inquired enablers of 175 industries in Pakistan, Nath and Agrawal (2020) studied SCA of Indian companies having a minimum annual turnover.
Items related to agility and scales of measurement to determine the intensity of their effects are generally established through literature reviews, then adjusted to the population under study through the help of practitioners and scholars.
In the articles analysed, SCA has been mainly related to the ability of satisfying customer preferences (C.-J. Chen, 2019; Dubey, Gunasekaran, et al., 2019; Ehtesham Rasi et al., 2019; Fadaki et al., 2019; D. Gligor, Holcomb, Maloni, et al., 2019; Çankaya, 2020), promptly detect changes in the business environment (Dubey, Gunasekaran, et al., 2019; Ehtesham Rasi et al., 2019; Feizabadi et al., 2019; D. Gligor, Holcomb, Maloni, et al., 2019; Nath and Agrawal, 2020), adjust operational parameters to enhance responsiveness (C.-J. Chen, 2019; Fadaki et al., 2019; Irfan et al., 2019; Moyano-Fuentes et al., 2019; Sanchez et al., 2019; Çankaya, 2020; Kareem and Kummitha, 2020; Yusuf et al., 2020), and improve IT systems for partners' collaboration and integration (C.-J. Chen, 2019; Dubey, Gunasekaran, et al., 2019; Wamba and Akter, 2019; Ahmed, 2021).
These approaches are based on subjective evaluations and define agility levels as a reflection of the implementation of agile attributes, determining "high-agility" or "low-agility" organizations (Sanchez et al., 2019, p. 608).
The implementation degree of each agile attribute is generally assessed through questionnaires with 5 or 7 points Linkert scale of measurement, and their average represents the agility level of the network. For instance, Rasyidi and Kusumastuti (2020) estimate the agility of an Indonesian humanitarian SC through experts subjective evaluations. They define agility as a reflection of flexibility, responsiveness and effectiveness, and relate these three elements to organizational capabilities that can be measured (e.g, effectiveness is associated to the percentage of demand filled in a time frame). Experts are asked to rate the level of implementation of the metrics in their SC according to a scale, and the aggregate score represents the level of SCA.
Experts' evaluations have been also integrated with multi-criteria decision making (MCDM) methods to measure agility. These can be distinguished in multi-objective decision making (MODM) and multi-attribute decision making (MADM) techniques (Divsalar et al., 2020). The former refers to problems with continuous decision variables and infinite number of alternatives, while the latter deals with problems containing discrete decision variables and finite number of alternatives.
Solving decision-making problems via MADM methods requires decision information, which is aggregated using different approaches in order to rank alternatives and determine the most satisfactory one among them.
Analytical hierarchy processes, structural modelling and fuzzy analysis are multi-decision methods to assess SCA computing agility indexes (AlKahtani et al., 2019). 10% of the analysed papers exploits an Analytic Hierarchy Process (AHP).

It is a pairwise comparison technique that measures the relative impact of a set of factors on specific outcomes, providing relevant information while improving the consistency of the decision-making process (Patel, Samuel, et al., 2020).
In AHP the problem target, selection criteria, and alternatives are first assessed. This allows to create a hierarchy of the problem, where the goal is at the highest level, criteria at second one and the alternatives at the last one. Questionnaires are exploited to gather empirical information based on judgments of experts and academics, and pairwise comparisons of criteria and alternatives are performed to determine the ones of primary importance to reach the target (Patel, Tiwari, et al., 2020).
As instance, Figure 2.2 shows the framework used in (Patel, Tiwari, et al., 2020) to prioritize agility enablers using the AHP methodology.

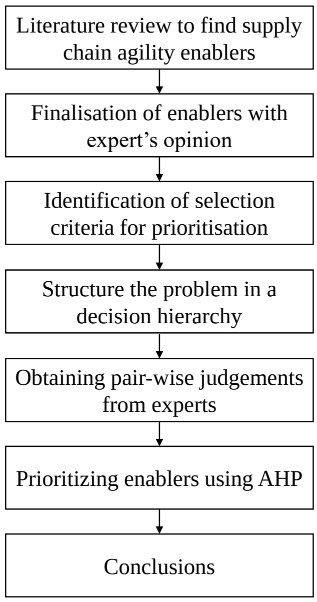

Figure 2.2. Analytic hierarchy process framework (Patel, Tiwari, et al., 2020, p. 8)

(Galankashi et al., 2019; Patel, Tiwari, et al., 2020) exploit this technique to determine the most influencing activities on agility of manufacturing industries.
Their results indicate that operations related to information sharing, customer satisfaction, flexibility and contracting activities are fundamental to improve agility levels. Zhukov et al. (2019) focus on the determination of the most influencing barriers in multinational companies. They used expert's evaluations to determine the agility level of each company considered (indicated as "high-level" or "low-level"), and then a hierarchical process to observe the most limiting factors. (Petrovic and Mimovic, 2019) uses AHP to determine indicators that enhance the SCA level when choosing suppliers, addressing on-time delivery as the critical metric to assess agility.
Patel, Samuel, et al. (2020) developed a model to maximize SCA by exploiting the appropriate input resources available to the network. Considering that the agility of a SC depends on how the system deploys its input resources, their optimum deployment provides maximum agility. Therefore, they combined AHP to a goal-programming approach, which is a methodology that deals with the problem of making a decision while balancing a set of conflicting goals. As a results, their hybrid model shows the required level of implementation of each enabler so that the targeted agility degree is

achieved within the available inputs.
Another MCDM technique to determine SCA levels is the Interpretative Structural Modeling (ISM). Similarly to the hierarchical process, influencing factors of a phenomenon are identified and the relationships between them and targets are analysed at different levels.
Designing an ISM is a way to examine the effect of each variable on other variables, defining a framework to achieve objectives (Jamshidiantehrani et al., 2020). It is generally combined with matrix impact cross-reference multiplication applied to classification (MICMAC) analyses, which involve the development of a graph to classify factors based on their driving and dependence power.
Among the papers considered, 12% of them exploited an ISM methodology to determine attributes that enhance SCA. (Wankhade and Kundu, 2020) investigates the key attributes to design an efficient automotive after-market SC, defining agility through effective risk management, adaptability, organizational and SC performance. Similarly, (Rahimi, Raad, Tabriz, et al., 2019) explores factors that could enhance SCA of defence industries, while (Piya et al., 2020) focuses on oil and gas supply chains investigating actions that can help monitoring and managing their agility. They recognise that to improve agility levels companies should concentrate on customer satisfaction, top management commitment, operational efficiency, suppliers relationships and coordination.
Despite the different research targets, these models follow the same structure. First, factors that could have an impact on the chosen target are identified through questionnaires and expert's evaluations, brainstorming. Then, contextual relationships between them are evaluated qualitatively through a structural self-interaction matrix, which helps understanding how to reach specific attributes through the interaction of the considered factors. In the end, to each attribute is assigned a level and the driving-dependence power matrix is built, showing the level of influences of structures and their power of dependence.
Since the functional relationship between agile attributes is based on specialist's qualitative evaluations, it may be difficult to define it objectively. For this reason, researchers adopted also fuzzy logics to assess network's agility levels, which allow to represent and process vague data to result in objective information.
Fuzzy approaches are adopted in research fields where there is necessity for processing imprecise or empirical information (Theagarajan and Manohar, 2019). A fuzzy set provides not only information on the relationships of some factors to the target but also their membership grade, expressing it in indexes varying between 0 and 1.
22% of papers analysed in this literature review exploit fuzzy logics to determine agility levels. For example, in (Shamout, 2020) a fuzzy sets qualitative analysis is used to assess the impact of data analysis combined with firm age, size and annual sales on SCA levels. Through questionnaires based on 5 point Linkert scales, authors gathered information regarding the relationship of attributes and agility, and then translated them to fuzzy numbers to explore their degree of membership.
Similarly, fuzzy index-based methods have been used in (Theagarajan and Manohar, 2019) to assess the impact of ninety-five attributes on agility of the SC Indian footwear industry, and in (Bathaei et al., 2019) to rank agility factors in Iranian diary companies.
(Hendalianpour et al., 2019) applied another MADM method defined Interval-Valued

Fuzzy-Rough Numbers Best Worst Method (IVFRN-BMW). Authors identified and weighted indicators affecting SCA of an automotive industry, and then measured their impact on the minimization of production line interruptions, complaints on supplied parts, defective parts, overall costs and maximization of on-time deliveries through a goal-programming model.

Rehman et al. (2020) identified four agile capabilities (responsiveness, competency, flexibility and quickness) related to six agility enablers and seventy-eight agile attributes of Saudi manufacturing organizations. They defined a valuation scale demarcated using fuzzy logic through linguistic translation and calculated the fuzzy weight of each attribute. These latter were then used to calculate the weight of each enabler and the overall SC agility fuzzy index, which was matched with linguistic term defining the SCA level from "extremely agile" to "slowly agile". Figure 2.3 shows this methodology.

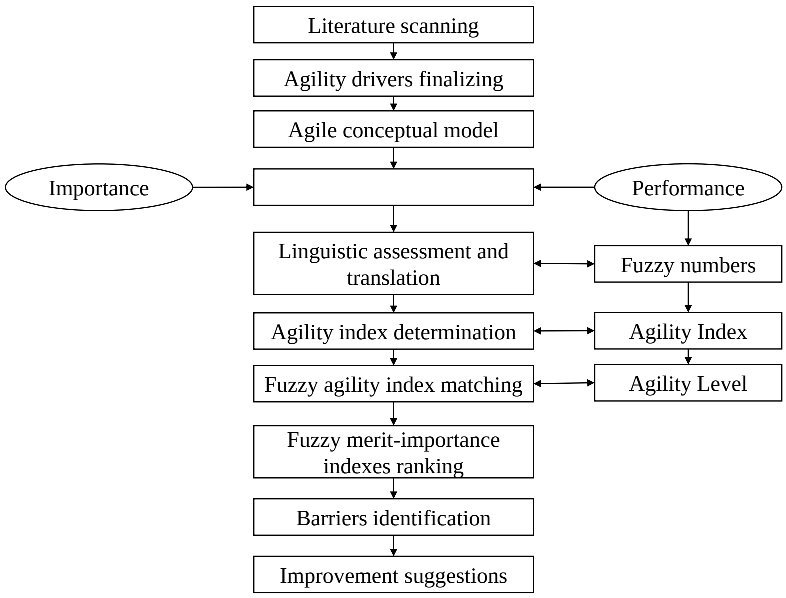

Figure 2.3. Fuzzy-index agility evaluation framework (Rehman et al., 2020, p. 6)

As the determination of these indexes could be time consuming for industrial experts, the authors developed a decision-supporting tool. It allows decision-makers to assess SCA directly inserting their subjective evaluation of enablers and attributes as input of the system, indicating barriers and the overall agility level of their SC as outputs.

Some authors used MADM and fuzzy-logic techniques to determine SCA enhancing practices referring to the Supply Chain Operation Reference (SCOR) system.

It is a reference model developed by the Supply Chain Council which provides a framework of standard processes, performance metrics, management and technology practices to manage the business activities associated with all phases of customer demand satisfaction (APICS, 2017).

This model considers agility a performance attribute that can be measured through several metrics related to adaptability and overall value at risk, and researchers used it to analyse different types of supply chains.

For example, Anas et al. (2019) exploit expert's opinions to understand the most important SCOR agile criteria of the hospital SC. Through a fuzzy AHP model they

find the weight of each criterium, and apply a best-worst method to rank them all. (Divsalar et al., 2020; Kiriş et al., 2019) use fuzzy Decision Making Trial and Evaluation Laboratory (DEMATEL) to analyse and reveal the causal relationships among SCOR performance metrics when dealing with lean-agile and environmental aspects of supply chains, prioritizing them according to their level of influence. (Jamshidiantehrani et al., 2020) exploit a fuzzy ISM-MICMAC methodology to prioritize SCOR agile criteria in a pharmaceutical company and select best suppliers. In (Kusrini et al., 2019) experts' evaluations are used to understand the most suitable SCOR attributes to assess the performance of a small-medium enterprise in Indonesia.
Besides the MADM methods presented, other qualitative assessment techniques have been found in literature. For example, Boubaker, Jemai, et al. (2019a) proposed the matrix shown in Figure 2.4 that helps in evaluating SCA by identifying the most critical SNA, the current implementation level of each agility lever and the ones that need to be improved to respond to such situations. It is aimed to give an indication of which agility levers could counteract the most severe SNA and show their required degree of implementation, helping managers improving the agility of their networks.

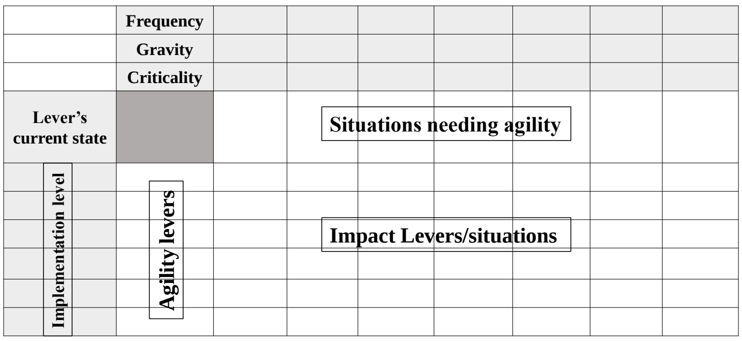

Figure 2.4. Supply chain agility matrix (Boubaker, Jemai, et al., 2019a)

The frequency and gravity of situations needing agility and the level of implementation of levers are assessed through specialists' opinions on a scale ranging from 0 to 3. Also the impact of lever on a situation needing agility is assessed from 0 to 3, where 0 means that it has no impact at all while 3 indicates that the activation of a lever allows to respond directly to it. The criticality of a situation is calculated multiplying its frequency and gravity, and it is used to prioritize the actions to be taken.
Other authors developed theoretical frameworks to highlight the most important factors that should be considered to improve agility, such as the ones presented in (Sharifi and Z. Zhang, 1999; Lin et al., 2006; X. Li et al., 2008).
Zhu et al. (2021) propose a SC framework called EDGE (Enablers, Drivers, Goals and Expertise) that considers the relationship between agility drivers, enablers and decision-making processes. It integrates agility and supply chain management concepts in order to achieve specific SC goals. It is presented in Figure 2.5. The aim of this framework is to build a structured approach for developing agile supply chains. Authors argue that practitioners should understand their SC context-specific agility drivers, exploit their know-how and enhance their agility level focusing on the proposed factors. By aligning organizations toward targets and enhancing sensing and responding abilities to customer and changes, organizations can meet their goals.

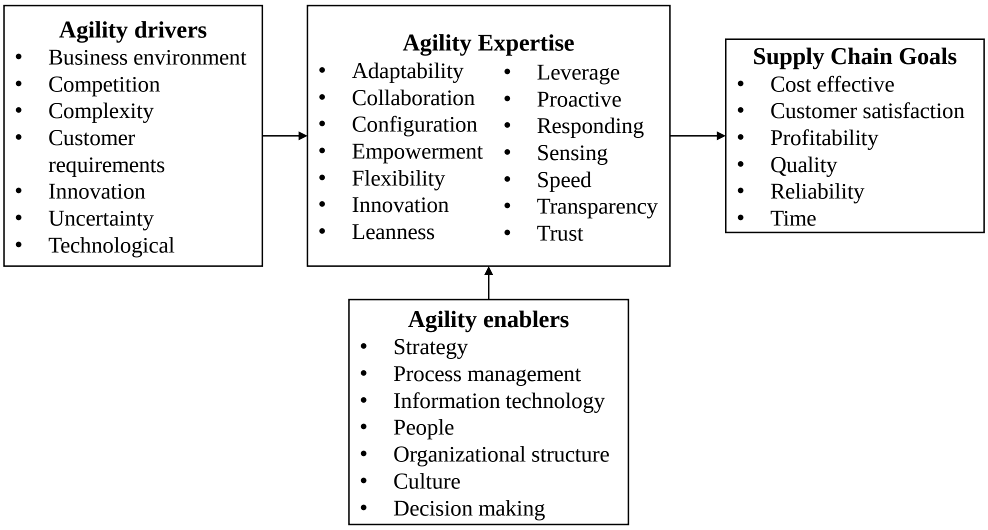

Figure 2.5. EDGE supply chain agility framework (Zhu et al., 2021, p. 13)

The models presented in this section are all based on qualitative evaluations made by experts, and assess the agility of a SC as a reflection of the implementation of agile attributes and capabilities.
In order to avoid the subjectivity that characterizes these techniques, some authors focused on the assessment of agility through quantitative evaluations. The next section is dedicated to the review of such methods, inquiring both on metrics and procedures.

2.2.2 Quantitative assessment methods

Hernández and Pedroza-Gutiérrez (2019) performed a bibliographical review to understand the quantitative agility assessment metrics employed in literature.
They recognised that some researchers have related SCA to the supply path length: since delays in receiving, processing and delivering activities are common in supply chains, a low average supply path length means that the material passes through few actors, reducing the total delay and increasing agility.
(Babaeinesami et al., 2020) adopts this metric to build a model able to address lean and agile closed loop SC. Authors apply a MODM optimization method to reduce the queue congestion of the system, shipment time and related costs by taking into consideration alternative routes and service-level constraints. A data-driven model is developed and location-allocation decisions are determined based on the proximity to local clients, in order to increase the service level and agility of the SC system.
Nonetheless, the average path length does not consider the impact of demand and supply variations, nor the recovery time against disruptions. Therefore, researchers used also other metrics to assess the SCA level, such as the time to complete and distribute products (Hernández and Pedroza-Gutiérrez, 2019).
In (Moradi et al., 2019) authors adopt a multi-objective optimization technique to design a multi-period, multi-product agile SC network with conflicting goals. The minimization of total costs, minimization of products delivery time, maximization of facilities' flexibility and process, information integration among echelons of the chain are addressed as main targets of an agile network.

Also (Dotoli and Epicoco, 2020) presents a model for designing SC networks under uncertainties. It provides an agile and resource-efficient design of the SC considering candidate selection, order allocation and transportation mode selection problems.
Authors apply a Data Envelopment Analysis (DEA) technique to rank the candidates of each SC's stage considering total procurement costs, total delivery, service level, transportation modes and their environmental impact. The assessment of supplier's performance and the corresponding ordered quantity is performed by trading off the overall potential SC efficiency, procurement costs, and delivery times accounting capacity and stock levels.
Most of the papers analysed relate agile capabilities to customer requirements satisfaction, and therefore consider demand variations as SNA to be mitigated while designing the network.
For example, (Rabbani et al., 2021) proposes a multi-objective optimization model to design a SC network where the variability of demand is answered by offering appropriate service levels while minimizing total costs. Authors develop a two-phase model with two different procurement plans. Initially demands data is assumed possibilistic and acquired by prediction, and authors define a function aimed to determine optimal outsource and production quantity, balancing the expectations of the customer, quality and price of products. Then, demand is assumed to become crisp and agility is related to the system's responsiveness, considering the penalty fees resulting by failing the meet of customer requirements.
Another metric related to SC response abilities to customers is the order fulfilment rate, defined as the percentage of fulfilled demand over the total demand issued in a specific time span.
Hernández and Pedroza-Gutiérrez (2019) develop a model based on the topology of networks that takes into account this metric to determine the highest level of SCA.
They build a simulation model to analyse SC partners relationships that leads to best agility levels focusing on food supply chains. The model considers a multi-agents three-level network including suppliers, wholesalers and retailers, and considers the interdependences among them. It is composed by a set of nodes and links, representing respectively the firms and their relationships.
Every node in suppliers and wholesalers levels have a constant capacity, defined as the maximum volume of product that the node can distribute in a certain unit of time. Agility is assessed by considering different levels of distribution among actors in upstream tiers. Figure 2.6 shows this representation.

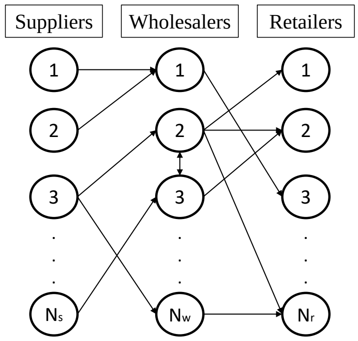

Figure 2.6. Topological representation (Hernández and Pedroza-Gutiérrez, 2019, p. 8)

SCA is measured through the response capabilities of the system, by calculating the order fulfilment of demand variations and the recovery time of this rate to previous values. They consider only sudden shocks in demand happening at a fixed time, and calculate the order fulfilment rate before and after the disruption.
Despite this model offers insights about managerial implications through simulations, it suffers of some limitations. As instance, costs are not considered and only demand changes are supposed to affect the SC, without considering the effect of supply shocks. In addition, inventory levels and delivery times are not modelled.
In the end, (Vlahakis et al., 2020) presents a model for facilitating managers in purchasing processes that considers SC's internal and external threats.
Authors propose a method to select suppliers and monitor events to improve decision making, focusing on the determination of proactive ways that can ensure effectiveness while minimizing costs. This framework is shown in Figure 2.7.

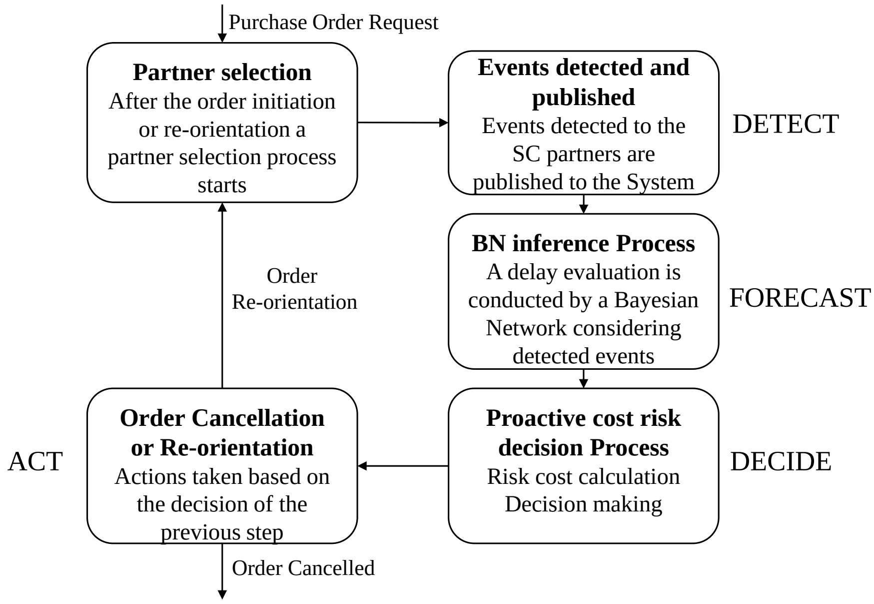

Figure 2.7. Proactive procurement framework (Vlahakis et al., 2020, p. 40)

The selection of suppliers is performed by taking into account unexpected events and potential reorientation or cancellation of orders. They are evaluated considering their reliability and costs. Undesired events (i.e. changes in planned resource availability, delays in deliveries, problems in orders' fulfilment, variations in quantities ordered) are detected and forecasts are used to assess their impact on the reliability of involved partners to fulfil a delivery in due time.
The decisional phase regards the implementation of actions aimed to minimize the forecasted impact of undesired events in a cost effective manner. Decision making is based on partners' risk costs evaluation, and proactive recommendations such as the selection of a new partner to deal with a specific order or the cancellation of the order are generated if the risk cost exceeds the expected limits.

2.3 Analysis of the literature review

The performed literature review has addressed articles published between January 2019 and April 2021. The outbreak of COVID-19 has led several authors to recognise in the lack of agility, responsiveness and resilience the main reasons why companies and supply chains have not been able to respond promptly to the sudden internal and external changes to which they have been exposed. Nonetheless, Figure 2.8 shows that only the 30% of the studies analysed related to the determination and improvement of SCA have been published after March 2020, when the World Health Organization officially declared the status of pandemic.

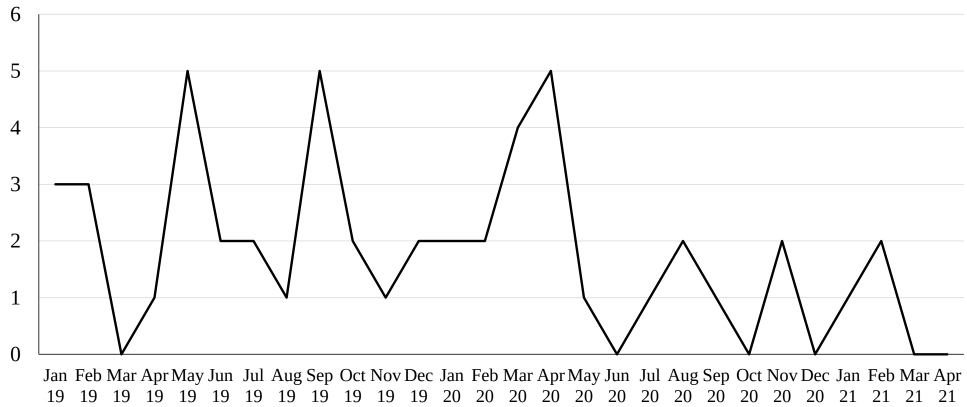

Figure 2.8. Publications in the area of SC agility assessment methods

Among the papers analysed, it is observed that 20% and 12% of them have been published by researchers affiliated to institutions from Iran and India respectively, followed by the 6% of China, France and Indonesia. Figure 2.9 reports the number of articles published for each country in the time range considered.

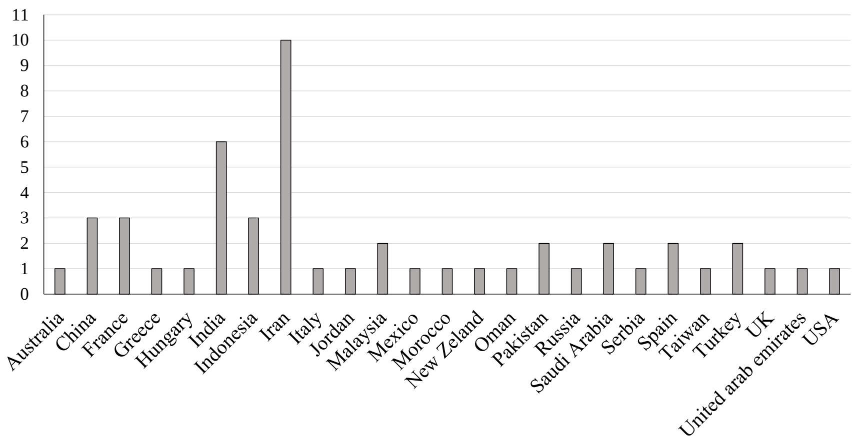

Figure 2.9. Country-wise distribution of the considered articles

To assess the agility of a supply chain, researcher have adopted models based on theoretical (T), empirical (E), real (R) or illustrative (I) studies.
Table 2.1 reports the methodologies and the type of study adopted in each paper.

Table 2.1. Type of studies to evaluate supply chain agility

Reference	**Method**	**Type**			
		T	I	E	R
(Ahmed et al., 2019)	Statistical analysis	X		X	
(Ahmed, 2021)	Statistical analysis	X		X	
(Al-Refaie et al., 2020)	ISM	X			X
(Al-Zabidi et al., 2021)	Fuzzy logic	X			X
(Anas et al., 2019)	Fuzzy AHP-BMW	X			
(Babaeinesami et al., 2020)	PMOPSO-MOSEO	X	X		
(Bathaei et al., 2019)	Fuzzy-ANP and VIKOR	X		X	
(Boubaker, Jemai, et al., 2019a)	Agility matrix	X			
(Çankaya, 2020)	Statistical analysis	X		X	
(C.-J. Chen, 2019)	Statistical analysis	X		X	
(Divsalar et al., 2020)	IVHF-DANP	X			X
(Dotoli and Epicoco, 2020)	Fuzzy DEA	X	X		
(Dubey, Gunasekaran, et al., 2019)	Statistical analysis	X		X	
(Ehtesham Rasi et al., 2019)	Statistical analysis	X		X	
(Fadaki et al., 2019)	Statistical analysis	X		X	
(Feizabadi et al., 2019)	Statistical analysis	X		X	
(Galankashi et al., 2019)	AHP	X			
(D. Gligor, Holcomb, Maloni, et al., 2019)	Statistical analysis	X		X	
(Hendalianpour et al., 2019)	IVFRN-BMW and Robust Goal Programming	X			X
(Hernández and Pedroza-Gutiérrez, 2019)	Network topology	X			X
(Ria Indriani et al., 2020)	DEA			X	
(Irfan et al., 2019)	Statistical analysis	X		X	
(Jamshidiantehrani et al., 2020)	ISM	X		X	
(Kareem and Kummitha, 2020)	Statistical analysis	X		X	
(Kiriş et al., 2019)	fuzzy DEMATEL	X			X
(Kusrini et al., 2019)	Statistical analysis				X
(Moyano-Fuentes et al., 2019)	Statistical analysis	X		X	
(Moradi et al., 2019)	PCA-MOPMIP	X	X		
(Nath and Agrawal, 2020)	Statistical analysis	X		X	
(Patel, Tiwari, et al., 2020)	AHP	X			X
(Patel, Samuel, et al., 2020)	AHP-GP	X			X
(Petrovic and Mimovic, 2019)	AHP-DEA	X		X	
(Piya et al., 2020)	Total-ISM	X		X	
(Rabbani et al., 2021)	Optimization model and RCFP	X			X
(Rahimi, Raad, Alamtabriz, et al., 2019)	ISM	X		X	
(Rahimi, Raad, Tabriz, et al., 2019)	SEM	X		X	
(Rasyidi and Kusumastuti, 2020)	Statistical analysis			X	
(Rehman et al., 2020)	Fuzzy decision-support system	X			X
(Sanchez et al., 2019)	Statistical analysis	X		X	
(Shamout, 2020)	fsQCA			X	
(Sindhwani et al., 2019)	Total ISM-MICMAC	X		X	
(Soltaninezhad et al., 2021)	Grounded Theory-SEM	X		X	
(Theagarajan and Manohar, 2019)	fuzzy QFD	X		X	
(Vlahakis et al., 2020)	Simulation model	X	X		
(Wamba and Akter, 2019)	Statistical analysis	X		X	
(Wankhade and Kundu, 2020)	ISM-MICMAC	X		X	
(Yao and L. Li, 2019)	Complex Network theory	X	X		
(Yusuf et al., 2020)	Statistical analysis	X		X	
(Zhu et al., 2021)	Framework to assess agility	X			
(Zhukov et al., 2019)	AHP			X	

It is possible to observe that 90% of the papers considered presents theoretical assessment models or approaches to determine the agile performance of supply chains. In the meantime, some researchers focused on showing their efficacy via illustrative (10%), empirical (60%) and real (22%) case studies.
Illustrative and experimental examples have been mainly used to explain the functionality of quantitative approaches, while empirical studies have been widely exploited to determine the relationship between agile attributes and performance.
The majority of authors exploiting empirical techniques focused on developing and exploring agile capabilities of supply chains, testing models through scale development processes and specialist's evaluations then translated in mathematical distributions. Real case studies have been deployed either to demonstrate the applicability of quantitative models or to investigate agile performance through qualitative-based approaches. Qualitative-based techniques include researches where the implementation degree of some attributes and factors related to agility are determined through experts' subjective evaluations. On the other hand, quantitative models are based on mathematical and simulation methodologies aimed to calculate specific KPIs associated to agility without the need of subjective assessments.
Figure 2.10 reports that the majority of articles focused on qualitative techniques (84%), while only the 16% of them developed quantitative approaches. Among qualitative techniques, scale development processes and fuzzy-logics methods have been the most exploited ones, accounting respectively for the 36% and 22%.

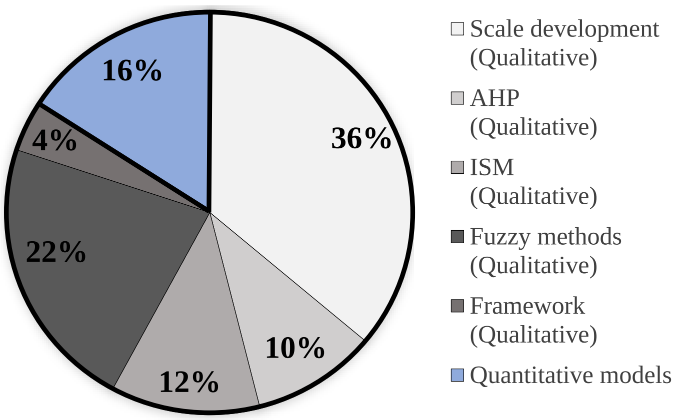

Figure 2.10. Methodologies to assess SC agility exploited in literature

Focusing of the quantitative assessment methods, it is noticed that 6 out of 8 of them address the issue of designing agile supply chains considering the selection of suppliers according to their agile capabilities.
In these papers agility is mostly associated to service levels and delivery times of suppliers, and costs are taken into account in the selection process. Therefore, potential agility levers are associated to the allocation of orders and the collaboration with suppliers that can maximize performance.
In (Ria Indriani et al., 2020) the focus is given to the determination of the agile performance of an existing supply chain, investigating the level of implementation of network's parameters with respect to a performance level targeted. Nonetheless, authors do not address the issue of improving the current performance but they limit to show which are the parameters that could be improved to reach the target.

In all these papers, agility is measured through metrics related to service levels, such as the order fulfilment rate, the delivery time and the time needed to recover a disruption. It is noticed that most of authors consider uncertainties in customer demand as the only situation needing agility that affect the system. Therefore, agile performance is associated to a the reactive capability to satisfy end customers requirements.
Only in (Babaeinesami et al., 2020) situations needing agility are related to routes or facilities disruptions, and authors apply queue systems and backup stores as levers to satisfy the retailers' demand.
Table 2.2 reports the targets and metrics adopted in the papers found in the literature review that present quantitative methods to address agility.

Table 2.2. Description of the quantitative models found in literature

Reference	**Description**
(Babaeinesami et al., 2020)	Design a closed loop SC considering proximity of suppliers, lot sizes, shortage and queue re-routing issues. Agility is related to responsiveness, service levels, costs under route and facility disruptions.
(Dotoli and Epicoco, 2020)	Design an agile SC network considering suppliers selection, order allocation, transportation modes issues under uncertain capacity and demand. Agility is related to the total delivery time and cost.
(Hernández and Pedroza-Gutiérrez, 2019)	Simulation and analysis of a food SC's topology to determine the configuration that maximizes agile performance. Agility is measured through the effect on order fulfilment rate and recovery time of a sudden demand shock.
(R. Indriani et al., 2019)	Data Envelopment Analysis is used to assess the agile performance of a food SC. Agility is related to delivery performance and order fulfilment rate.
(Moradi et al., 2019)	Design and optimization a SC network selecting suppliers to minimize costs, delivery time, maximize flexibility. Agility of suppliers is related to their delivery time, WIP level, product price.
(Rabbani et al., 2021)	Design and optimization of a leagile SC network considering a two-phase model where a reactive procurement plan is defined when demand changes. Agility is related to costs and service levels.
(Vlahakis et al., 2020)	Selection of reliable suppliers to handle unexpected events considering costs and on-time deliveries. Agility is related to the order fulfilment rate.
(Yao and L. Li, 2019)	Definition of a theoretical methodology to measure the performance of an agile supply chain exploiting the Complex Network Theory.

2.4 Conclusions

This chapter is dedicated to the description of the main methodologies and metrics to assess or improve the agility level of supply chains found in literature. It is based on research papers published between 2019 and April 2021 as no literature reviews were found concerning this period.
The systemic revision performed has highlighted that authors have addressed several aspects of SCA, and many of them focused on the investigation of attributes and capabilities that can enhance the responsiveness of networks.
Researchers have exploited both qualitative and quantitative methods, based respectively on experts' evaluations and mathematical models. Some of them focused on large samples of study, while others concentrated on specific networks.
Among the articles found in the review it emerged that mainly theoretical, empirical and real case studies have been considered in the literature related to agility of the past two years. Some authors presented theoretical models and approaches to assess specific performance metrics contributing to SCA, while others focused on the determination of the efficacy of these models through empirical demonstrations.
Real and empirical case studies focused on disparate types of industries, such as food, automotive, diary and fashion supply chains.
These models allow to understand how close networks are to become agile by aligning and integrating agility capabilities and drivers to gain competitive advantage. Several metrics were employed to this aim, most of which related to customer satisfaction (order fulfilment rate, responsiveness, etc.) and costs.
Although many concepts and methodologies for achieving agility have been identified, a tool able to deal with the heterogeneity of situations related to SCA presented in Chapter 1 has not been found neither in this literature review nor in the ones considering articles up to 2018.
Qualitative-based approaches provide insights on the potential ways to improve agility, but they can be criticized as they are mainly based on specialist's knowledge. Nonetheless, most of the articles considered in this literature review exploited qualitative evaluation approaches, while only 8 articles dealt with mathematical and quantitative assessment methods.
Dotoli and Epicoco (2020, p. 4537) state that "as SC networks become increasingly digitized and partners are connected with each other, there is a great deal of data that can be collected and analysed. Therefore, there is a strong need for mathematical models to measure SC networks performance and allow continuous improvement".
However, the models in the articles considered suffer of some limitations. For example, most of them dealt only with customer's demand variations, leaving aside disruptions in supply, inventory levels and time parameters characteristic of the SC. Some of them are built and applicable only to specific types of network, therefore their performance evaluations and metrics are not comparable to all organizations.
In the next chapter it is presented a mathematical model aimed to overcome these issues. It can be used to calculate the level of agility of a generic SC network composed of different operations, levels and agents considering a series of heterogeneous situations needing agility and levers. Therefore, it could be exploited by managers to assess the agile performance of their supply chains and analyse proper actions to improve it.

Chapter 3

Supply chain agility evaluation model

3.1 Introduction

Chapter 2 presents a literature review about the methodologies dedicated to the assessment of SCA. Although some approaches result in quantitative measurements, most of proposals estimate the level of agility through specialists and experts' qualitative evaluations of SC-attributes, then converted in mathematical distributions.
Due to the fragmentation and multidimensionality of SCA, different metrics are adopted to assess such level. Most of them are based on conceptual elements such as the implementation of agility enablers, dynamic capabilities, specific attributes.
Nonetheless, situations requiring agility and levers are heterogeneous and a holistic evaluation might not be comprehensive of all the aspects of SCA. In order to overcome this issue, KPIs need to be able of measuring quantitatively the agility of networks and a model that can embed the heterogeneity of situations must be designed.
The following Chapter is dedicated to the presentation and development of an instrument aimed to measure quantitatively the agility of networks. It is defined Supply Chain Agility Evaluation Model (SCAEM) and it has been proposed by the Supply Chain Chair of CentraleSupélec in (Boubaker, 2019).
Differently from methodologies presented in Chapter 2, SCAEM does not need qualitative evaluations. It is based on the simulation of the physical and informational flows along the SC in order to measure quantitatively the impact of changes on the network through appropriate KPIs.
Its objective is to determine the SCA level when situations requiring agility happen. The assessment of the agility degree of implementation in supply chains serves as an indicator of their strategic position (Patel, Samuel, et al., 2020). Indeed, to foster proactive and reactive capabilities networks should be aware of their agility level with respect to potential disruptions, and then decide which agility levers to implement. For this reason, the model should be able to measure the current SCA level as well as the one reached activating one or more levers.
SCAEM is based on three steps. First, required inputs are modelled. The SC configuration is built by defining the operations that characterize the network, their parameters and the inventory management policy adopted. In addition, through the analysis of the SC context potential threats and opportunities that need agile responses are identified, as well as available and appropriate agility levers.

Next, the agility metric to be measured is defined and simulations are performed to observe the behaviour of the system with respect to the SNA identified.
In the end, the metric is assessed and agility levers are applied to mitigate their impact on performance. Figure 3.1 shows this approach.

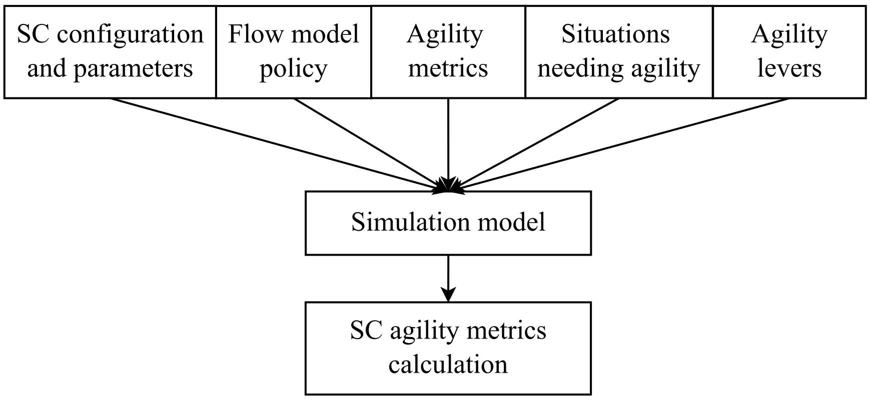

Figure 3.1. Supply chain agility evaluation model (adapted from (Boubaker, 2019))

The rest of this chapter is entirely dedicated to the development of SCAEM in order to create a tool that can be utilized by SC managers to take appropriate decisions when dealing with SC agility.
In order to avoid limitations on its applicability, this model has been designed to simulate the behaviour of open-loop SC networks characterized by several different operations. With respect to quantitative approaches proposed in Chapter 2, it can deal with multi-level supply chains without addressing only a specific SC structure.
As SCAEM is aimed to quantify the effects of situations needing agility on networks to understand whether they need agility improvements and the most appropriate levers to apply, a mathematical model has been developed to represent the information and material flows that characterize a supply chain.
These elements have been translated in the Visual Basic for Applications (VBA) coding language, which allowed the simulation of the SC flows. Besides, an interface between VBA and Microsoft Excel has been created to allow users to exploit SCAEM potentiality.
The remaining of this chapter is organized as follows: first, the KPIs used to assess SCA levels are described. Next, the configurations modelled to represent a generic SC are presented. Their combination allows to recreate networks' patterns, therefore to measure the agility level of specific supply chains.
Once defined these configurations it is shown how the information and material flows characterizing supply chains have been modelled, as well as the mathematical modelling of situation needing agility, agility metrics and levers.
In the end, it is described how the VBA simulation model has been developed, the input parameters needed and an illustrative case study to show its functioning and potentialities.

3.2 Agility metrics

The first step to assess the agility level of a SC is the definition and selection of appropriate KPIs to measure the impact of situations requiring agility on networks. Some researchers addressed the issue of calculating this level in relation to variations of final-customer's demand, therefore measuring agility through customer-related metrics such as the order fulfilment rate or the time to complete and distribute products (Hernández and Pedroza-Gutiérrez, 2019). Others based their models on the calculation of SCOR metrics.
Agility's key performance indicators presented in SCOR are related to "Upside Supply Chain Adaptability", "Downside Supply Chain Adaptability" and "Value-at-Risk". The first two metrics represent respectively the maximum sustainable percentage increase in quantity delivered that can be achieved in 30 days and the reduction in quantities ordered sustainable at 30 days prior to delivery with no inventory or cost penalties. Value-at-risk is a measure of an organization's exposure to supply chain risk events, and is defined as the sum of probability of risk events times the monetary impact of the events in several types of activities (APICS, 2017).
These metrics are aimed to measure agility when situations external to the SC happen, and address the effects generated by demand fluctuations. However, in Chapter 1 it has been highlighted that SCA is influenced by a set of heterogeneous situations and agility metrics should be able to measure the ability of networks to respond promptly and effectively to each of them.
In order to overcome this issue, in (Boubaker, 2019) authors propose two metrics that focus on effects and not on causes of situations needing agility, therefore attention is given to their implications rather than the type of situation considered. They are:

- Supply Chain Agility Response Metric (SCARM): time required to the SC to respond to an unforeseen situation needing agility and re-achieve the previous performance level.
- Supply Chain Agility Preparation Metric (SCAPM): time required to anticipate the occurrence of a situation needing agility so that it has no impact on the final customer.

Authors associate the agility of a SC to the ability of maintaining the standard performance level when a disruption occurs.
SCAPM regards the proactive capability to anticipate opportunities and threats by detecting in advance their upcoming and taking appropriate countermeasures to avoid the harm to final customers.
If situations requiring agility are sudden or cannot be detected with sufficient anticipation, the system should be able to promptly react in the most effectively manner to avoid or minimize performance reductions. SCARM is aimed to give an indication of the time needed to recover original performance levels after SNA have taken place.
Besides these two KPIs, the industrial partners of the Supply Chain Chair proposed the adoption of a parameter related to SC-resiliency. It has been defined:

- Supply Chain Resiliency Evaluation Metric (SCREM): time required to re-achieve the target inventory stock levels after a situation requiring agility has happened.

It is aimed to measure the time needed for the SC to fully recover from a situation needing agility in terms of reaching targeted inventory levels in order to be ready to face another threat. For example, if the final product demand of a SC sharply drops an agile network should be able to counteract in a timely manner the increase of stock that could be observed across it. On the other hand, a sudden increase of demand might be mitigated using available stock which has to be replenished in order to be ready to face a new disruption.
The agility of a SC depends on the configuration and characteristics of the network itself. Therefore, the representation of the SC configuration and its relevant parameters are necessary to calculate these three KPIs.

3.3 Supply chain configuration

Mentzer et al. (2001, p. 4) defined supply chains "a set of three or more entities (organizations or individuals) directly involved in the upstream and downstream flows of products, services, finances, and/or information from a source to a customer".
In other words, a SC is a network that embeds both multiple firms and the ultimate customer, presenting a certain degree of complexity depending on the actors involved. A SC could be composed only of a company, a supplier and a customer, or it may include all the organizations involved in upstream and downstream flows from raw-materials' suppliers to final customers (Mentzer et al., 2001).
Multi-level supply chains are networks composed by several supplier-client relationships, where stages are connected to upstream suppliers and downstream clients through different operations.
In order to represent generic open-loop SC networks, the first step has been the modelling of operations that could take place in real supply chains.
This task has been performed shaping first the most basic serial configuration, where each stage can have only one supplier and one client. Afterwards, extensions have been added to represent more complex and realistic networks. Their combination has allowed to create a unified model that simulate the material and information flows from the most downstream level of the chain to the raw-material one.
Operations have been classified into two macro categories. The first one regards mono-product operations that involve only one type of product output, such as serial manufacturing and transportation activities, multi-sourcing procurement, assembly and distribution. On the other hand, the second category includes multi-product output operations such as manufacturing activities where a production resource is shared between more than one product.
Each of these operations has different characteristics. For example, a stock point that is supplied by more than one supplier can split its customer's demand between them according to an order allocation policy. On the other hand, a stage that supplies more than one customer should adopt a stock allocation policy if its inventory level is not sufficient to satisfy them all.
The rest of this section is dedicated to the description of the configurations modelled, explaining the elements that have been considered to develop the SCAEM.
Figure 3.2 shows the set of operations modelled.

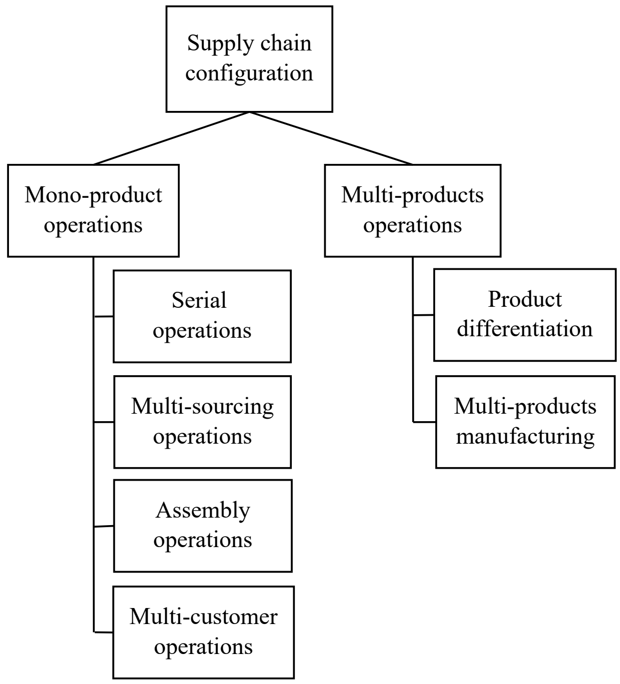

Figure 3.2. Operations modelled

3.3.1 Modelling of the supply chain configuration

It is considered an open-loop, multi-level SC network as the one shown in Figure 3.3.

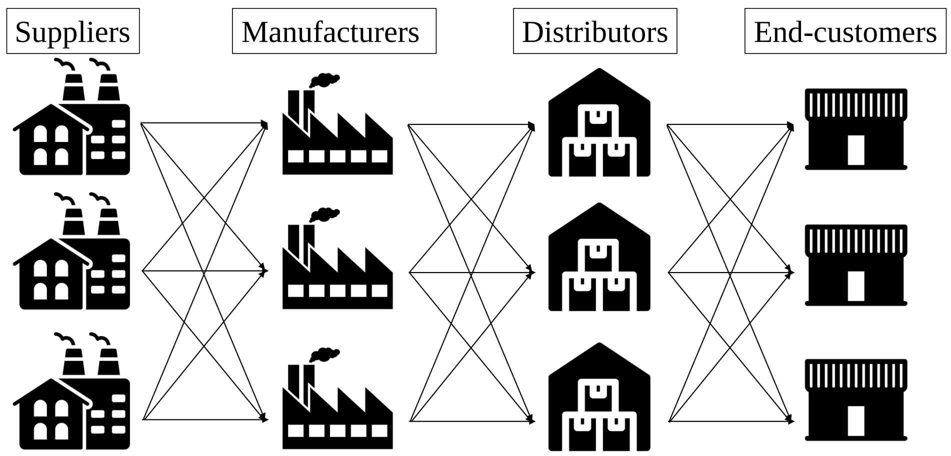

Figure 3.3. Open-loop supply chain network

A schematic representation is adopted to represent SC networks. Inventory points in different levels are depicted as triangles, and are connected through oriented arrows. Rectangles among them represent the operational stages that allow items to move from one level to the successive one.
Each tier contains at least one stock point $k \in [1, \ldots, K]$, where K is the number of stock points composing the network. Each stock point k is served by suppliers located in its upstream level, through either production, logistics or transportation operations.

The set of stock points supplying k is defined $Predecessors(k)$, and $k_p \in Predecessors(k)$ indicates its generic element. All stages have at least one predecessor, except for the ones in the most upstream (raw materials) level which are supposed to have ample stock at all time.
Similarly, each stock point k responds to the demand of customers located in its downstream level. The set of stock points supplied by k is defined $Successors(k)$, and its generic element is $k_s \in Successors(k)$.
All stock points have at least one successor, except for the ones in the most downstream level which represent the finished goods inventory and final customers of the SC. These latter respond to the external customer demand $\boldsymbol{D}_{(k,t)}$, which is considered time dependent and independent for each customer.
Two stock points at different levels are connected through an oriented arrow, that represents the vehicle for the transmission of information and the flow of materials.
A generic stage may have one or more input-type items, and one or more output-type products. However, each stock point can contain only one type of item, so different product-type outputs are allocated in different stock points even if produced by the same operation. For example, if in a level two types of goods are stored in the same location, two stock points are modelled.
Each stage $n \in [1, ..., N]$ is defined by the set of stock points containing its inputs, defined $Inputs(n)$, and the one containing its outputs, defined $Outputs(n)$.
$n = N$ represents the last and most downstream operation modelled.
For any generic stage n, the physical flow is characterized by three deterministic and stationary parameters, which can vary when impacted by a situation needing agility or an agility lever. Manufacturing and logistics operations are defined through:

- Capacity $\boldsymbol{C}_{(n,t)}$: available time in a reference period to produce or prepare orders/products.
- Lead time $\boldsymbol{L}_{(n,t)}$: time required to move an item from $Inputs(n)$ to $Outputs(n)$ through operation n.
- Frozen planning period $\boldsymbol{F}_{(n,t)}$: time interval during which the production plan is fixed, and quantities intended to be launched cannot change.

Similarly, transportation stages are defined through:

- Capacity $\boldsymbol{C}_{(n,t)}$: maximum number of units that can be shipped by operation n in a reference period.
- Lead time $\boldsymbol{L}_{(n,t)}$: time required to transport an item from $Inputs(n)$ to $Outputs(n)$ through operation n.
- Frozen planning period $\boldsymbol{F}_{(n,t)}$: time interval during which the quantities intended to be transported cannot be changed.

Therefore, a generic operation n is characterized by a frozen planning horizon $\boldsymbol{H}_{(n,t)}$, defined as the sum of its lead time and frozen planning period.

$$\boldsymbol{H}_{(n,t)} = \boldsymbol{L}_{(n,t)} + \boldsymbol{F}_{(n,t)} \tag{3.1}$$

In addition, it is considered the presence of a target stock $\mathbf{S}_{(k,t)}$ in every stage k except the ones in the most upstream level. This stock is an extra inventory that is kept for protecting against out-of-stock circumstances because of the SNA under study. It could vary with time, so it is considered a time-dependent parameter.
In order to model a generic open-loop SC, the following configurations have been considered.

Serial configuration

The serial configuration represents the most basic layout, where each stock point k has only one supplier to which it orders its total required quantity, except for the one in the raw-material level that is supposed to have ample stock at all time. Similarly, it has only one customer to satisfy, expect for the one in the most downstream level which represents the final customer.
Thus, each stock point k has at most one predecessor and one successor. No order-allocation or stock-allocation policies are necessary in this configuration, since each actor orders its total requirement to its only predecessor and launches quantities to its only successor.
Stock points are supplied by either transportation or manufacturing operations, defined through the three parameters explained before. Figure 3.4 shows an example of a three-level serial SC configuration with one manufacturing and one transportation stage.

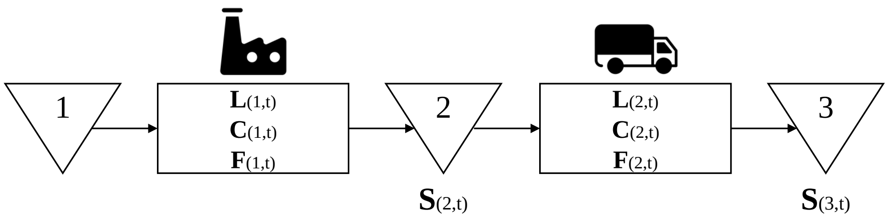

Figure 3.4. Serial configuration

Multi-sourcing configuration

Sourcing from multiple suppliers is a common industrial practice and can have several advantages. Minner (2003) explains that multi-sourcing allows to mitigate supply risks preventing interruptions due to labour strikes, machine breakdowns, material shortages, natural disasters. This technique can improve customer service and reduce safety stocks, inventory holding and shortage costs when demand is uncertain.
In the present model multi-sourcing operations are represented as an extension of the serial ones. The same item is supplied from multiple suppliers that may have different characteristics. For example they could have different lead times, production capacity, contractual and shipment costs.
In this configuration at least stock point has two or more predecessors. On the other hand, all stock points have only one successor. As a consequence, each stock point launches quantities as in a serial system, and at every time the stock point with multiple suppliers receives the sum of the items supplied by upstream stages.

Figure 3.5 shows an example of multi-supplier configuration where the most downstream level stock point is supplied by two suppliers.

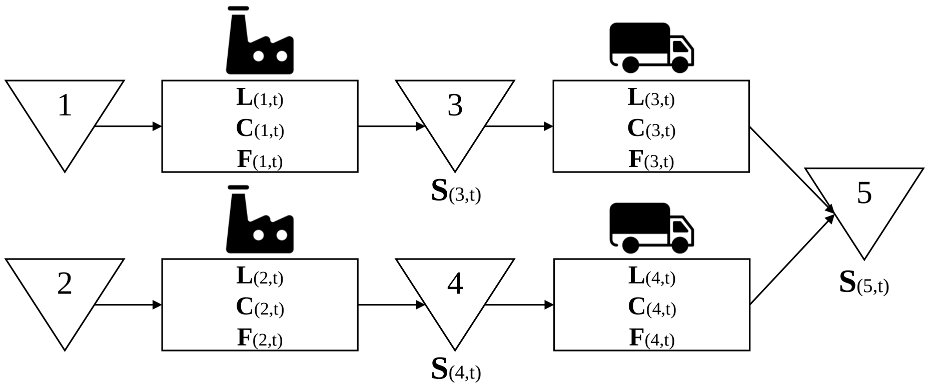

Figure 3.5. Multi-sourcing configuration

At every period, the requirement of each stock point k is split among its predecessors according to an order coefficient $\boldsymbol{o}_{(k_p \to k,t)}$. It represents the proportion of k's total requirement allocated to its predecessor k_p, therefore the order allocation policy.
It is modelled as a time-dependent parameter and it is considered an agility lever able to mitigate SNA that afflict supply relationships. Indeed, it could vary at any period according to the availability of its suppliers in terms of stock, capacity or reactivity. Once demand information is updated, managers may decide to vary order replenishment policies for speeding up orders, in order to avoid extreme shortages or out-of-stock situations. For example, sourcing from a onshore supplier to face SNA could guarantee the availability of products, improving responsiveness (Minner, 2003).
While in a serial operation each stock point allocates its total order to only one supplier ($\boldsymbol{o}_{(k_p \to k,t)} = 1$), in multi-sourcing operations k allocates to each predecessor k_p only a fraction of its total requirement, therefore $0 < \boldsymbol{o}_{(k_p \to k,t)} < 1$.
In the model the order coefficient is used as a discriminant between a stage involved in a serial or multi-sourcing operation. In case a supplier went out of business, this coefficient would be set to 0 for the corresponding branch.
In order to optimize inventory levels, it is considered that at each period the sum of the order coefficients of stock points involved in a multi-sourcing operation must be equal to 1. Therefore, $\forall k_p \in \mathit{Predecessors}(k)$, $\forall\ t$:

$$\sum_{k_p} \boldsymbol{o}_{(k_p \to k,t)} = 1 \tag{3.2}$$

Order proportions can impact the agility level of a network. For example, when a situation needing agility determines variations in customer's external demand or in the parameters of a stage, the variation of these coefficients may permit to find a more reactive supply solution. Therefore, order coefficients can be used to observe how agile performance varies while changing the order allocation policy.

Assembly configuration

The assembly operation consists of putting together at least two sub-component parts in order to obtain a final assembled product. This latter may need several sub-parts in order to be assembled, and each of these may be required in different quantities.
The central issue in an assembly system is the coordination of sub-components, as the operation can start only if the adequate amount of each part is ready to be assembled.
The modelling of the assembly configuration has been addressed similarly to multi-sourcing. Each tier can contain one or more stock points, and each of them can have more than one predecessor. On the other hand, each stage has at most one successor, which orders accounting the order coefficient $\boldsymbol{o}_{(k_p \to k,t)}$.
Differently from multi-sourcing operations, this coefficient is used to indicate the number of units of the sub-component in stock point k_p needed to obtain one unit of the final product in stage k. Therefore, for an assembly system it is considered $\boldsymbol{o}_{(k_p \to k,t)} \geq 1$, as multiples of k's requested units are needed to start the operation.
For example, to produce one syringe a cylinder and a piston are assembled, therefore their order coefficients are both equal to 1.
Figure 3.6 shows the model of an assembly configuration.

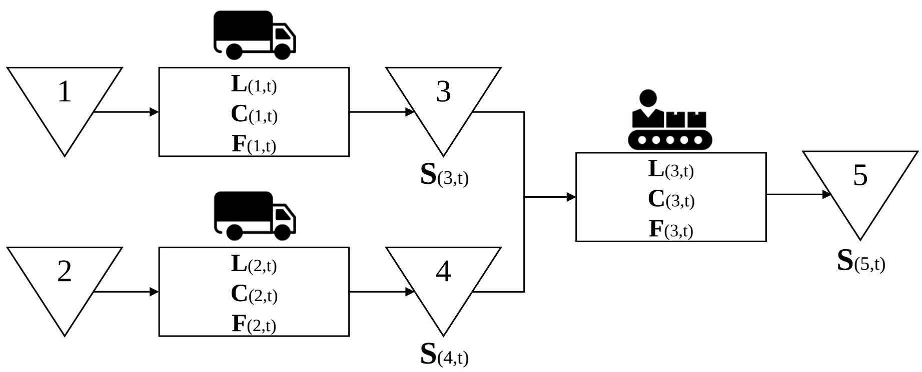

Figure 3.6. Assembly configuration

As already said, the central issue in assembly operations is the coordination of sub-components.
To understand the quantity that can undergo the assembly, at every period it is calculated the potential available quantity of final assembled product that could be obtained considering the number of sub-components in each upstream stage. Then, the minimum of these quantities multiplied by the proper order coefficient is launched by each sub-component stock point. In this way inventory levels are optimized and proper quantities to assembly are launched.
When all components have the same lead time, they are always coordinated and the problem reduces to a serial system. On the other hand, when lead times of different components are not equal the replenishment decision in one period will affect the inventory levels in the future (Song and Zipkin, 2003).

Multi-customer (distribution) configuration

In a distribution system each stage has at most one predecessor, while at least one stage has multiple successors. It is represented through an arborescent configuration as the one shown in Figure 3.7.

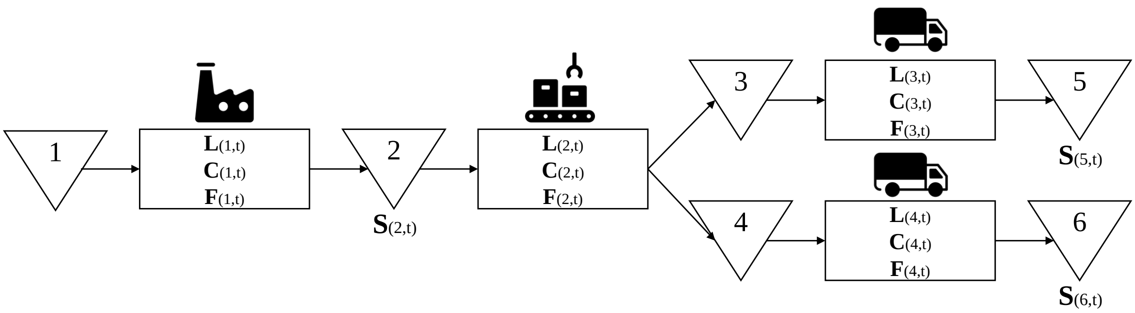

Figure 3.7. Multi-customer configuration

A single supplier serves the same product to different customers through logistics operations. In the example of Figure 3.7 Stage $n = 2$ represents the logistics centre dedicated to the allocation of goods to end-customer stages.
Distribution operations are assumed to have finite capacity as well as operational lead time and frozen planning period.
Goods received from stage $k = 2$ are allocated to two dummy stock points in the downstream level according the parameters of the logistics centre. Then, they are distributed through transportation activities to final customers.
Differently from the assembly system, the key issue of a distribution operation is the allocation of products to downstream stages. Each stage orders exactly its required quantity as in a serial system, so with an order coefficient equal to 1. Therefore, stage $k = 2$ receives the sum of its successors' demands.
On the other hand, four situations may happen when distributing products:

1. The stock available at the supplier stage and the capacity of the logistics operation are large enough to satisfy the requests of all customers. In this case, the quantity launched to each downstream stage is equivalent to its order.

2. The stock available at the supplier stage is not sufficient to satisfy all downstream demands, so a stock-allocation policy has to be adopted.

3. The capacity of the logistics centre is not sufficient to manage all downstream requirements, so a capacity-allocation policy has to be adopted.

4. Both available stock at the supplier stage and capacity of the logistics centre are not sufficient to satisfy customers demand. In this case, it is considered the strictest constraint.

Allocation policies are presented and explained in Section 3.4.2. The multi-customer system is the last configuration modelled belonging to the mono-product family.

Product differentiation configuration

In the industrial reality it may happen that more than one product is processed by the same production line. For example, a painting system may paint an item in various colours, resulting in different final products.
Differently from distribution operations where only one product-type is provided to downstream stock points, differentiation operations produce more than one type of item starting from a common input stock point. These products are represented as stocked in different inventory points even if processed by the same stage.
Figure 3.8 shows this operation, where one common component is transformed in two different outputs.

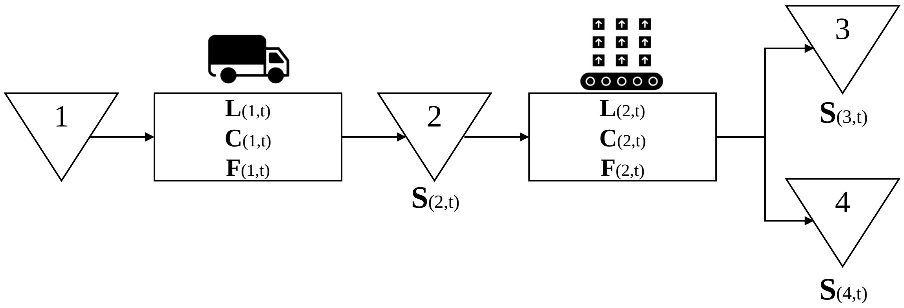

Figure 3.8. Product differentiation configuration

It is considered that products share a common component or raw material, and they need the same resource to be produced. The main difference with respect to mono-product operations is that each product has its own production speed, that may be different for all of them.
Considering the example of Figure 3.8, stock points containing the outputs of the differentiation stage are independent among themself, and they order their needed quantities as in a serial system with an order coefficient equal to one. As a result, stock point $k = 2$ receives the sum of their orders.
Recalling that capacity is defined as the available production time per period, it may happen that it is not sufficient to satisfy the demand of all products when situations needing agility happen. Therefore, a capacity-allocation policy has to be adopted in order to split the available capacity among actors involved.
However, as this operation has a common input for all outputs, also the availability of raw material or component's could represent a constraint as it might be not sufficient to satisfy the overall downstream demand. For this reason, it may be necessary to adopt also a stock allocation policy.
Similarly to the distribution operation, in case both stock and capacity would limit the ability of the system to satisfy customer's demand the strictest limitation between them would be considered. The stock-allocation and order-allocation policies adopted are equivalent to the ones of mono-product configurations, shown in Section 3.4.2.

Multi-product production configuration

The last type of operation modelled is multi-product production. Similarly to differentiation operations, a common resource is exploited to produce different products.

Nonetheless, it is considered that these latter do not have a unique input-type item, nor a common component or raw material.
Figure 3.9 shows an example of multi-product production operation.

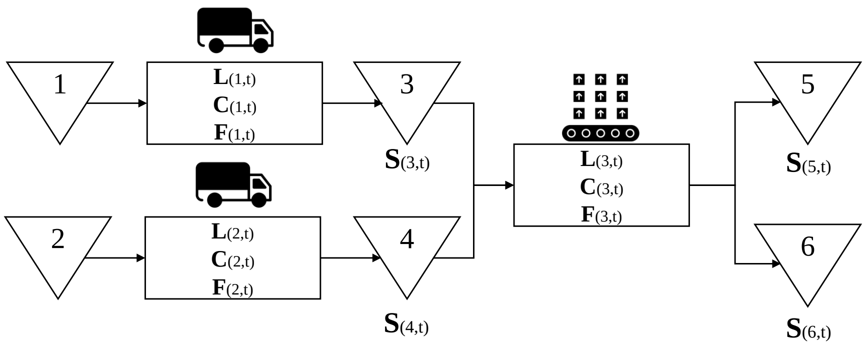

Figure 3.9. Multi-product production configuration

Stock points in downstream levels order to their respective suppliers their total requirement as in a serial system. Therefore, stock allocation policies are not necessary to be applied as no stock points have to allocate their availability to more than one customer. On the other hand, capacity-allocation rules are needed and consider both the required quantity of each customer and the different processing times of products.

3.3.2 Assumptions

Independently from the SC configuration under study, a set of assumptions have been adopted to develop the model. They are:

- Parameters characterizing a stage are deterministic and stationary, and can vary only when impacted by situations requiring agility or agility levers.
- Capacity of transportation stages is considered ample at all times. Compared to production capacity, it is assumed that transportation means are always able to transport needed quantities.
- Each stock point k has at least one supplier, except for stock points in the most upstream raw-material level.
- Each stock point k has at least one customer, except for stock points in the most downstream level that represent the SC's final customers.
- Stock points in the most upstream level are considered to be ample at all times, therefore they have always enough raw materials to cover downstream demand and unexpected situations.
- Each stock point k is considered to have infinite storage capacity.
- Each stock point has visibility on its immediate upstream suppliers. Therefore, every time the parameters related to its upstream stages are known.
- Products' life-cycles are considered greater than procurement times, therefore they are not subjected to obsolescence or deterioration.

3.4 Mathematical model

Supply chains are networks of connected organisations that mutually and cooperatively work together to control, manage and improve the flow of materials and information from suppliers to final users (Yusuf et al., 2020). These two flows are related to the inventory control policy and the information sharing technique adopted, and depend on the parameters of the system.
Once the network's configuration is defined, it is necessary to model them in order to simulate the SC's behaviour when situations needing agility happen. The following sections present how the modelling of the cited flows, SNA, agility metrics and levers have been addressed.

3.4.1 Demand dependent flow management

Babai and Dallery (2009) classify production-inventory control policies into two groups, depending on the type of demand information exploited.
The first approach is defined *inventory consumption-based*, and it assumes that there is no advance demand information. For example, static inventory control policies which consider un-capacitative supply systems and stationary demand (order-up-to level, reorder-point policies) are classified as inventory consumption-based. They consider distribution probabilities to replenish up to a specified level the inventory consumed to satisfy customer demand in previous periods.
The second approach assumes the anticipation of demand information through either forecasts methods or firm orders, and it is defined *future requirement-based*. Some examples are MRP-type or forecasts-based dynamic inventory control policies.
In (Collin and Lorenzin, 2006) demand anticipation is considered the process of determining the most probable future demand for planning purposes. Indeed, future requirement-based approaches are aimed to plan the requirement of goods in order to maximize customer's demand satisfaction while optimizing inventory levels throughout the SC. A stage orders to its upstream supplier a quantity based on its present downstream demand and on an estimation of the upcoming periods. Requirement plans are derived from these estimations in order to maintain a proper demand-supply balance, generating a flow of information.
The information flow across the SC can be managed according to two main policies. The first one is defined demand-independent flow management policy, and considers that each stage has its own control mechanism based on a local estimation of demand. Therefore, each of them perform requirement plans based on their own information. The second approach is defined demand-dependent flow management policy and considers that only stages in the most downstream level anticipate demand information of final clients, which is then propagated to all upstream stages until the raw material level. Only the most downstream stages see the independent demand of the end customers, while others receive a derived requirement (Collin and Lorenzin, 2006).
This backward flow propagation mechanism allows to instantaneously update the requirement of all the upstream SC's stages in a synchronous manner, therefore each of them is impacted by a variation of estimations or parameters of downstream stages at the same time. On the other hand, in demand-independent flow policies delays could be encountered before each stage detects changes in its customer's mean demand.

As already seen in Chapter 1, scholars argue that agile capabilities depend on the ability to share quickly complete information across the network. Possible delays in providing early warning signals have to be taken into account when calculating SCA, as operations need to be planned considering updated market forecast information. Members of the SC should collaborate and cooperate to transfer external and internal variations' information instantaneously, allowing all of them to adapt their flow management parameters immediately after the situation detection.
Thus, SCA depends on how information related to a given situation is detected and propagated across the different stages of the SC. In agile supply chains suppliers should be shared with the latest changes information on quantities and timing to assure that resource plans are continuously aligned (Collin and Lorenzin, 2006).
In the following sections it is adopted a demand-dependent flow policy which exploits a future requirement-based approach to anticipate demand information.
It is considered that information propagation about requirements and supply plans occurs instantaneously along the various stages of the network. Therefore, when a situation needing agility impacts a stock point k the information is shared instantaneously and all stages are impacted synchronously.
When customer's demand exceeds inventory availability it is considered to incur in a stock-out situation. Two different policies are modelled depending on the willing of customers to wait for the product to be delivered:

- Lost sales: the non-satisfied demand is lost and cannot be reported to next periods.
- Backlog: the non-satisfied demand is reported and back-ordered to the demand of next periods.

The modelling of material and information flows that characterize a SC are presented in the next sections.

3.4.2 Information and material flows modelling

In order to describe the movement of goods along the supply chain it is modelled a deterministic, discrete-event framework where each event happens in a specific instant determining a change of the state of the system.
It is considered a single period replenishment policy where each stock point $k \in [1, \dots, K]$ receives the vector of required quantities of its downstream customers.
For stock points in the most downstream level it is a predefined input and represents the exogenous external customer's demand, while for the others it represents the net requirement of their immediate downstream customers. The external demand vector is updated at the beginning of every time $t \in [1, \dots, T]$.
Variables related to the physical and informational flows are vectors describing the inventory movement in each stock point k at every time t for the whole planning horizon subsequent the current period t. The following notation is adopted:

- T: Number of simulation periods. It should be chosen depending on the supply chain length (considering lead times and frozen periods) and the situation needing agility under study. It must be large enough compared to the problem scale.

- $U_{(n,t)}$: Length of the time vector used. It is considered a rolling horizon and $i \in [0, \ldots, U_{(n,t)}]$ is the planning horizon to be accounted at each time t for each stage.

The planning horizon should be chosen in relation with the SC's length in terms of frozen periods and lead times of the operations composing the network. It is modelled as a time-dependent parameter, as situations needing agility might vary these parameters. Ideally it could be an infinite horizon, as variables evaluated at $i > 0$ are estimation of future quantities. Nonetheless, in the following model it is adopted the shortest planning horizon that allows to not lose any information across the network. Its calculation is reported in Appendix A.

Notation and variables

Vectors can refer to stages $n \in [1, \ldots, N]$, stock points $k \in [1, \ldots, K]$ or links between stock points. The connection between a generic stock point k and its successor k_s is represented as $k \rightarrow k_s$. Similarly, the connection between k and its predecessor k_p is represented as $k_p \rightarrow k$. The notation adopted to represent a generic variable vector is:

$$\boldsymbol{X}_{(a,t)}{=}(X_{(a,t,t)}, \ldots, X_{(a,t,t+i)}, \ldots, X_{(a,t,t+U_{(n,t)})})$$

where

- a is the object considered (n if the variable is related to a stage, k to a stock point, $k \rightarrow k_s$ to a connection between stock points).
- t is the current time.
- $X_{(a,t,t+i)}$ is the value of parameter X projected at time $t{+}i$. Depending on the situation, the projected values may be firm values that will not change when moving to $t+1$ or estimated values at time t that can be updated when moving to $t+1$.

Considering a generic connection $k \rightarrow k_s$, the following dynamic variables are defined:

- $\boldsymbol{BFR}_{(k \rightarrow k_s,t)}$= Backward Future Requirement vector from stock point k_s to k calculated at time t when capacity constraints are considered and the backward workload smoothing algorithm is applied.
- $\boldsymbol{BO}_{(k \rightarrow k_s,t)}$= Vector of end of period (projected) Backorder of stock point k with respect to k_s at time t. It represents the unsatisfied demand of stock point k_s by k when a backlog policy is adopted.
- $\boldsymbol{FFR}_{(k \rightarrow k_s,t)}$= Forward Future Requirement vector from stock point k_s to k calculated at time t when capacity constraints are considered and the forward workload smoothing algorithm is applied.
- $\boldsymbol{FR}_{(k \rightarrow k_s,t)}$= Future Requirement vector from stock point k_s to k calculated at time t. It represents the physical material requirement that k_s wants k to have at a certain time in its stock.

- $\boldsymbol{lbs}_{(k \to k_s,t)}$= Batch size used by stock point k to launch quantities to its successor k_s at time t.
- $\boldsymbol{LNB}_{(k \to k_s,t)}$= Number of Batches Launched from stock point k to k_s at time t.
- $\boldsymbol{LQ}_{(k \to k_s,t)}$= Launched Quantity vector from stock point k to k_s at time t.
- $\boldsymbol{LS}_{(k \to k_s,t)}$= Vector of end of period (projected) Lost Sales of stock point k with respect to k_s at time t. It represents the unsatisfied demand of stock point k_s by k when a lost-sales policy is adopted.
- $\boldsymbol{NR}_{(k \to k_s,t)}$= Net Requirement vector from stock point k_s to k at time t. It represents the requirement of stock point k_s from k.
- $\boldsymbol{o}_{(k \to k_s,t)}$= Order coefficient of stock point k_s when ordering to k at time t.
- $\boldsymbol{obs}_{(k \to k_s,t)}$=Batch size of stock point k_s when ordering to k at time t.
- $\boldsymbol{ONB}_{(k \to k_s,t)}$= Number of Batches Ordered by stock point k_s to k at time t.
- $\boldsymbol{ps}_{(k \to k_s,t)}$= Percentage of stock dedicated by k to its successor k_s at time t. It depends on the stock allocation policy chosen.
- $\boldsymbol{RQ}_{(k \to k_s,t)}$= Received Quantity vector by stock point k_s from k at time t.
- $\boldsymbol{UFR}_{(k \to k_s,t)}$= Unconstrained Future Requirement vector from stock point k_s to k calculated at time t without considering capacity constraints.

For a generic stock point $k \in [1, \dots, K]$ the following variables are defined:

- $\boldsymbol{AQ}_{(k,t)}$= Available Quantity vector of stock point k. It represents the quantity that can be received from k at time t accounting the availability of its suppliers.
- $\boldsymbol{BO}_{(k,t)}$= Vector of end of period (projected) backorder at stock point k calculated at time t.
- $\boldsymbol{CFR}_{(k,t)}$= Cumulated Future Requirement vector of stock point k at time t.
- $\boldsymbol{CLQ}_{(k,t)}$= Cumulated Launched Quantity vector from stock point k at time t.
- $\boldsymbol{CNR}_{(k,t)}$= Cumulated Net Requirement vector of stock point k at time t.
- $\boldsymbol{D}_{(k,t)}$= External customer demand vector at time t. It impacts only stock points in the most downstream level.
- $\boldsymbol{FR}_{(k,t)}$= Total Future Requirement vector of stock point k calculated at time t.
- $\boldsymbol{IN}_{(k,t)}$= Vector of end of period (projected) physical inventory at stock point k at time t.
- $IP_{(k,t)}$= Inventory Position of stock point k at the end of time t. It represents the potential material quantity that k has available at time t, given by the inventory on-hand plus the quantity on order. It is a scalar value.

- $\boldsymbol{LS}_{(k,t)}$= Vector of end of period (projected) total Lost sales of stock point k at time t.
- $\boldsymbol{PQ}_{(k,t)}$= Externally Purchased Quantity vector by stock point k at time t.
- $\boldsymbol{pc}_{(k,t)}$= Percentage of capacity dedicated to the production of the item stocked in k at time t by its upstream operation.
- $\boldsymbol{RQ}_{(k,t)}$= Total Received Quantity vector from stock point k at time t.
- $\boldsymbol{r}_{(k,t)}$= Production rate vector at time t of the item stored in stock point k. This parameter embeds also the setup time in case of multi-product operations: for each product, it is split among the number of items composing a batch and then added in a pre-processing phase to the production rate.

In the end, for a generic stage n it is calculated the following variable:

- $\boldsymbol{CA}_{(n,t)}$= Capacity Allocated vector from stage n calculated at time t. It is used to calculate the remaining available capacity of a multi-output stage.

At the beginning of each period t it is assumed that all the variables defined above have been calculated at period $t-1$, defining the state of the system.
Starting from the state of the system at time $t-1$ and the demand vectors for stock points in the most downstream level ($\boldsymbol{D}_{(k,t)}$) at time t, it is calculated the state of the system at time t, updating all variables.

Flow model

Information and material flows are modelled as separated flows. For each stock point k at every time t, the implementation of the procedure can be explained as follows:

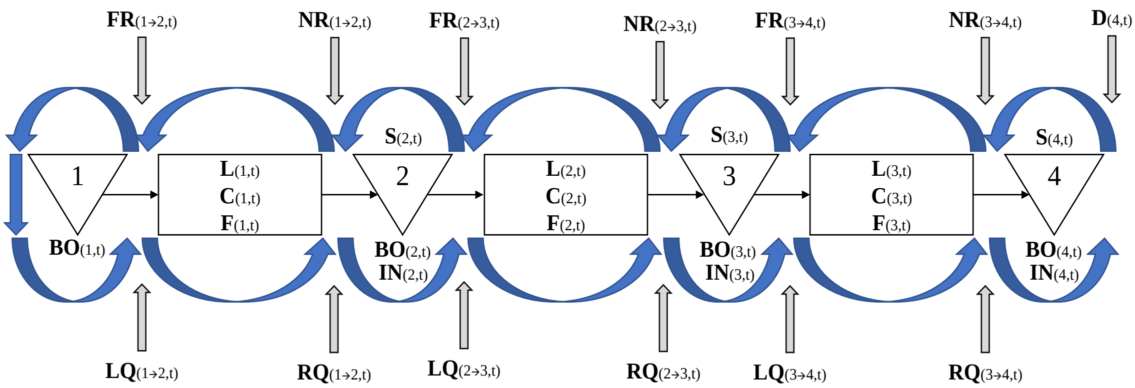

Figure 3.10. Representation of the flow model

1. Calculation of the future requirement vector $\boldsymbol{FR}_{(k,t)}$. It is equivalent to the sum of the net requirements $\boldsymbol{NR}_{(k\rightarrow k_s,t)}$ of downstream stock points, shifted by the respective lead times $\boldsymbol{L}_{(n,t)}$ of the operations connecting them. This vector is equal to the customer external demand $\boldsymbol{D}_{(k,t)}$ for stock points in the most downstream level.

2. Considering the future requirement on k, its potential requirements still not satisfied, the physical inventory and the quantity that is planned to be received, it is calculated the net requirement needed by each upstream predecessor $\boldsymbol{NR}_{(k_p \to k,t)}$.

3. Each period k receives a quantity $\boldsymbol{RQ}_{(k,t)}$ equal to the sum of all the quantities launched by its supplier. These quantities have been sent $\boldsymbol{L}_{(n,t)}$ periods before, according to the lead time of the connecting stage n.

4. k launches quantities $\boldsymbol{LQ}_{(k \to k_s,t)}$ to all its downstream successors k_s in order to satisfy their demand. However, it is limited by physical inventory availability and capacity constraints.

It is recalled that each stage n is characterized by lead time $\boldsymbol{L}_{(n,t)}$ and frozen period $\boldsymbol{F}_{(n,t)}$ vectors. Their sum defines the frozen planning horizon $\boldsymbol{H}_{(n,t)}$.
At every time t, orders of the first $(t + H_{(n,t)} - 1)$ periods are planned and fixed, so quantities that will be received cannot change. Therefore, any order variation can take place from time $(t + H_{(n,t)})$ until the end of the planning horizon.

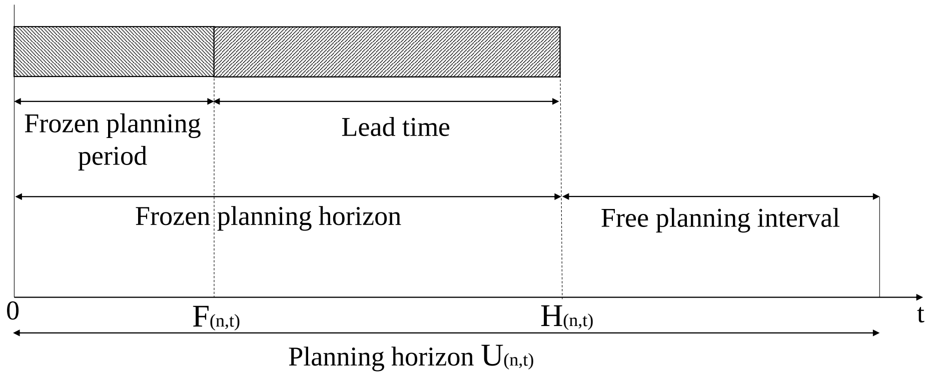

Figure 3.11. Planning horizon (adapted from (Yeung et al., 1998))

Information flow

The information flow across the supply chain is modelled with a backward algorithm from the most downstream level until the most upstream one. Therefore:

For $n = N$ to $n = 1$, for $k = K$ to $k = 1$

If $k \in Input(n), \forall k_s \in Successors(k)$

$$UFR_{(k \to k_s,t,t+i)} = NR_{(k \to k_s,t,t+i+L_{(n,t,t+i)})} \tag{3.3}$$

Where $UFR_{(k \to k_s,t,t+i)}$ is equal to the external customer demand $D_{(k,t,t+i)}$ for stock points in the most downstream level. At each time t, this demand vector is assumed to be known.
As explained in Section 3.3.2 each stock point k has visibility on its upstream stages, therefore on its parameters. For this reason, it may decide to order either independently from operational capacity constraints or smoothing its requirements according to

them, generating a capacity-feasible schedule.
To model this latter case it is considered a workload-smoothing algorithm which accounts for finite capacity of the stage n under consideration. It is made of two parts:

1. First, a backward algorithm is applied to compare the unconstrained future requirement vector and the production capacity. If orders exceed constraints, the future requirement component is set equal to the capacity and exceeding quantity is added to previous time buckets. In this way future requirements are spread across the planning horizon, trying to never exceed capacity limits.

Algorithm 1 Backward algorithm for workload smoothing

```
for i = U_(n,t) to F_(n,t) + 1 do
    if UFR_(k→k_s,t,t+i) > C_(n,t,t+i) r_(k_s,t,t+i) then
        FR_(k→k_s,t,t+i) = C_(n,t,t+i) r_(k_s,t,t+i)
        BFR_(k→k_s,t,t+i−1) = UFR_(k→k_s,t,t+i−1)
        UFR_(k→k_s,t,t+i−1) = BFR_(k→k_s,t,t+i−1) + UFR_(k→k_s,t,t+i) − C_(n,t,t+i) r_(k_s,t,t+i)
    else FR_(k→k_s,t,t+i) = UFR_(k→k_s,t,t+i)
    end if
end for
```

2. In case the unconstrained future requirement exceeds operational capacity, a forward algorithm is applied. Orders are re-allocated according to the capacity limit and, in case cumulative capacity cannot meet cumulative demand, the exceeding quantities are allocated in the last time period of the planning horizon $t = U_{(n,t)}$ in order to be smoothed in the next iteration.

Algorithm 2 Forward algorithm for workload smoothing

```
if UFR_(k→k_s,t,t+F(n,t)) > C_(n,t,t+F(n,t)) r_(k_s,t,t+F(n,t)) then
    for i = F_(n,t) to U_(n,t) − 1 do
        if i = F_(n,t) then
            FR_(k→k_s,t,t+i) = C_(n,t,t+i) r_(k_s,t,t+i)
            FFR_(k→k_s,t,t+i+1) = FR_(k→k_s,t,t+i+1)
            FR_(k→k_s,t,t+i+1) = FFR_(k→k_s,t,t+i+1) + UFR_(k→k_s,t,t+i) − C_(n,t,t+i) r_(k_s,t,t+i)
        else
            if FR_(k→k_s,t,t+i) > C_(n,t,t+i) r_(k_s,t,t+i) then
                FFR_(k→k_s,t,t+i+1) = FR_(k→k_s,t,t+i+1)
                FR_(k→k_s,t,t+i+1) = FFR_(k→k_s,t,t+i+1) + FR_(k→k_s,t,t+i) − C_(n,t,t+i) r_(k_s,t,t+i)
                FR_(k→k_s,t,t+i) = C_(n,t,t+i) r_(k_s,t,t+i)
            end if
        end if
    end for
else FR_(k→k_s,t,t+F(n,t)) = UFR_(k→k_s,t,t+F(n,t))
end if
```

On the other hand, when capacity constraints are not considered each stock point orders to its suppliers according to its total requirement, therefore:

$$FR_{(k \to k_s, t, t+i)} = UFR_{(k \to k_s, t, t+i)} \tag{3.4}$$

In the end, in both cases the total future requirement on stock point k is given by the sum of the orders of all its successors k_s:

$$FR_{(k,t,t+i)} = \sum_{k_s} FR_{(k \to k_s, t, t+i)} \tag{3.5}$$

To determine the Net Requirement vector of k on its upstream suppliers, the first step is the calculation of its Inventory Position $IP_{(k,t)}$. It represents the total potential available quantity of the stock point given by the sum of physical inventory already in stock at the beginning of time t, the quantity that is going to be received and backorder of suppliers.

if $k \in Output(n), \forall k_p \in Predecessors(k)$

$$IP_{(k,t)} = IN_{(k,t-1,t-1)} + \sum_{i=0}^{H_{(n,t)}-1} RQ_{(k,t-1,t+i)} + \sum_{k_p} \frac{BO_{(k_p \to k, t-1, t+F_{(n,t+i)}-1)}}{\max(1; o_{(k_p \to k,t,t)})} \tag{3.6}$$

In case of lost-sales policy, no backorder is allowed.

$$IP_{(k,t)} = IN_{(k,t-1,t-1)} + \sum_{i=0}^{H_{(n,t)}-1} RQ_{(k,t-1,t+i)} \tag{3.7}$$

Next, it is calculated the cumulative total gross demand of stock point k. It is given by the sum of the target stock it wants to keep at time t, its demand not yet satisfied and the cumulative sum of its future requirements up to time $t+i$.

$$CFR_{(k,t,t+i)} = S_{(k,t)} + \sum_{j=0}^{i} FR_{(k,t,t+j)} + BO_{(k,t-1,t-1)} \tag{3.8}$$

The difference between the cumulative gross demand and the inventory position defines the cumulative net requirement of k, which cannot be smaller than 0.

$$CNR_{(k,t,t+i)} = \max(0; CFR_{(k,t,t+i)} - IP_{(k,t)}) \tag{3.9}$$

In the end, the net requirement of k on its predecessors is calculated accounting the number of batches ordered to suppliers. Orders must account for the frozen planning horizons of predecessors. Therefore, it is assumed that up to the end of $H_{(n,t)} - 1$ orders have already been placed and in execution, so that the first time bucket where a new quantity can be asked is $H_{(n,t)}$.
The number of batches ordered from k to upstream predecessors is equal to the smallest integer number to cover the cumulative net requirement at time $t + H_{(n,t)}$, while it needs to cover the difference between cumulative requirements for all the next periods. The number of batches is always rounded to the next integer number.

- if $i = H_{(n,t)}$ then

$$ONB_{(k_p \to k,t,t+i)} = RoundUp\left(\frac{CNR_{(k,t,t+i)} * o_{(k_p \to k,t,t+i)}}{obs_{(k_p \to k,t,t+i)}}\right) \tag{3.10}$$

- if $i > H_{(n,t)}$ then

$$ONB_{(k_p \to k,t,t+i)} = RoundUp\left(\frac{(CNR_{(k,t,t+i)} - CNR_{(k,t,t+i-1)}) * o_{(k_p \to k,t,t+i)}}{obs_{(k_p \to k,t,t+i)}}\right) \tag{3.11}$$

The net requirement on each predecessor is:

$$NR_{(k_p \to k,t,t+i)} = ONB_{(k_p \to k,t,t+i)} * obs_{(k_p \to k,t,t+i)} \tag{3.12}$$

Material flow

The material flow across the supply chain is modelled through a forward algorithm, starting from the most upstream raw-material level until the most downstream one. Once calculated the future requirement of each stock point k at time t, it is possible to determine the quantity it can launch to its successors in order to satisfy their requests. When launching quantities, 3 constraints have to be respected:

- Storage availability: the physical flow sent by a stock point k to its customers cannot exceed its material availability. Stock points in the most upstream level are considered ample at all times.
- Supply capacity: sourcing options have capacity limitations. The physical flow between levels cannot exceed the operation capacity of the connecting stage.
- Downstream demand: quantities launched from a stock point to its successors cannot exceed the overall demand, accounting also stock-out policies.

Considering these limitations, stock and capacity allocation policies have to be calculated at the beginning of each time t for the relative planning horizon. Two different allocation policies are considered:

- **Priority allocation policy**

This policy may be used in case contractual terms forces a supplier to serve its customer with a priority, or when significant stock-out penalties arise if requirements of a specific customer are not satisfied.
The available inventory at stock point k is split among its customers by using a priority allocation, according to which to each successor is assigned a priority rank defined $rank(k_s)$. Customers are satisfied following a priority list, therefore from the successor with highest priority to the lowest one. For the sake of simplicity, the priority index of this list is defined $priority$.
Priorities follow an increasing order, so the smaller rank the higher priority.
Ranks must be associated to each customer. For example, when a stock point k has just one successor k_s, $rank(k_s) = 1$.
At each time t the available stock is allocated to the customer with highest priority

which demand has not been satisfied yet. Therefore, the percentage of stock availability dedicated is:

$$ps_{(k \to k_s,t,t+i)} = 1 \tag{3.13}$$

if and only if $rank(k_s) = priority$. On the other hand, no stock is allocated to successor which rank is different from the considered priority index.
Similarly, when a stage n has more than one output it is possible to follow the priority list to allocate the available capacity. Therefore, at each time t if $rank(k_s) = priority$:

$$pc_{(k_s,t,t+i)} = 1 \tag{3.14}$$

- **Proportional allocation policy**

The available stock at stage k is split among its successors by using a demand-proportional allocation, where to each customer is designated a fraction of its total order (backorder + future requirement) accounting the quantity it required over the total requirement. Therefore $\forall k_s \in Successors(k)$ the percentage of stock allocated to each successor is:

$$ps_{(k \to k_s,t,t+i)} = \frac{FR_{(k \to k_s,t,t+i)} + BO_{(k \to k_s,t,t+i)}}{FR_{(k,t,t+i)} + BO_{(k,t,t+i)}} \tag{3.15}$$

When using this allocation policy, all the successors of k have the same priority. Therefore, the priority rank of each of them is set to $rank(k_s) = 1$.
Also the production capacity of a stage n can be allocated according to a proportional policy. In this case, the time dedicate to produce an item stocked in the inventory point k_s accounts for the demand of this product over the total demand that n has to process at time t:

$$pc_{(k_s,t,t+i)} = \frac{FR_{(k \to k_s,t,t+i)} + BO_{(k \to k_s,t,t+i)}}{\sum_{k \in Inputs(n)} (FR_{(k,t,t+i)} + BO_{(k,t,t+i)})} \tag{3.16}$$

Once the allocation policy is chosen, it is possible to calculate the material flow. This latter allows to determine the quantity launched from each stock point k to its successors k_s at time t. Its calculation for $i = 0$ represents the quantity that is sent at the time t considered, while for $i > 0$ it is a projection needed for planning purposes. It is modelled through a forward algorithm, from the most upstream level to the most downstream one. Therefore:

For $n = 1$ to $n = N$, for $k = 1$ to $k = K$

- if $i = 0$

At the beginning of each period of the planning horizon the priority to be satisfied is set to 1 as the successor with highest priority must always be satisfied first: $priority = 1$. Then, it is calculated the potential quantity that would be received by each stock point considering the availability of its predecessors. This variable is necessary when dealing with assembly operations that need the coordination of more than one component to take place. If just one of them was not available, the operation could not be performed and the potential quantity received would be equal to zero.

if $k \in Inputs(n)$, $\forall k_s \in Successors(k)$

$$AQ_{(k_s,t,t)} = \min_{\forall k \in Predecessors(k_s)} \Bigg(\frac{RQ_{(k,t,t)} + IN_{(k,t-1,t-1)}}{\max(1; o_{(k \to k_s,t,t)})} * ps_{(k \to k_s,t,t)}; \frac{FR_{(k \to k_s,t,t)} + BO_{(k \to k_s,t-1,t-1)}}{\max(1; o_{(k \to k_s,t,t)})}; C_{(n,t,t)} * r_{(k_s,t,t)} * pc_{(k_s,t,t)} \Bigg) \tag{3.17}$$

This potential available quantity establishes the maximum quantity that can be received by a stock point considering its suppliers' inventory availability, operational capacity and the allocation policy chosen.
Nonetheless, when a priority allocation policy is adopted only the customer with highest rank could exploit all the stock availability and operational capacity of its supplier. For this reason, it must be accounted that a part of capacity and suppliers' inventory may have been designated to customers with higher priority.
Therefore, the launched number of batches is calculated as:

$\forall k_s \in Successors(k)$, if $rank(k_s) = priority$

$$LNB_{(k \to k_s,t,t)} = \min \Bigg[\frac{\max(1; o_{(k \to k_s,t,t)})}{lbs_{(k \to k_s,t,t)}} \Bigg(AQ_{(k_s,t,t)}; (C_{(n,t,t)} - CA_{(n,t,t)}) * r_{(k_s,t,t)}; RQ_{(k,t,t)} + IN_{(k,t-1,t-1)} - CLQ_{(k,t,t)} \Bigg) \Bigg] \tag{3.18}$$

Oppositely to the ordered number of batches, this variable is always rounded to the smallest unit to respect capacity and stock availability limits. As a consequence the launched quantity from k to its successor k_s is:

$$LQ_{(k \to k_s,t,t)} = lbs_{(k \to k_s,t,t)} * LNB_{(k \to k_s,t,t)} \tag{3.19}$$

with $LQ_{(k \to k_s,t,t)} = D_{(k,t,t)}$ for stock points in the most downstream level.
Next, the cumulative launched quantity from k, its backorder with respect to successor k_s and the physical inventory level are updated.

$$CLQ_{(k,t,t)} = CLQ_{(k,t,t)} + LQ_{(k \to k_s,t,t)} \tag{3.20}$$

$$IN_{(k,t,t)} = \max\left(0; IN_{(k,t-1,t-1)} + RQ_{(k,t,t)} - CLQ_{(k,t,t)}\right) \tag{3.21}$$

$$BO_{(k \to k_s,t,t)} = \max\left(0; BO_{(k \to k_s,t-1,t-1)} + FR_{(k \to k_s,t,t)} - LQ_{(k \to k_s,t,t)}\right) \tag{3.22}$$

In case unsatisfied demand is lost:

$$LS_{(k \to k_s,t,t)} = FR_{(k \to k_s,t,t)} - LQ_{(k \to k_s,t,t)} \tag{3.23}$$

Also the allocated capacity is updated to keep track of the time dedicated for the production of k_s.

$$CA_{(n,t,t)} = CA_{(n,t,t)} + \frac{LQ_{(k \rightarrow k_s,t,t)}}{\max(1,\ o_{(k \rightarrow k_s,t,t)}) * r_{(k_s,t,t)}} \tag{3.24}$$

Then, the priority is updated in order to satisfy all successors of stock point k according to their rank: $priority = priority + 1$.
In the end, the total backorder of k is calculated considering the sum of unsatisfied demand of each of its successors

$$BO_{(k,t,t)} = \sum_{k_s} BO_{(k \rightarrow k_s,t,t)} \tag{3.25}$$

In case of lost sales policy:

$$LS_{(k,t,t)} = \sum_{k_s} LS_{(k \rightarrow k_s,t,t)} \tag{3.26}$$

- if $i > 0$:

The priority list is set to 1 at the beginning of each period $t+i$: $priority = 1$.
The potential available quantity at each stock point is:

if $k \in Inputs(n)$, $\forall k_s \in Successors(k)$ then

$$AQ_{(k_s,t,t+i)} = \min_{\forall k \in Predecessors(k_s)} \Bigg(\frac{RQ_{(k,t,t+i)} + IN_{(k,t-1,t+i-1)}}{\max(1; o_{(k \rightarrow k_s,t,t+i)})} * ps_{(k \rightarrow k_s,t,t+i)}; \frac{FR_{(k \rightarrow k_s,t,t+i)} + BO_{(k \rightarrow k_s,t-1,t+i-1)}}{\max(1; o_{(k \rightarrow k_s,t,t+i)})} C_{(n,t,t+i)} * pc_{(k_s,t,t+i)} * r_{(k_s,t,t+i)} \Bigg) \tag{3.27}$$

Rounding to the smallest integer unit, the launched number of batches from k to its successor k_s are:

$\forall k_s \in Successors(k)$, if $rank(k_s) = priority$ then

$$LNB_{(k \rightarrow k_s,t,t+i)} = \min \Bigg[\frac{\max(1; o_{(k \rightarrow k_s,t,t+i)})}{lbs_{(k \rightarrow k_s,t,t+i)}} \Bigg((C_{(n,t,t+i)} - CA_{(n,t,t+i)}) * r_{(k_s,t,t+i)}; AQ_{(k_s,t,t+i)}; RQ_{(k,t,t+i)} + IN_{(k,t-1,t+i-1)} - CLQ_{(k,t,t+i)} \Bigg) \Bigg] \tag{3.28}$$

As a consequence, the projected launched quantities are:

$$LQ_{(k \rightarrow k_s,t,t+i)} = lbs_{(k \rightarrow k_s,t,t+i)} * LNB_{(k \rightarrow k_s,t,t+i)} \tag{3.29}$$

with $LQ_{(k \rightarrow k_s,t,t+i)} = D_{(k,t,t+i)}$ for stock points in the most downstream level.
As before, the other variables related to stock point k are updated once quantities have been launched:

$$CLQ_{(k,t,t+i)} = CLQ_{(k,t,t+i)} + LQ_{(k \rightarrow k_s,t,t+i)} \tag{3.30}$$

$$IN_{(k,t,t+i)} = \max\left(0; IN_{(k,t-1,t+i-1)} + RQ_{(k,t,t+i)} - CLQ_{(k,t,t+i)}\right) \tag{3.31}$$

When a backlog policy is adopted to manage unsatisfied demand:

$$BO_{(k\to k_s,t,t+i)} = \max\left(0; BO_{(k\to k_s,t-1,t+i-1)} + FR_{(k\to k_s,t,t+i)} - LQ_{(k\to k_s,t,t+i)}\right) \tag{3.32}$$

In case of lost-sales policy:

$$LS_{(k\to k_s,t,t+i)} = FR_{(k\to k_s,t,t+i)} - LQ_{(k\to k_s,t,t+i)} \tag{3.33}$$

As before, also the allocated capacity variable is updated:

$$CA_{(n,t,t+i)} = CA_{(n,t,t+i)} + \frac{LQ_{(k\to k_s,t,t+i)}}{\max(1,\ o_{(k\to k_s,t,t+i)}) * r_{(k_s,t,t+i)}} \tag{3.34}$$

The priority list is updated: $priority = priority + 1$ and the total backorder of stock point k is calculated:

$$BO_{(k,t,t+i)} = \sum_{k_s} BO_{(k\to k_s,t,t+i)} \tag{3.35}$$

In case of lost-sales policy:

$$LS_{(k,t,t+i)} = \sum_{k_s} LS_{(k\to k_s,t,t+i)} \tag{3.36}$$

In the end, it is calculated the received quantity by each stock point k. It is equivalent to the sum of the launched quantity of its predecessors considering the lead time of the upstream operation. Therefore:

if $k \in Outputs(n)$, $\forall k_p \in Predecessors(k)$

- for $i = 0\ to\ L_{(n,t)} - 1$

Quantities received in the lead time interval are known and cannot be changed as sent $L_{(n,t)}$ periods before.

$$RQ_{(k,t,t+i)} = RQ_{(k,t-1,t+i)} \tag{3.37}$$

- for $i \geq L_{(n,t)}$

The quantity received from each predecessor k_p is equivalent to the quantity launched $L_{(n,t)}$ periods before:

$$RQ_{(k_p\to k,t,t+i)} = \frac{LQ_{\left(k_p\to k,t,t+i-L_{(n,t)}\right)}}{\max(1,\ o_{(k_p\to k,t,t+i)})} \tag{3.38}$$

The total received quantity by stock point k is given by the sum of the received quantity by each supplier, plus potential outsourced quantities.

$$RQ_{(k,t,t+i)} = \sum_{k_p} RQ_{(k_p\to k,t,t+i)} + PQ_{(k,t,t+i)} \tag{3.39}$$

This algorithm allows to model the information and material flows characterizing the SC. In next sections it is shown how situations needing agility, metrics and levers have been integrated to evaluate the SCA level of a network.

3.4.3 Modelling of situations needing agility

In order to evaluate the agility level of a network, it is necessary to understand how it behaves with respect to the occurrence of threats and opportunities.
These latter have been addressed as situations requiring agility, and in Section 1.4.1 it has been listed a series of potential events that scholars have identified in literature. SNA affect supply chains' performance, and in the present model it is considered that they have a reflection on the parameters that characterize the system.
They impact the physical flow of the SC and may lead to:

- Demand variations: sudden or gradual increase/decrease of the total external demand of the SC, variation of the external demand of a specific product or market/distribution channel.
- Planning variations: increase or decrease of operations' lead times and/or frozen planning periods, which determine delays in order's deliveries.
- Capacity variations: decrease of the product quantity that can be manufactured or managed by a stage over time, variations of the production mix of a multi-product operation.
- Supply variations: end of the relationship with a supplier or variation of the maximum quantity that it can supply, variations of the order coefficient.

Situations needing agility can afflict one or more system's parameters at the same time. Their impact on the network is modelled through 4 elements: the parameter of the system i impacted by the situation, the amplitude of variation pertaining to this parameter V_i, the instant $t_{situation}$ at which the variation occurs and its duration $\Delta_{situation}$ (if it is permanent, $\Delta_{situation} = +\infty$).
It is considered that some events could be detected before their occurrence, for example the increase of demand due to promotional campaigns.
The detection instant of a situation needing agility is defined $t_{detection}$, and the detection interval $\Delta_{detection}$ represents the gap between a situation's occurrence and its detection:

$$\Delta_{detection} = t_{detection} - t_{situation} \tag{3.40}$$

The achievable SCA level depends on the detection time. In fact, if situations needing agility are detected sufficiently in advance, anticipation is possible and performance is not impacted.
Proactive agile capabilities depend on the ability of the SC to have an adequate detection interval $\Delta_{detection} < 0$. The shorter it is, the more reactive the network should be to counteract disruptions.
If $\Delta_{detection} = 0$ the network can only react to the disruption.
For example, let us consider a serial SC and a situation of sudden demand increase. Initially, the stock point k in the most downstream level has a periodic demand $D_{(k,t)} = d$ at each time t, that suddenly increases of $V_d = 50\%$ at $t_{situation} = 10$, and this variation lasts for $\Delta_{situation} = 20$ days. The trend of the demand is shown in Figure 3.12.

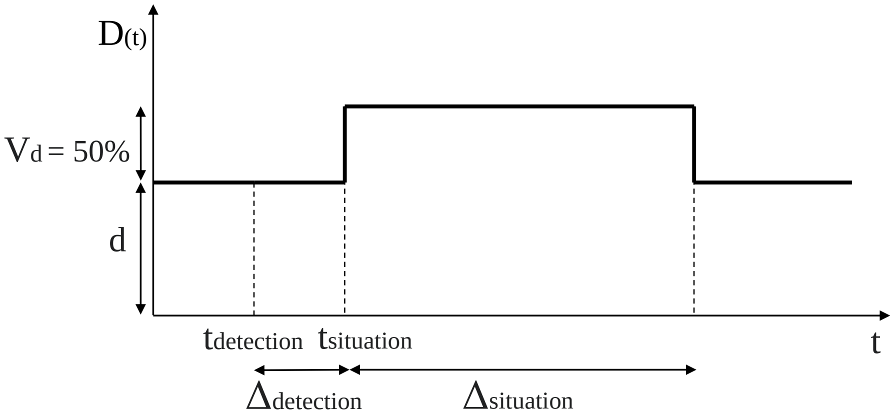

Figure 3.12. Temporary increase of demand

Therefore, the function that describe this situation needing agility is:

$$D_{(k,t)} = \begin{cases} d & \text{if } t < t_{situation} \\ (1 + V_d) * d & \text{if } t_{situation} \leq t \leq t_{situation} + \Delta_{situation} \\ d & \text{if } t > t_{situation} + \Delta_{situation} \end{cases}$$

3.4.4 Modelling of agility metrics

In Section 3.2 three metrics to measure the agile performance of supply chains have been presented. They are used to assess the SCA level of a network and compare the effect of agility levers in improving performance. As agility is addressed as a customer-focused capability, these metrics have been related to the ability of networks in satisfying their requirements.

Situations needing agility affect the physical and information flows of supply chains and lower their performance until the system can adapt to the new condition re-achieving previous levels. They may have a detrimental effects on the SC's service level, provoking stock-out conditions. In this case, backlog or lost-sales policies can be adopted depending on the willingness of customers to wait for the product.

The SCARM metric addresses the ability of a SC to respond to a situation. When backorder is allowed SCARM measures the time needed to satisfy downstream demand and the totality of backorder cumulated since the occurrence of the situation.

On the other hand, in case of lost sales policy it represents the time required to satisfy final customer's demand without losing any additional sale.

Defining $t_{agility}$ the time at which disruptions are completely mitigated and the performance level antecedent the situation needing agility is recovered, SCARM is defined as:

$$\text{SCARM} = t_{agility} - t_{situation} \tag{3.41}$$

Therefore, the smaller SCARM the higher SCA level. Considering the demand trend shown in Figure 3.12 and assuming that customers are willing to wait for unsatisfied demand, Figure 3.13 reports an illustrative example of backorder trend and the deriving SCARM metric.

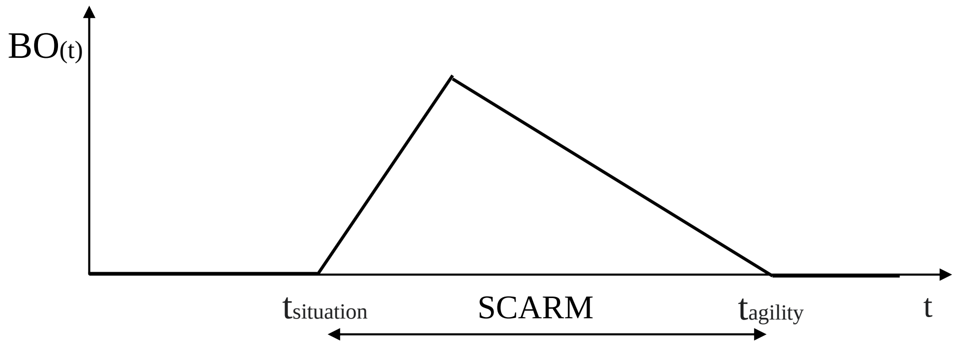

Figure 3.13. Supply chain agility response metric

It is worthwhile to notice that the SCARM depends on the stock-out policy adopted, and generally it is longer when backlog is allowed.
Moreover, the mechanism on which the dynamic equations composing the model in Section 3.4.2 are based allows the system to re-assess at each period t. Therefore, the evaluation of SCARM depends only on the stock-out policy adopted in the last level, while it is independent from the policy adopted across the rest of the supply chain. As instance, if stock points in the most downstream level adopt a lost-sales policy, the resulting SCARM will be independent by the choice of a backlog or lost-sales management across the rest of the network.
Scholars defined agility also as a proactive capability, able to anticipate disruptions and mitigate their impact. The SCAPM metric assesses the anticipation time required to not have any backorder or lost sale, therefore to not lower the performance level. In other words, it is the smallest detection interval that allows the network to nullify the SCARM:

$$\text{SCAPM} = |\min(\Delta_{detection} \ni \text{SCARM}(\Delta_{detection}) = 0)| \tag{3.42}$$

In the end, SCREM addresses the issue of having larger or smaller stock levels than the targeted ones across the supply chain due to situations needing agility. Both these condition could threaten the survival of companies, which could not have sufficient available stock to face other disruptions or too high inventory costs.
Defining $t_{recovery}$ the instant at which the target stock level is achieved after the occurrence of a situation requiring agility, the SCREM is defined as:

$$\text{SCREM} = t_{recovery} - t_{situation} \tag{3.43}$$

It is possible to observe that these KPIs can be calculated for each stock point composing the network. However, the SCARM and the SCAPM of a SC are the ones of nodes in the most downstream level, i.e. the final customer one. On the other hand, the SCREM refers to the stock point that requires the largest time across the chain. These three KPIs allow to evaluate the level of agility of a network. When this level is considered unsatisfactory to guarantee adequate service levels, agility levers could be deployed. The next section shows how these latter have been modelled in order to observe their impact on the system.

3.4.5 Modelling of agility levers

Once the SCA level is assessed with respect to the situations requiring agility considered, levers can be deployed to improve it.
In Section 1.4.2 it is presented a series of managerial and technical means that practitioners and researchers investigated to proactively and/or reactively enhance an unsatisfactory agile performance level.
In this model it is considered that these actions impact the physical flow of the SC, providing a variation of its parameters. For example hiring new people, working overtime or training employees to react promptly to changes could increase the production capacity of a stage, while outsourcing can be exploited to have stock availability ready to counteract SNA. The agility levers modelled are shown in Table 3.1:

Table 3.1. Agility levers modelled

Category	**Agility lever**
Proactive	Variation of target stock levels
Reactive	Product outsourcing
Proactive and Reactive	Production capacity increase
	Lead time reduction
	Frozen planning period reduction
	Change of order allocation policies

- Production capacity increase: as the production capacity of a product is the time allocated on the production resource multiplied by its production rate, either increasing the available time of the stage (e.g., overtime, extra-shifts, hiring additional employees) or increase its production rate (e.g., reduce set-up time) allows to increase it. In addition, if the SNA can be spotted with a sufficient detection interval it is possible to order additional quantities to suppliers according to their capacity before the situation occurs, therefore the workload smoothing algorithm can work as an agility lever.

- Lead time reduction: each transportation or production stage is characterized by a lead time, therefore changing the initial resource for another with a shorter lead time can lever agility. For example, the variation of supplier's transportation means can impact decrease the lead time of an operation.

- Frozen planning period reduction: it is considered that supplier's frozen planning periods could be reduced to face an emergency situation, therefore reducing the overall planning horizon and improving the accuracy of schedules.

- Target stock variation: as each stock point can keep a target inventory level to avoid stock-out situations, its proactive variation can allow to mitigate threats.

- Product outsourcing: external purchasing of final or intermediate goods.

- Variation of order allocation policies: in case of multi-sourcing operations it is possible to change the initial allocation of orders among suppliers in order to foster agile solutions.

One or more of these parameters can vary simultaneously when a lever is activated to counteract a situation needing agility.
Similarly to SNA, a lever is modelled as a variation from an initial stationary condition through 4 elements: the parameter of the system j impacted, the amplitude of the variation V_j, the instant t_j at which it is activated and the duration of activation Δj.
For example, in order to improve the agility level of Figure 3.13 it may be possible to increase the capacity of the bottleneck operation n of the SC of 20%.
Therefore, said the initial capacity $C_{(n,t)} = c$, the variation $V_c = 20\%$, the activation instant t_c and its duration Δ_c, the trend of the production capacity is:

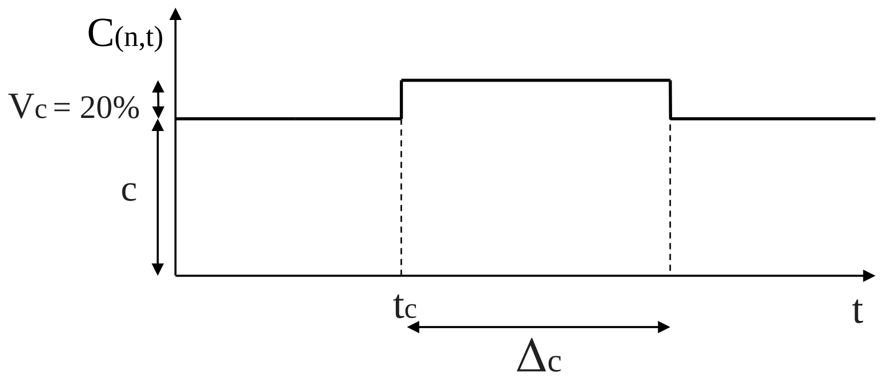

Figure 3.14. Increase of capacity to lever agility

and its describing function is:

$$C_{(n,t)} = \begin{cases} c & \text{if } t < t_c \\ (1 + V_c) * c & \text{if } t_c \leq t \leq t_c + \Delta_c \\ c & \text{if } t > t_c + \Delta_c \end{cases}$$

3.5 Simulation model

In order to evaluate the agility level of a network and observe the impact of levers on performance, it has been developed a simulation model.
Supply chain simulation techniques are used to support the decision-making process. They allow the evaluation of SC performances in virtual environments, reducing decisional risks (Timperio et al., 2020).
SCAEM is based on the simulation of different scenarios to assess the impact of situations needing agility and levers on the agile performance of the SC configuration under study. Therefore, the dynamic equations of state describing material and information flows have been translated in VBA coding language to simulate the system's behaviour.
The rest of this section is dedicated to show how this simulation tool have been developed explaining the methodology adopted, the input parameters and an illustrative case study.

3.5.1 Implementation of the simulation model

The SC configuration has been represented using the Graph Theory. It is a mathematical methodology based on the representation of a system through a structure called graph. It allows to model and analyse the relationships among actors in a network, considering the impact of the system's parameters and the interdependences between links of the SC.
A graph $G = (V, E)$ is defined by the set of its nodes V and the set of its ordered couples of nodes E, these latter addressed as arcs. A generic node i is defined the predecessor of node j if there is an oriented arc from i to j. To each of these arcs it is possible to associate a weight.
Graphs can be represented through the means of adjacency matrices. An adjacency matrix $A = (a_{(i,j)})_{i,j \in V}$ is a VxV matrix composed of coefficients 0 and 1 where $a_{i,j} = 1$ only if $(i, j) \in E$, otherwise $a_{(i,j)} = 0$. Therefore, when the graph is oriented the $a_{(i,j)}$ element is equal to 1 only if the i-th node is connected to the j-th node from i to j, otherwise it is equal to 0. In this case the matrix is upper triangular.
Beside the adjacency matrix that exploits the boolean notation to indicate the relationship between nodes of the graph, it is possible to build the weighted matrix where to element $a_{(i,j)}$ is associated the arc's weight.
This methodology allows to model the SC configuration using adjacency matrices, representing the dynamic interrelationships of the system as operations between them. It permits to indicate the relationships among the different actors composing the network simplifying the addition, removal and check of arcs in a time efficient manner. Nonetheless, each variable of the model is modelled as a VxV matrix, reflecting on the memory usage.
In the present model stock points $k \in [1, \ldots, K]$ represent the nodes of the graph.
Each node is associated to a level of the SC through a Breadth First Search algorithm. As it is considered an open-loop network, they are connected by oriented arcs that define a tree structure. Each node at a time is considered as a root, and a breadth search is performed to identify its successors and predecessors. Nodes without predecessors are allocate to the most downstream raw-material level, while nodes without successors are put in the most downstream one.
All the variables presented in the mathematical model are represented as KxK matrices. Operations among stock points allow to consider the relationships among nodes, simulating the dynamic behaviour of the SC under study.
The state of the system at time t is calculated considering a set of dynamic equations that embeds the state of the system at time $t - 1$ and the inputs that affect the system at time t. Therefore, a discrete-event simulation technique is adopted, as the behaviour of the system can be represented by a series of events.
Discrete-event simulations allow to replicate the structure of the system and performance measurement under a number of scenarios.
In the next section, the inputs required to simulate these scenarios are listed, and an illustrative case study shows the functionalities of the tool developed to assess and improve the agility level of a SC.

3.5.2 Inputs of the simulation model

The simulation model requires a set of inputs. They are related to:

- Simulation period T
- Supply Chain configuration
  - Number of stock points K
  - Initial target stock of each stock point $S_{(k,0)}$
  - Initial Order coefficients $o_{(k_p \to k,0)}$
  - Priority rank of each stock point $rank(k)$
  - Production rates of each product $r_{(k,0)}$
  - Ordering batch size of stock point k on its predecessor k_p $obs_{(k_p \to k,0)}$
  - Launching batch size of stock point k on its successor k_s $lbs_{(k \to k_s,0)}$
  - Initial Demand vectors on stock points in the most downstream level $D_{(k,0)}$
- Stages' parameters
  - Initial Lead time of each stage $L_{(n,0)}$
  - Initial Frozen period of each stage $F_{(n,0)}$
  - Initial Capacity of each stage $C_{(n,0)}$
- Supply chain management policies adopted
  - Stock management policy (Lost sales or Backorder)
  - Stock and Capacity allocation policy (Priority or Proportional)
  - Finite Capacity order algorithm (Workload smoothing)
- Situations needing agility parameters
  - Parameter(s) i impacted
  - Entity of the variation V_i
  - Time of the variation $t_{situation}$
  - Duration of the variation $\Delta_{situation}$
- Agility levers parameters
  - Parameter(s) j impacted
  - Entity of the variation V_j
  - Time of the variation t_j
  - Duration of the variation Δ_j
- Agility metric to evaluate (SCARM, SCAPM or SCREM)

In addition, inventory levels of each stock point are initialised to start simulations in a steady-state configuration. These levels are set equal to the quantity needed by each stock point to cover the future requirement of their successors considering the initial frozen planning horizon $H_{(n,0)}$ of their upstream stage n.
Stock points in the most downstream level are initialised as:

$$IN_{(k,0)} = \sum_{i=1}^{H_{(n,0)}} D_{(k,0)} + S_{(k,0)} \tag{3.44}$$

where n is their upstream stage. Stock points in other levels accounts for the sum of the future requirements of their successors. Said m the stage such that $k \in Inputs(m)$:

$$IN_{(k,0)} = \sum_{i=1}^{(H_{(n,0)}-F_{(m,0)})} FR_{(k,0)} + S_{(k,0)} \tag{3.45}$$

This model allows to calculate the agility metric chosen, as well as assess the impact of situations needing agility and levers. It allows to simulate and observe the trend of backorder or lost sales in each stock point of the SC over time, the evolution of the system's parameters, inventory levels and launched quantities at each time.

3.5.3 Illustrative case study

Nominal case

In order to illustrate the model described, it is presented the illustrative case study related to the SC configuration shown in Figure 3.15.

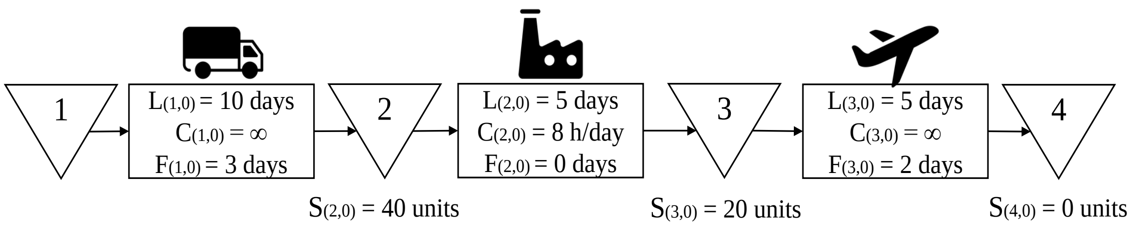

Figure 3.15. Illustrative case study

It is considered a four-level, mono-product, serial SC configuration composed of two transportation stages and an intermediate manufacturing stage.
Each stage is characterized by the three parameters explained in Section 3.3.1, and stock points 2 and 3 hold a stock to counteract potential situations requiring agility. For assumption (Section 3.3.2) stock point 1 has ample inventory at all times, while stock point 4 represents the final product delivery point. Stages representing transportation activities are always able to manage the required quantities.
The intermediate manufacturing stage is characterized by a nominal production lead time $L_{(2,0)} = 5$ days and has a nominal production capacity $C_{(2,0)} = 8$ h/day. It is considered that the product stocked in 3 has a production rate $r_{(3,0)} = 20$ units/h.
The demand-dependent flow management policy is adopted and stock point 4 anticipates customer's demand. Information sharing is synchronous and instantaneous

among levels.
All the parameters modelled are deterministic, as well as the external daily demand on stock point 4 that is 100 units/day. As it is considered a serial SC configuration, all the stock points have the highest priority and each of them orders the total requirement to the only supplier. For the sake of simplicity, batch sizes are set equal to 1 as one only product is treated.
Adopting the same approach of (Hernández and Pedroza-Gutiérrez, 2019), agility is related to the ability of the network to answer promptly a variation of demand. Therefore, it is considered that the external demand of this SC unexpectedly increases at time $t_{situation} = 35$ of 30%, stabilizing at 130 units/day for 30 days.
Figure 3.16 shows this trend over $T = 100$ simulations periods.

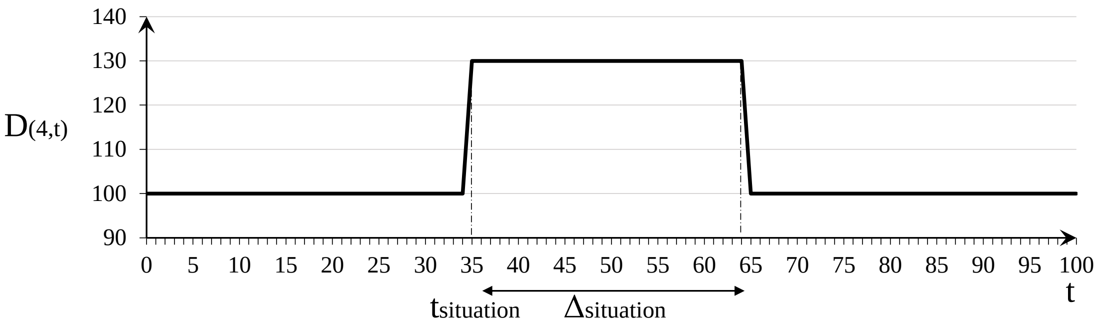

Figure 3.16. Situation needing agility under study

This sudden demand increase lowers the performance of the supply chain in terms of service levels, indeed the network is not able to immediately satisfy total end-customer's orders.
Depending on the out-of-stock policy chosen, this reduction of performance is reflected on backorders or lost sales. The scenario representing the situation needing agility's impact on the network is defined S0.
Considering a backlog policy, the evolution of backorder in the most downstream stock point is shown in Figure 3.17.

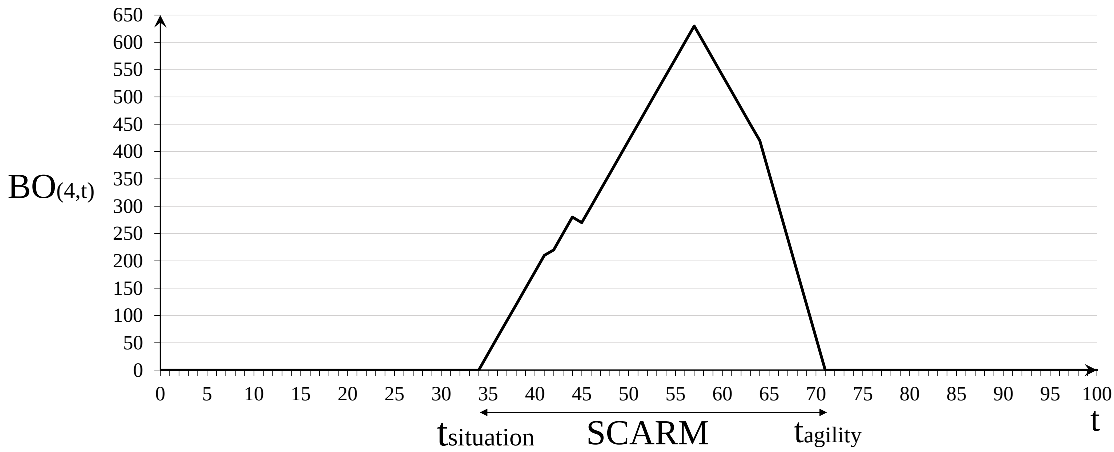

Figure 3.17. Evolution of backorders in stock point 4 for scenario S0

The SC is able to re-achieve its standard performance level at day 71, therefore $36 days$

elapse from when the situation needing agility occurs ($t_{situation}$) to when the SC can re-achieve its standard performance level ($t_{agility}$).
The tool allows to calculate also the minimum detection interval needed to not have any performance reduction and the time needed to restore initial target inventories across the SC. The results for scenario S0 are:

$$\text{SCARM}_{BO} = 36 \text{ days}$$
$$\text{SCAPM}_{BO} = 21 \text{ days}$$
$$\text{SCREM}_{BO} = 49 \text{ days}$$

Analysing Figure 3.17, it is possible to observe that the trend of backorder starts increasing with a slope of 30 units/day when the demand increase occurs. Indeed, the material flow of the SC is set to satisfy a demand of 100 units/day, therefore an unexpected increase of 30% cannot be immediately met.
This trend slightly decreases at day 42, as stock point 4 receives the $S_{(3,t)} = 20$ units contained in the target stock of node 3. These quantities are launched at day 37 and received 5 days later, accounting for the frozen period and the lead time of Stage 3. Similarly, at day 45 stock point 4 receives the quantities kept in stock by node 2, launched $L_{(2,t)} + L_{(3,t)}$ periods before.
The peak of backorder is reached immediately before day $t_{situation} + F_{(1,t)} + L_{(1,t)} + L_{(2,t)} + L_{(3,t)} = 58$, and it is equivalent to 630 units, i.e the sum of the extra demand cumulated in this period minus the sum of target inventories launched.
From day 58 the quantities corresponding to the new demand coming from the raw material supplier are received at stock point 4. Nonetheless, they are limited by the bottleneck capacity of the system, equivalent to 160 units/day at stage 2.
As a consequence backorders decrease with a linear slope of 30 units/day until day 64, which is the difference between the bottleneck capacity and the external demand.
When this latter returns to the initial 100 units/day, the system can recover backorders at a pace of 60 units/day until they become null at day 71.
If stock-out situations were treated with a lost-sales policy, the time needed by the flow to adjust to new customer requirements would have been the same of the backlog policy. Therefore, at day 58 no lost-sales are expected.
Figure 3.18 confirms that the SCARM difference between the two policies is the time needed to recover backorders.

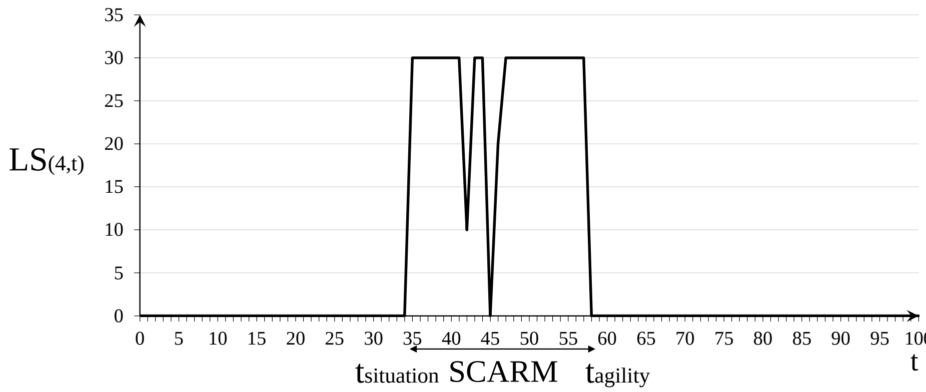

Figure 3.18. Evolution of lost sales in stock point 4 for scenario S0

The falls of lost-sales shown in 3.18 corresponds to the receiving by node 4 of the units in inventory stock points 2 and 3. Indeed, they occur at the same days of the decrease of backorders shown in Figure 3.17.
The three agile KPIs when a lost-sales policy is adopted are:

$$\text{SCARM}_{LS} = 23 \text{ days}$$
$$\text{SCAPM}_{LS} = 21 \text{ days}$$
$$\text{SCREM}_{LS} = 49 \text{ days}$$

where the SCAPM and the SCREM are equivalent to the backlog policy.
These metrics are related to the anticipation time required to not have any performance decrease and to achieve targeted stock levels. In this example the time required for the material flow to adjust to the increase of customer's demand is equivalent for the two policies, therefore the two KPIs are the same.

Activation of agility levers

Once determined the SCA level of the network with respect to the situation requiring agility under study, it is possible to improve it by activating agility levers.
In order to illustrate their effects and identify the most effective action to improve agile performance, the following reactive and proactive levers are considered:

- Reduction of the lead time at Stage 1 of 50% for 30 days at day 35.
- Reduction of the frozen periods at Stage 1 and Stage 2 of 100% for 30 days at day 35.
- Increase Stage 2's capacity of 25% for 30 days at day 35.
- Purchase of 300 units of intermediate or finished product at each stock point of the chain at day 40.

The application of a lever with respect to another generates a different agile scenarios. Table 3.2 reports the results:

Table 3.2. Comparison of reactive agility levers on agile performance

Scenario	**Lever**	**SCARM**$_{BO}$ [$days$]	**SCARM**$_{LS}$ [$days$]	**SCAPM** [$days$]	**SCREM** [$days$]
S0	No levers	36	23	21	49
S1	$L_{(1,35)} = 5$ days	31	18	21	47
S2	$F_{(1,35)} = 0$ days	33	20	21	45
S3	$F_{(3,35)} = 0$ days	36	23	21	49
S4	$C_{(2,35)} = 10$ h/day	31	23	21	49
S5	$PQ_{(2,40)} = 300$ units	36	23	21	49
S6	$PQ_{(3,40)} = 300$ units	31	23	21	49
S7	$PQ_{(4,40)} = 300$ units	33	23	21	49

To analyse the impact of proactive levers, four other scenarios are considered.
Table 3.3 reports the agile performance when proactive levers are applied:

- Increase of target stocks across the SC. To completely absorb the demand variation, inventory levels should be set equal to the product of their upstream stage's lead time and the extra demand. Nonetheless, in this case $S_{(k,t)}$ are initialised to 100units to observe the impact of keeping higher stock levels on agility. In general, stock holding costs increase approaching the end of the SC.
- Reduction of lead time at Stage 1 of 50% for 60 days at day 10.

Table 3.3. Comparison of proactive agility levers on agile performance

Scenario	**Lever**	**SCARM**$_{BO}$ [$days$]	**SCARM**$_{LS}$ [$days$]	**SCAPM** [$days$]	**SCREM** [$days$]
S8	$S_{(2,t)} = 100$ units	35	23	19	49
S9	$S_{(3,t)} = 100$ units	35	23	19	49
S10	$S_{(4,t)} = 100$ units	33	23	18	49
S11	$L_{(1,10)} = 5$ days	31	18	16	43

Analysing the results obtained, it is possible to observe that scenario S1, S4, S6 and S11 give best performance in terms of SCARM when a backlog policy is adopted. However, S1 and S11 enhance SCARM also when a lost-sales policy is chosen.
This is due to the fact that an improvement of the bottleneck capacity allows to increase the quantities processed in Stage 2, but it does not shrink the time needed for materials to flow from node 1 to node 4. Therefore, the updated demanded quantity comes to stock point 4 at day 58, and the additional quantities permit the system to recover backorders in less time.
Figure 3.19 shows the comparison of the backorder trend for scenarios S1, S2, S3, S4.

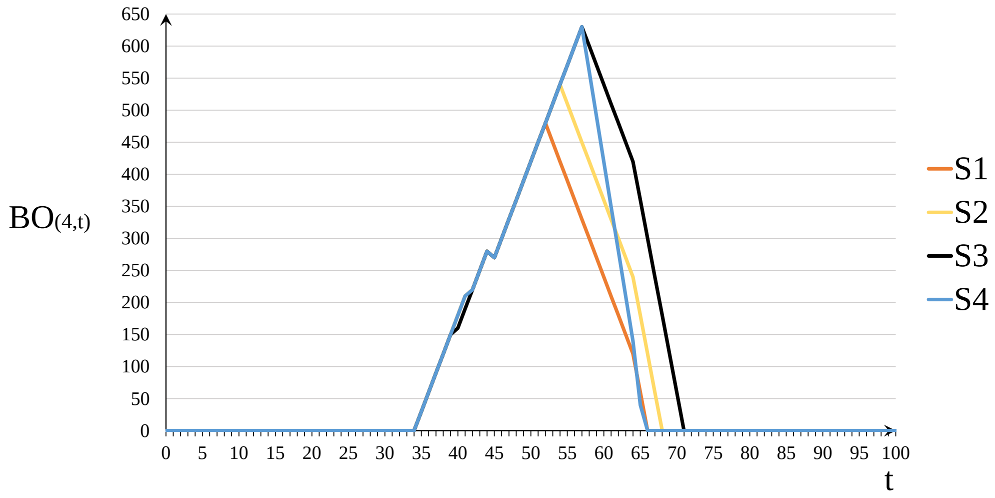

Figure 3.19. Comparison of scenarios S1, S2, S3, S4

A reduction of lead time of Stage 1 allows to decrease the overall time needed for the material flow to go from node 1 to stock point 4. In this case the peak of backorders is smaller than in scenario S0 and it is reached 5 days before, allowing a faster recover. Besides, the shrinking of the total time required to receive updated quantities at node 4 decreases the interval needed to not not have any additional lost sale.

Similarly, a reduction of Stage 1's frozen period (S2) permits to vary the scheduled quantity to launch at day 35 from node 1, reducing the SCARM for both policies.
On the other hand, a reduction of Stage 3's frozen period (S3) does not impact the agility of the system. Indeed, it does not change the total time needed by goods to reach stock point 4, but only the day at which node 3 launches the quantities in its inventory. As a consequence, applying this lever the flection of day 42 in Figure 3.17 is obtained at day 40. Nonetheless, it does not change diminish neither the cumulative level of backorder/lost sales or the time needed to recover them.
The purchasing of quantities through product outsourcing at stock points 3 and 4 (S6 and S7) allows to reduce the SCARM in case of backorder policy. Figure 3.20 reports the trend of backorders when quantities are purchased externally to react the situation.

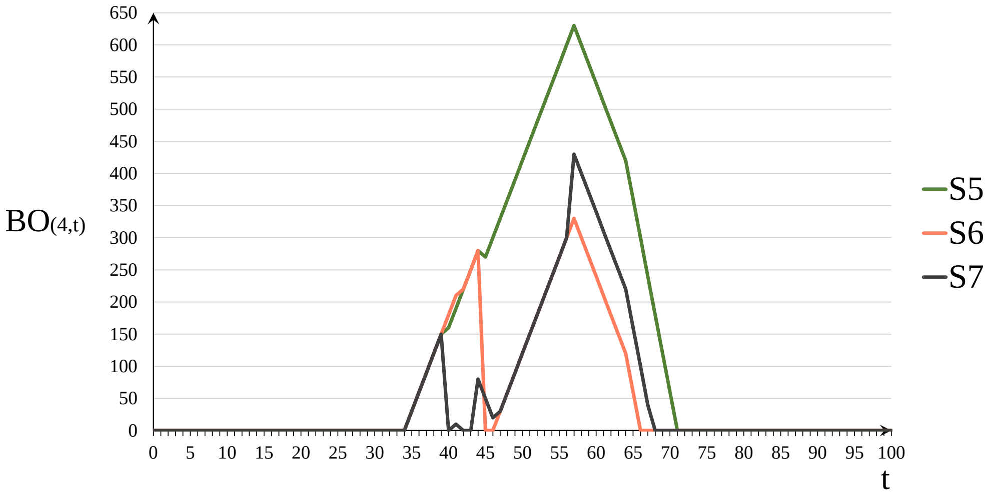

Figure 3.20. Comparison of scenarios S5, S6, S7

These outsourcing activities reduce the total amount of cumulated backorders, but they are not sufficient to completely absorb the variation of demand and do not allow to receive the updated flow before the required time. For this reason, they do not vary SCARM in case of lost-sales policy.
Focusing on the purchasing of quantities at the final stock point (S7), it reduces the peak of back-ordered quantities to 430 units at time 57, which then decrease with the same slope of Figure 3.17. The application of this lever generates an increase of stock levels in node 4, which then orders a minor quantity to its supplier to balance it. As a consequence, this lever generates a SCARM of 33 days.
On the other hand, the purchasing of intermediate products at stock point 3 (S6) determines the nullification of backorders after $L_{(3,t)}$ periods, therefore node 4 keeps asking additional quantities for a longer time interval. This results in a peak of backorders of 330 units at day 57, and so in a smaller time needed to recover them.
The buying of additional quantities at stock point 2 (S5) does not afflict the agility of the system, as their movement is constrained by the production capacity of Stage 2. In addition, this purchasing slightly impacts the trend of backorders, as at day 43 stock point 2 would receive all the ordered quantities because supplied by a transportation stage linked to the raw material stock point.

In the end, considering proactive agility levers in scenario S8, S9, S10, it is possible to observe that the enhancement of stock levels reduce SCARM only in case of backlog policy, while it does not influence the one related to lost sales. Once again, it happens because inventories are able to reduce the level of cumulative backorders, but not to shrink the time interval needed to receive the new demanded quantity from the most upstream level.
On the contrary, scenario S11 reduces this time interval of 5 days, shortening of the same amount of time the impact on lost-sales. As a result, the reduction of lead time either proactively or reactively results to be the lever that improve the most the agile performance, assessing that agile supply chains should reduce lead time to improve their dynamic response (S. K. Sharma and Bhat, 2014).
Even if some of the levers applied impact the agility level just marginally, they can improve the average backorder level and the total lost sales generated in each scenario, enhancing customer's satisfaction and reducing potential penalty fees.
Table 3.4 shows the results:

Table 3.4. Average backorder and lost sales level of each scenario

Scenario	**Average backorder level** [*units*]	**Lost sales level** [*units*]
S0	341	630
S1	261	480
S2	296	540
S3	341	630
S4	321	630
S5	333	630
S6	165	330
S7	157	430
S8	308	570
S9	285	550
S10	265	530
S11	261	480

Considering the SCAPM, it is trivial that reactive levers do not have any impact on the anticipation time needed to not have any detrimental impact on performance. Indeed, SCAPM is mainly improved by proactive levers that can mitigate the situation needing agility before its happening.
In this example, the keeping of higher stock levels in each node allows to reduce the time needed to not have any backorder or lost sale of the same interval they cover the demand variation. Focusing on scenario S10, the holding of 100 units in stock permits to absorb the demand variation of 3 periods, decreasing SCAPM of 3 days. The same phenomenon verifies in scenario S11, where a reduction of 5 days of the total time needed for the material flow to cross the SC corresponds to an anticipation interval 5 days shorter.
In general, it is possible to observe that SCAPM $<$ SCARM.
The SCREM agility metric instead is related to the time needed to re-achieve the target stock level in each node of the SC in order to be ready facing another situation. In this case, the SCREM is given by stock point 2. Indeed, this node is connected

upstream to the raw-materials stock point through a transportation stage, which is considered to have always enough capacity to transport the required quantities. On the other hand, it is limited in launching quantities by the finite capacity of Stage 2. The main issue in recovery its target stock level is given by the sudden decrease of demand at day 65. When external demand drops, the future requirement of node 3 on node 2 goes to zero for three periods, as the inventory position of node 3 keeps into account that more quantities than needed are going to be received.
When demand re-assesses on 100 units/day, node 2 will continue receiving 130 units/day for the whole frozen planning horizon of Stage 1, increasing its inventory level until day 77 and reaching 770 units of stock. Next, 100 units/day of this extra inventory are launched until the target stock of node 2 is reached at day 84.

Impact of information sharing on agility

In the end, it has been chosen to investigate the impact of a non-simultaneous information sharing system on agility.
Chapter 1 reports that authors consider information sharing capabilities as a pillar of agility, arguing that inappropriate communication and lack of visibility has a detrimental effect on the agile performance of the network.
To investigate this proposition it is considered the case where a lag time occurs before a stock point updates its supplier with the information of about the variation of external demand.
Let us consider scenario S11, assuming that managers have already tried to improve the SC agility level by reducing lead time of Stage 1 proactively. The backorder trend for the most downstream stock point in scenario S11 is reported in Figure 3.21.

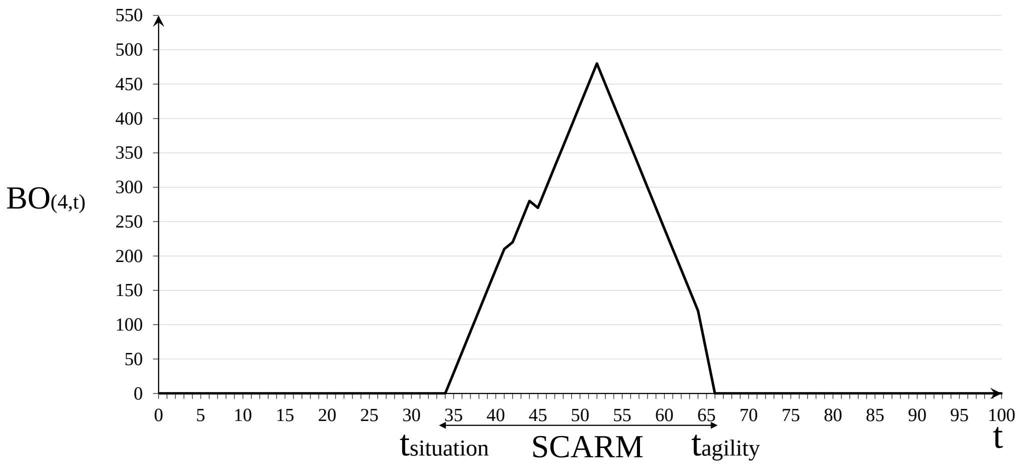

Figure 3.21. Evolution of backorders in scenario S11

Stock point 4 sees the variation of the external customer demand and orders its updated net requirement to node 3. However, it communicates the variation of the external mean demand after a certain time delay, defined reactivity delay $dr_{(3\to4,t)}$.
As a result, at day 35 stock point 3 receives the updated net requirement of its downstream client, but it has not information about the variation of external demand and keeps on planning with a forecast of 100 units/day for next the $dr_{(3\to4,t)}$ periods.

Table 3.5 reports the SCARM values varying this parameter.

Table 3.5. SCARM values varying the information lag time

Sub-scenarios of S11	$dr_{(3\to 4,t)}$ $[days]$	SCARM $[days]$
S11	0	31
S11.1	1	31
S11.2	2	31
S11.3	3	31
S11.4	4	31
S11.5	5	31
S11.6	6	31
S11.7	7	31
S11.8	8	32
S11.9	9	32
S11.10	10	33
S11.11	11	33
S11.12	12	34

It is possible to observe that if information sharing is not instantaneous and a certain period elapses from when the situation needing agility occurs and its communication to partners, the agile performance of the SC is impacted.
In this illustrative example, a lag time larger than 7 days has a negative impact on the system increasing SCARM, and the more it gets larger the more the system is impacted. Figure 3.22 shows how the lag influences the system.

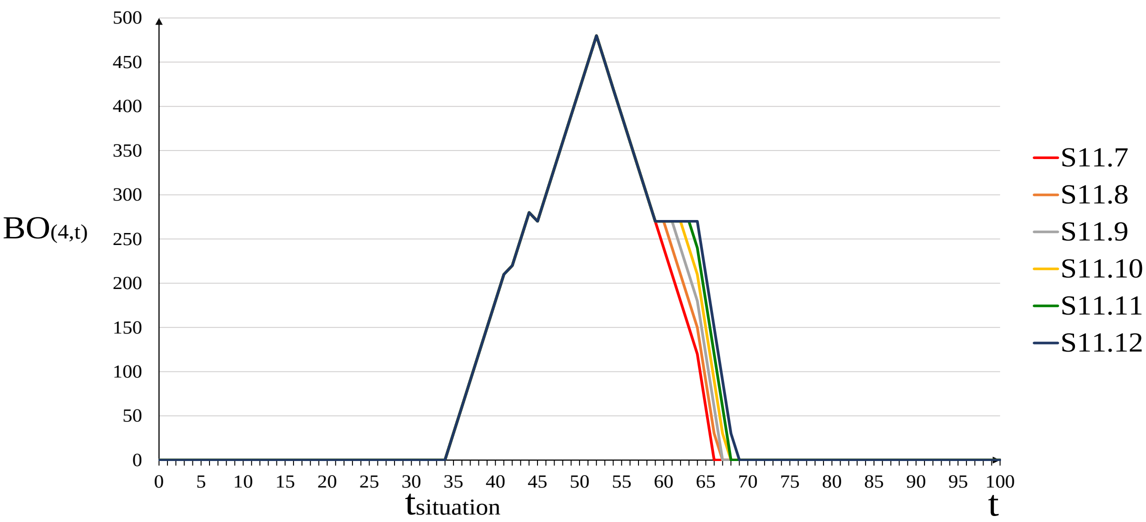

Figure 3.22. Impact of information lag time on backorders

A reactivity delay between nodes 3 and 4 prevents the update of planning horizons with the new external quantity for all the stock points upstream the affected connection. When the information sharing was instantaneous, the algorithm generated an order of 670 units at day 35 on the most upstream stock point, equivalent to the quantity needed from node 4 to fully satisfy backorders and the external demand accounting the time needed for goods to move from 1 to 4:

$$D_{(4,35)} + (L_{(1,t)} + F_{(1,t)} + L_{(2,t)} + L_{(3,t)}) * \Delta D = 670units \tag{3.46}$$

This would happen because all the nodes were able to plan their ordered quantities accounting an downstream demand equal to 130 units/day.
On the other hand, with a lag time the quantity ordered on stock point 1 is equivalent to the future requirement on node 3 at day 35, $FR_{(3\rightarrow 4,35)} = 340$ units. Indeed, if the external demand is not updated in all stock points simultaneously, it is considered a demand of 100 units/day in the planning horizon of upstream nodes and the variation of day 35 will be considered an isolated case.
Therefore, accounting also the existing stocks in nodes 2 and 3, the difference between scenario S11 and the ones with a generic reactivity delay is

$$670units - 340units - 60units = 270units \tag{3.47}$$

As a result, scenarios with reactivity delays order $270units$ less than the nominal scenario. For this reason, if the system is not able to recover this quantity before day 60 ($BO_{(4,60)} = 270$ units), the agile performance of the system starts decreasing.
The recovery of these units depends on the reactivity delay and on the bottleneck capacity of the system. Up to $dr_{(3\rightarrow 4,t)} = 7$ days upstream stock points are able to adapt their plans in time to the new external demand in a way that stock point receives 160 units/day, decreasing backorders with a slope of 30 units/day. Indeed:

$$t_{situation} + F_{(1,t)} + L_{(1,t)} + L_{(2,t)} + L_{(3,t)} + dr_{(3\rightarrow 4,t)} = 60 \tag{3.48}$$

For $dr_{(3\rightarrow 4,t)} > 7$ days the delay is too large and stock point 4 is not able to receive additional quantities before day 60, but only the 130 units/day required at each time. Therefore, the backorder trend results flat and the system and agile performance is impacted.
Once the planning horizon is updated, the system recovers backorders with a slope of 30 units/day or 60 units/day, depending on the value of the external customer demand. For example, in scenario S11.12 the system is able to recover backorders with a pace of 60 units/day, as at day 65 the demand re-assesses on its original value.

3.6 Conclusions

An agile SC can be defined as a dynamic supply-demand network which can adapt to the competitive and changing market environment (Zhu et al., 2021). It is composed of several actors and operational stages, which determine the complexity of the system. This chapter is focused on the development of a tool that allows to determine the agility level of a generic open-loop SC network.
This model embeds several elements: the parameters through which a SC configuration can be characterized, the situations needing agility presented in Section 1.4.1, agility metrics, the flow management policy adopted and agility levers.
It is based on dynamic equations that define the state of the system at every time t, starting from the state at the previous period $t-1$ and inputs occurring at time t.
It allows to determine the agility level of a network with respect to a situation needing

agility that occurred or that is going to occur. The metrics adopted give an indication of the time required to re-achieve nominal service levels when SNA happen, the anticipation time needed so that they do not impact the system and the time required to reach desired inventory levels after a disruption occurred.
In order to improve the agile performance of the SC under study, a set of agility levers related to the parameters of the system are modelled. The implementation of a lever with respect to others may generate different scenarios, as each of them can have a different impact on the system.
Managers may decide to apply a specific lever because of technical or organizational constraints, and the simulation model developed allows to quantify its impact and compare the different solutions in terms of agile performance.
In order to allow the use of this model, a decision-making tool has been created exploiting the interface between VBA and Microsoft Excel. It allows to simulate the information and material flows for a defined simulation period and an input configuration, observing the trend of backorders/lost sales, launched quantities, inventory levels, received quantities at each time t and for each stock point k. Besides, it calculates the three KPIs needed to assess the agile performance of the network.
In Chapter 2 it is shown that some authors present illustrative case studies to show the applicability of their models. Therefore, an illustrative example has been developed to analyse the impact of a sudden and temporary demand variation on a serial system. Besides the comparison of some scenarios generated by the activation of agility levers, it has been shown that a information sharing capabilities influence the agile performance of a system. Indeed, the example shows that if the information related to the occurring of a situation needing agility is not shared among partners of the chain within a certain time range, the SCARM increases.
The agile performance of a SC depends on a multiplicity of factors, and agility levers may impact the system in a different way depending on their time of application, their duration, the position along the chain where they are applied.
Similarly, situations requiring agility impacting the system can have different effects depending on the instant at which they occur, and this is highlighted when partners adopt batch sizes to launch products. Indeed, if no inventory is available in a stock point to counteract disruptions, their effects may be amplified.
As a general result, the simulations performed have shown that the interval of time needed to anticipate a threat (SCAPM) is smaller than the time needed to reactively recover it (SCARM).
Together with the performance of a system in terms of service levels, in Chapter 1 it has been shown that authors related SCA also to social, environmental and economic aspects. In (Zhu et al., 2021) it is argued that an agile SC to be competitive should enhance its business while emphasizing people and technologies that can face modern challenges, and in recent years the theme of sustainability is gaining increasing attention (Ciccullo et al., 2018).
For these reasons, Chapter 4 presents instruments to compare the scenarios obtained through the application of this simulation model not only under the agile performance point of view, but accounting also the sustainable cost supported to reach it.

Chapter 4

Comparison instruments

4.1 Introduction

The model presented in Chapter 3 allows to calculate the SCA level when a situation needing agility occurs and to investigate the most effective levers that enhance agile performance in terms of service level.
Levers are technical and managerial means that can be deployed to improve agility in SC networks, and in this model it is considered that they affect system's parameters. Nonetheless, a variety of actions can be implemented to activate each of them.
These actions can have different impacts on networks' agile performance, as well as different economic implications for organizations. For example, increasing the capacity of a stage by hiring new people or purchasing new machines may be substantially different in terms of costs.
Therefore, an instrument that can allow managers to keep into account the activation and run costs of agility levers is necessary to evaluate the best trade-off between agile and economic performance in the different simulated scenarios.
In addition, the growing consumer awareness for the environmental and social impact of products is leading companies for improving in terms of sustainability, and supply chains have faced the need for integrating sustainability measures in operational decision-making practices in recent years (Arıkan and Jammernegg, 2014b).
As instance, regulations of greenhouse gas (GHG) emissions and carbon cap-and-trade systems are gaining more consideration among academics and practitioners. An example is the European Union Emission Trading System, the first major carbon market that sets on the total amount of certain greenhouse gases that can be emitted by the installations covered by the system. Within the cap, installations buy or receive a limited number of emissions allowances which they can trade.
For these reasons, the following Chapter is dedicated to the modelling of costs related to agility levers in order to allow managers evaluating the most suitable trade-off between agile performance and lever's costs. This instrument has been then integrated to the simulation model shown in Chapter 3, providing a comparison method for the scenarios that can be obtained.
Next, it is presented a qualitative framework that may help managers to consider environmental and social benefits and drawbacks of the levers they apply.

4.2 Agility cost modelling

(Rabbani et al., 2021) argues that supply chains should answer to changes with proper service levels, considering the penalty fee resulting by failing to meet demand.
Agility levers become central to avoid these penalties, even if in most of cases their implementation generate additional costs. For example, the increase of production capacity in a reference period by adding extra-shifts leads to an increase of costs related to employees, energy, machines' utilisation.
Considering that SC managers could be concerned to achieve agility at the minimum cost, they should be aware of the economic impact related to the implementation of levers. Therefore, it can be useful to compare the scenarios obtained with simulations and decide which levers to apply in order to minimize SCARM given budget constraints, or oppositely to identify actions that minimize costs to achieve a targeted SCARM.
The cost of agility represents all expenses incurred to achieve the desired level of SCA. It is the sum of investments and operating costs resulting from the actions implemented and activated, i.e. the agility levers.
In Section 3.4.5 levers have been related to the improvement of the SC parameters (Lead time, Frozen planning period, Capacity), variation of order allocation policies, product outsourcing and variations of target inventory levels at each stock point. They are the results of technical and managerial decisions and could be obtained in different ways, generating different costs. For example, considering:

- **Increase of Capacity**

As the production capacity of an item is the time allocated on the production resource multiplied by its production rate, it can be increased either increasing the available time of the machine or the production rate. For these reasons, adding shifts or working overtime may increase the available time to produce, while purchasing new equipment, hiring people, or improving the effectiveness of resources may help improving the throughput.

- **Reduction of Lead time**

Lead time embeds several elements such as the process time, the inspection time, the move time, the wait time and carrying/transportation time depending on the type of operation considered. Its reduction may help to improve flexibility in rapidly changing markets, save transportation costs and replenish the stock faster to avoid stock-outs. Different actions can be considered to reduce it, such as selecting suppliers, third parties located closer to the facility or adopting faster transportation means.

- **Reduction of Frozen planning periods**

The frozen period is related to the scheduling of activities, and it may impact the availability of products. Companies may require some time for planning their operations in which downstream orders cannot be modified.
These fixed planning periods may lead to inflexibility, limiting the agility of a network. As instance, if the demand for a product surges the inability to reschedule production may lead to stock-outs, forcing companies to keep higher inventory buffers to assure appropriate service levels. On the other hand, if its demand slumps and it is on the

frozen production schedule, excess inventory is created.
Sharing sales data with suppliers, keep customers up to date with appropriate communication means can help reduce their frozen periods. For example, if seasonality determines fluctuations of customer's demand, informing suppliers that an increase is expected may allow them to be prepared handling new quantities as quickly as possible. Besides, the increase of planning frequency by reducing the time needed to generate manufacturing and purchasing plans can help enhancing reactivity.

- **Product outsourcing**

As explained in Chapter 1, the purchasing of finished or intermediate products from third-parties or competitors can improve the agility of a SC by enhancing timeliness and customer satisfaction. (Contractor et al., 2010) addresses outsourcing as a strategy aimed to increase efficiency, reduce costs, explore the knowledge of other companies and exploit the development of foreign markets. Indeed, this technique can be performed either in the same nation of the firm or offshoring abroad.

- **Variation of the order allocation policy**

In Section 3.4.5 is stated that multi-sourcing strategies can enhance agility by improving the SC's responsiveness. Minner (2003) explains that two main strategies can be adopted: dual or contingency sourcing. The first one considers that the replenishment quantity is split among suppliers and placed simultaneously. On the other hand, in contingency sourcing orders are placed mainly to a supplier, while others are used as a backup only in case the primary one cannot meet the requirement. For example, a supplier with shorter lead time can be used as a contingent source if the cheaper one is insufficient. Therefore, the variation of the order allocation policy adopted to face situations needing agility can determine additional costs.

- **Variation of target stock levels**

As shown in the illustrative case study in Section 3.5.3, the increase of target stock levels kept in a node can counteract situations needing agility enhancing performance and reducing lost sales and backorder levels. Nonetheless, it should be accounted that high inventory levels generate additional holding costs, which generally increase the more downstream on the chain they are kept.

Due to the diversity of actions that can be deployed to activate a lever, the cost of their implementation has been modelled considering the operating expenses for purchasing, processing and distributing materials, parts, and finished products.
Expenses have been categorized into direct costs, which are directly associated to the output (e.g. material acquisition, salaries), and indirect costs, that cannot be directly assigned to an output (e.g. rents for product equipment, energy consumption, administrative costs).
Direct costs are considered variable, therefore they vary in proportion to the duration of the activation of the lever. In contrast, indirect costs can be either fixed or variable. For these reasons, agility levers have been modelled considering both their fixed activation cost and the variable one associated to ongoing operations during the interval of their activation. Also costs related to outsourced quantities of intermediate

or final goods are considered.
Therefore, the total cost incurred to reach the agile performance level of the scenario under study is:

$$Cost\ of\ agility = Operating\ costs + Outsourcing\ costs \tag{4.1}$$

Defining j the generic agility lever activated and $\Delta_{(j)}$ the duration of its activation, its operating cost $OP_{(j)}$ is given by the sum of its fixed and variable costs.
Said $FC_{(j)}$ the fixed cost for its activation and $VC_{(j)}$ its ongoing expenses:

$$OP_{(j)} = FC_{(j)} + VC_{(j)} * \Delta_{(j)} \tag{4.2}$$

Therefore, the total operating cost of the scenario under study is the sum of all the agility lever activated:

$$Operating\ costs = \sum_{\forall j} OP_{(j)} \tag{4.3}$$

It is observed that generally the costs of implementation of agility levers increases the more downstream the chain they are activated.
Similarly, the outsourcing cost depends on the type of product purchased, as generally a finished product is more expensive than an intermediate one. To calculate this cost it is taken into account the stock point involved and the unitary price of the purchased quantities. Said $PQ_{(k,t)}$ the purchased quantity at stock point k at time t and $u_{(k)}$ their unitary price of the product stocked in k, the total cost of outsourcing is:

$$Outsourcing\ costs = \sum_{t=1}^{T} \sum_{k=1}^{K} (PQ_{(k,t)} * u_{(k)}) \tag{4.4}$$

This model allows to compare the different scenario simulated with SCAEM, accounting for the budget needed for the activation of levers in order to respond to a situation needing agility. In this way the tool allows to face two problems: identify the most suitable levers to minimize agility costs while reaching an acceptable performance or maximize this latter at the minimum agility cost.
Nonetheless, the actions through which a lever is activated influence not only the cost of agility, but also its environmental and social impact. In the next section, a qualitative framework based on a literature research is presented to take into account also these two sustainability aspects in the decision-making process.

4.3 Sustainability in the decision-making process

Supply chains consist of the set of processes such as production, sourcing, transport or warehousing activities needed to supply customers with the required products.
SC management decisions are generally based on the economic performance of the involved parties, like profit and customer service. Economic evaluations influence the adoption of strategies (e.g. outsourcing, offshoring, centralization of production and warehouse facilities) to manage flows across the SC (Rosič and Jammernegg, 2013).
Nonetheless, in recent years supply chains have been facing pressures from stakeholders for sustainable business development, therefore for including social and environmental

performance measures into the conventional metrics (V. Sharma et al., 2021).
For example, the measurement of carbon emissions related to companies' activities is gaining increasing attention, as they have been addressed to be a major cause of the greenhouse gas effect (Rosič and Jammernegg, 2013).
Golini et al. (2014) argue that companies should be committed to sustainability, safeguarding the environment and the welfare of people. They consider the interrelationship among society, environment and economic development the pillar of sustainability: the economic dimension is related to the ability of generating cash flow and produce a long term return; the environmental one to the consumption of natural resources at a slower pace than their regeneration; social sustainability to the fostering of health and welfare of people inside and outside company's borders.
Despite the increasing attention given to these topics, only a few authors have investigated the relationship among SC agility and environmental or social sustainability (Ciccullo et al., 2018). In particular, in their systematic literature review on lean, agile and sustainable paradigms, Ciccullo et al. (2018) highlight that agility has received a very little attention with regard to social sustainability, and only a few studies in the SC literature focus on it.
In order to help managers taking into account sustainable decisions when dealing with SC agility, it has been decided to build a theoretical framework based on a literature research. It is focused on the sustainable impact of decisions to improve the agility of a network, therefore on environmental and social effects of agility levers.

4.3.1 Environmental and social sustainability of agility levers

The activation of the agility levers presented in Chapter 3 can be performed in several ways, most of which can have a positive or negative impact on sustainability.
The costs of manufacturing, distribution, transshipment modelled in Section 4.2 are associated to the internal costs of the network, as they are connected with the physical flow of units between clients and suppliers. On the other hand, externalities related to sustainability can be considered as the burdens that are indirectly related to the activities of a supply chain (Ortolani et al., 2011).
The implementation of agility levers can contribute to increase external costs, therefore managers may be interest in activating levers through actions that can reduce the environmental and social drawbacks of their supply chains.
Considering the increase of production capacity, Tridech and Cheng (2011) argue that the environmental impact of manufacturing activities can be reduced by the lowering of carbon dioxide from source, the enhancement of energy efficiency, the minimization of wastes and the improvement of resource's utilization.
The authors state that industrial machines exploit electricity as primary energy, therefore adjusting, improving or renewing equipment helps reducing the carbon dioxide intensity emitted while increasing the throughput. Besides, the enhancement of machines' utilisation reduces CO_2 emissions by diminishing the waste of energy and improving its efficient utilisation.
Franciosi et al. (2018) recognise that also sustainable maintenance activities increase productivity while reducing environmental problems such as hazardous emissions, production waste, in-efficient energy and resource consumption. They report that such activities improve also human safety, reducing accidents and ameliorating unhealthy

working conditions.
Production capacity can be improved also enhancing workforce utilisation. Working overtime, adding extra-shifts or hiring employees can help enhancing the throughput. Nonetheless, several authors have pointed out the risks of long working hours on health (Dembe et al., 2005; Devetter and Rousseau, 2011).
Wong et al. (2019) argue that these practices can bring to cardiovascular and cerebrovascular diseases, depression, stress, injuries that decrease the productivity of workers. Similarly, Costa (1996) states that shifts and night work can harm health and well-being of workers, generating issues in maintaining relationships both at family and social level.
These strategies can have an impact also on environmental sustainability. In (Devetter and Rousseau, 2011; Fitzgerald et al., 2015) overtime working hours are related to higher incomes and higher domestic consumption levels that lead people to choose non-ecological solutions. In addition, Fitzgerald et al. (2015) highlight that long working hours are related to an increase of energy consumption. They point out that this phenomenon is amplified when capacity-outsourcing techniques in developing countries are adopted, endangering both their social and environmental sustainability. On the contrary, employees' training and empowerment can result in an increase of throughput and in a sustainable choice.
Training workers to several tasks instead of being highly-specialised can enhance agile capabilities to face unforeseen events, and the support of the top management towards environmental issues can foster a sustainable organizational culture (Daily and Huang, 2001). Moreover, the enhancement of employment levels can improve productivity while bringing benefits to workers, as employed people report lower levels of depression and distress with respect to unemployed individuals (Creed and Macintyre, 2001).
Beside increasing production capacity, reducing lead time of the operations composing the network can help enhancing the agility level of a SC. This lever is related to operations' speed and variability, therefore to transportation and logistics activities. X. Chen and Wang (2016) state that these operations represent a significant portion of the total carbon emission throughout the whole SC and that each transportation mode has different characteristics that lead to different environmental performance. Their study reports that companies tend to adopt the cheapest transportation solution when cap-and-trade emissions systems are not applied, while ecological decisions are taken into consideration when emission limits are imposed. They argue that the use of transportation means that guarantees shorter lead time within emissions allowances can positively mitigate the environmental impact of a SC. On the other hand, the choice of the cheapest and fastest mean may increase emissions (Arıkan and Jammernegg, 2014b).
Skrucany et al. (2018) state that to make the transport of goods sustainable the choice of transportation modes must account their energy consumption, the greenhouse gas production levels, the quantity and nature of the transported goods and the traction or fuel used. In their research they compare road, water and rail transports, showing that railway transportation modes are the ones that emit less tons of pollutants to cover the same distance and with the same cargo parameters. Oppositely, trucks are the most polluting and widely used freight transports (Konur and Schaefer, 2014).
Another way to improve the environmental impact while reducing lead time could be the purchasing of goods from on-shore suppliers (Arıkan, Fichtinger, et al., 2014a).

Arıkan and Jammernegg (2014b) show in their study that selecting on-shore suppliers can reduce emissions and lead-time variability with respect to off-shore solutions, without endangering profits.
Besides the environmental impact of transportation and logistics activities, also their social effects should be accounted. Indeed, they can represent a threat for health due to the generation of vibrations, noise and pollutants in the air, as well as a danger for the housing, cultural/aesthetic values of people when lands need to be over-exploited for the existence of transportation paths (Dora et al., 2000).
In (Bouchery et al., 2012) authors propose an inventory management model defined Sustainable Order Quantity (SOQ), aimed to provide the optimal order quantity, the safety stock level, and the transportation means to minimize logistic and environmental costs. Digiesi et al. (2013) affirm that fast transportation means allow to reduce the variability of lead time, but they are characterized by the highest costs of externalities. On the contrary, slow transportation give lower external costs while require high inventory level due to large order quantity.
The increase of stock levels can generate externalities depending on the type of product that has to be stocked. For example, items that need refrigeration systems increase the energy consumption, while disposal of goods can enhance wastages and lands exploitation (Z. Li et al., 2019). In addition, companies might face the need to get rid of excess inventory levels of a specific product to make buffer space for unpredictable situations (Pourhejazy, 2020).
Pourhejazy (2020) investigates the impact on sustainability of destruction decisions to eliminate excess inventory. The author argues that this technique may be necessary to avoid additional expenses or to improve operational flexibility. This research points out that such activity can have a detrimental effect on sustainability, as the burning or discarding of useless substances can cause environmental issues and health risks.
In order to avoid inventory management problems when SC's internal or external situations occur, the definition of reliable and accurate schedules can help improving agility by allowing a reduction of frozen planning periods, increasing the flexibility of demand-supply activities.
In their literature review on operations' scheduling for waste minimization, Le Hesran et al. (2019) argue that incorporating sustainability aspects into the operational production scheduling can improve energy-efficiency and reduce wastes.
Authors investigate the relationship between scheduling activities and wastage in production processes, highlighting that wastes may be present in several elements characteristic of manufacturing (e.g. batch dimension, setup times, operation sequencing). They state that proper scheduling can increase production flexibility and reactivity. In addition, schedules that account for uncertainty are helpful to mitigate risks and ensure robustness, limiting wastes even in case of unforeseen events.
As already stated in Chapter 1, unexpected situations that affect supply chains can be effectively mitigated using multi-sourcing solutions. Minner (2003) explains that several authors have integrated environmental initiatives into multi-supplier inventory models in order to take into account emissions related to production, transportation and stocks of sourcing operations.
In (Azadnia et al., 2015) it is proposed a model aimed to help companies selecting the appropriate suppliers for each product and period while optimising their lot size based on sustainability criteria. It is built a supplier-evaluation tool that can allow companies

to recognise the opportunities given by the improvement of suppliers' sustainability. The proposed approach can be used as a map for suppliers to constantly assess and evaluate themselves rather than be assessed by other organisations which are seeking for sustainable suppliers, and that considering sustainability issues on multi-period, multi-product lot-sizing can lead to a better value of sustainable purchasing.
In order to assess the environmental impact of dual-sourcing solutions when considering offshore suppliers, Rosič and Jammernegg (2013) investigate the carbon emissions related to the combined sourcing by an off-shore supplier (long lead time, cheap and inflexible) and an on-shore one (short lead time, flexible and expensive).
Their results indicate that using a dual sourcing strategy instead of a single offshore supplier helps improving both the economic and environmental performance of the SC. In addition, they show that multi-sourcing becomes advantageous under the environmental point of view if carbon regulations are considered, as the emissions related to transport further reduce.
Also in (Nourmohamadi Shalke et al., 2018) authors report that the selection of suppliers considering economic, social and environmental aspects may demonstrate superior performance. They investigate the impact of choosing and allocate orders to suppliers which guarantee larger discounts on environmental and social sustainability, considering parameters such as the GHG emissions and workers safety/health.
Results indicate that the allocation of orders to suppliers that assure best discounts may not allow to achieve the sustainable objective desired.
Price discounts are related also to product outsourcing activities, that is another technique considered to improve the agility of a SC. The purchasing of quantities from an external company can be an effective method to reduce the time needed to recover backorder or lost-sales, and it can be performed either onshore or offshore.
Choi and Yu (2018) affirm that a firm's decision to outsource can be driven by a variety of factors including the lowering of labour costs, technology, organizational competency. Their research highlights that goods' outsourcing can have a detrimental effect on the environment of countries where the product is purchased.
They propose the tightening of environmental regulations and the fostering of international cooperation to promote welfare by fully internalize external costs to avoid over-outsourcing and environmental deterioration in the vendor country.
In addition, in (Sarkar et al., 2018) authors argue that the reworking in local stores of potential defective parts received by outsourcing activities can improve the sustainability of the SC with respect to the application of return policies, above all when the distance between actors is significant.
In the end, Ramioul and De Bruyn (2008) point out the social benefits and drawbacks of outsourcing. On the first side, the author affirms that for some countries it implies a growing specialisation in high-tech and knowledge-intensive activities, while it can negatively impact working conditions, wages and quality of production.
The author argues that several techniques can be adopted to improve the social sustainability of this practice. For example, the effective redeployment of existing employees displaced by the introduction of offshoring, the training and support if alternative employment is necessary, the enhancement of employees' skills.
All the aspects related to environmental and social sustainability are respectively reported in Table 4.1 and 4.2, in order to provide a framework that may be taken into account by managers when applying agility levers.

Table 4.1. Agility levers impacting environmental sustainability

Agility Lever	**Positive environmental impact**	**Negative environmental impact**
Capacity increase	• Sustainable maintenance *(Franciosi et al., 2018)* • Low-carbon manufacturing *(Tridech and Cheng, 2011)* • Employee's training *(Daily and Huang, 2001)*	• Overtime *(Devetter and Rousseau, 2011)* • Working-shifts *(Fitzgerald et al., 2015)* • Off-shore capacity outsourcing *(Fitzgerald et al., 2015)*
Lead time reduction	• Low-emission transportation means *(X. Chen and Wang, 2016)* • On-shore supply *(Arıkan, Fichtinger, et al., 2014a)*	• High energy/GHG transportation means *(Arıkan and Jammernegg, 2014b)*
Frozen period reduction	• Scheduling activities embedding sustainable aspects *(Le Hesran et al., 2019)*	
Product outsourcing	• Internalize external costs *(Choi and Yu, 2018)* • Rework defective parts *(Sarkar et al., 2018)*	• Outsource from off-shore countries *(Choi and Yu, 2018)*
Order allocation policy	• Promote sustainable suppliers *(Azadnia et al., 2015)*	• Sourcing from a single offshore supplier *(Rosič and Jammernegg, 2013)*
Variation of stock levels	• Sustainable inventory control models *(Digiesi et al., 2013)* *(Konur and Schaefer, 2014)*	• Increase of inventory levels *(Z. Li et al., 2019)* • Inventory destroy techniques *(Pourhejazy, 2020)*

Table 4.2. Agility levers impacting social sustainability

Agility Lever	**Positive social impact**	**Negative social impact**
Capacity increase	• Sustainable maintenance *(Franciosi et al., 2018)* • Employment levels *(Creed and Macintyre, 2001)* • Training of workers *(Daily and Huang, 2001)*	• Overtime *(Devetter and Rousseau, 2011)* • Working-shifts *(Fitzgerald et al., 2015)*
Lead time reduction		• Transportation modes impacting people's health/habits *(Dora et al., 2000)*
Product outsourcing	• Global sharing of knowledge *(Ramioul and De Bruyn, 2008)*	• Externalize production *(Ramioul and De Bruyn, 2008)*
Order allocation policy		• Allocation of orders only according to discounts *(Nourmohamadi Shalke et al., 2018)*
Variation of stock levels		• Inventory destroy techniques *(Pourhejazy, 2020)*

4.4 Conclusions

This Chapter is aimed to provide comparison instruments that can be taken into account to evaluate the choice of levers when improving the SC agile performance.
Economic, environmental and social aspects of agility levers have been investigated, in order to build a framework that allows to consider the sustainable aspects of agility in the decision-making process.
Sustainability in supply chains is gaining attention in recent years, both because it represents an essential element for the preservation of social and environmental values and because of its role in the profit growth of organizations. In (Golini et al., 2014) it is associated to economic performance and profits, to environmental preservation and safety, to social responsibility both within and outside the organization's borders.
Regarding the economic aspect of sustainability, a cost model has been developed. It allows to estimate the activation and operative costs of agility levers, in order to allow managers choosing the most suitable actions that can guarantee adequate agile performance under a constraining budget or the ones that maximize agility at the minimum cost.
In literature costs related to the movement, processing and management of goods are addressed as internal costs of the SC. Nonetheless, these activities may indirectly reflect on environmental and social aspects, generating also external costs.
The increasing customers' awareness toward environmental issues and the introduction of regulatory measures like the Emission Trading System, carbon cap-and-trade and carbon taxes have led researchers to investigate the impact of network's activities on ecological aspects. On the other hand, just a few works related to social sustainability have been found in literature, confirming the study of (Ciccullo et al., 2018).
This lack of researches is highlighted observing Table 4.2, where only a few articles regarding the effects of agility levers on social sustainability have been found. For example, no articles on the social impacts of variations of schedules and frozen planning periods on social aspects were detected, as well as related to the reduction of lead time or to stock levels.
Golini et al. (2014) argue that the development of sustainable competencies in all the plants composing a SC can enhance the performance of networks. They show that site competencies regarding environmental and social issues can positive influence the impact on sustainability of a SC influencing production, procurement and distribution operations. In order to develop them, the support and the awareness of top management on the benefits deriving from the enhancement of sustainability is needed.
Observing Tables 4.1 and 4.2, it can be noticed that the role of management is central in taking decision regarding sustainability issues, as the activation of some actions requires long-term plans and investments.For example, performing sustainable maintenance activities and adopt maintenance 4.0 in companies may require analyses and planning activities, while working overtime can be seen as a short-term solution both in terms of implementation and planning.
For these reasons, this Chapter focused on the determination of actions that can enhance the agility of SC networks while impacting sustainability, allowing managers to account in their decisions the trade-off between agile and economic, environmental, social performance.

Chapter 5

Case study

5.1 Introduction

In Chapter 3 it is presented the mathematical and simulation model developed to calculate the SC agility level, while Chapter 4 describes both quantitative and qualitative ways to evaluate the impact of agility levers on the system.
This chapter is aimed to validate the theoretical research performed through a case study in a real company, showing the applicability of the decision-making tool built. It is targeted to give an indication of the significance of the topic addressed, providing organizational and managerial insights for the company that can be exploited to improve its performance in terms of service levels. Besides, it is also aimed to show the novelty of this topic, stimulating future researchers on the development of quantitative models to evaluate and enhance SC agility levels of networks.
The application has been performed in collaboration with BCS, a leader company in the production of agricultural machinery located in Abbiategrasso, between April 2021 and June 2021.
This chapter is organized as follows. First, the company and the supply chain of the product under study are presented, defining their position in the business context. Then, Section 5.3 is dedicated to the description of the case study methodology adopted. It is provided a description of the product and its innovativeness in the market of agricultural machines, as well as the framework adopted to perform interviews and the analyses. It is based on 6 steps that recall the elements modelled in Chapter 3 and 4, focusing on the determination of disrupting events and levers that can mitigate them. Data are gathered through interviews based on a questionnaire and performed to professional figures internal to the company belonging to different departments. The questionnaire is reported in Appendix B, while the data gathered in Appendix C. In the end, Section 5.4 reports the application of the simulation model to the company. One main situation needing agility that can affect the performance of the product's supply chain emerged from the interviews, and it has been analysed both considering proactive and reactive mitigating solutions.

5.2 Company profile

BCS is a member of the BCS S.p.A. Group, a corporation composed of 4 companies and leader in terms of sales and profits in the production of agricultural machinery and machines for the autonomous production of electricity.
Its headquarter is located in Abbiategrasso (MI) where there is one of the three manufacturing plants and R&D centres. Together with the ones in Luzzara (RE) and Cusago (MI), the Group expands for an overall surface of $300000m^2$.
Founded in 1943, it is specialised in the production of green-maintenance and farming machines, generating sets, engine driven welders and lighting towers.
It has subsidiaries in Spain, France, Portugal, Brazil, Germany, India, China and USA, and a series of distributors all over the world that allowed its expansion worldwide.
The case study has been performed in the headquarter of Abbiategrasso, where all the single-axle machinery (two-wheel tractors, motor mowers), professional lawn-mowers and haymaking equipment are designed, built and set up.
The factory plant expands for over $70000m^2$ with more than 300 employees, and most of the manufacturing processes to produce mechanical parts take place internally. Indeed, the company has Computer Numerical Control machines to manufacture gearboxes, axles, gears, transmission axles and other products' components as well as painting and quality control systems, thermal processes, assembly lines.
The internalisation of such manufacturing activities allowed to improve the standards of quality and reliability in each phase of the production process. In addition, it permits the minimization of semi-finished goods' outsourcing, with the consequent risks of defective or low-quality parts.
Its supply chain is composed of a set of suppliers for the procurement of raw-materials, a manufacturing and assembly centre where raw materials are transformed in final products, a logistics/distribution warehouse equipped for the packaging and shipping of goods to retailers and dealers.
Its suppliers are located either onshore or offshore, and are chosen mainly depending on the procurement lead times they guarantee and on costs of raw material.
Similarly, the company operates in local and foreign markets, producing a large assortment of machines that can suit the different requests. For example, its product portfolio includes hobby and professional machines, products certified for the European and North-American markets, machines homologised for Asian and African channels.
The implementation of manufacturing activities almost completely internally the plant and the standardisation of most of the parts composing the machines allow the company to manage the production mix to face demand fluctuations. Nonetheless, in case of high seasonality or unexpected changes of demand, capacity outsourcing from third parties can be used to perform mechanical processes and assure service levels.
Besides, in order to increase such levels and verticalize processes, a single automated spare parts warehouse is set up for all machine's components. The various production centres are integrated with each other, both through a single information system that plans and manages deliveries and through a fleet of vehicles dedicated to supplies within the Group.

5.3 Case study methodology

The case study technique has been chosen to validate the model proposed in Chapter 3, addressing a phenomenon that is gaining attention in the context of the organization under study in recent years.
After the breakout of COVID-19, the industry of agricultural machines has seen a rapid growth of demand, combined with a set of issues related to restrictions and procurement of materials. Companies had to face a series of unforeseen situations that threatened their survival, highlighting the importance of agility in supply chains. Therefore, it has been chosen to perform an explanatory case study in order to explore the level of agility of the company under study and its impact on performance.BCS represents the unit of analysis, and data gathering has been performed through interviews based on a questionnaire. It is reported in Appendix B.
Because of the lack of a SC manager, this questionnaire has been proposed to 13 professional figures inside the company belonging to the purchasing department, the sales office, the logistics and the production divisions.
Semi-structured interviews with a mean duration of 30 minutes each have been used to gather data regarding the structure of the SC under study, the situations needing agility that may afflict the company and potential managerial or technical agility levers. Both quantitative and qualitative data have been gathered, based on the experience of the respondent.
The analysis has been carried out on the SC of an innovative product that BCS has recently introduced to the market. It constitutes a representative case for the study of agility, as it has a short life-cycle and it can be subjected to several situations needing agility (Gyarmathy et al., 2020).
The product under study represents an innovation in the market of single-axle agricultural machines as it encloses the capabilities of motor mowers and two-wheel tractors in the same machine, defining an hybrid with the benefits of both the type of devices. Besides, it represents the first product of this kind appeared in the market.
It adopts a multi-plate clutch with a continuously variable transmission and a hydrostatic transmission that outweighs typical issues related to safety and movement capabilities. According to the design director, these features will allow different categories of customers to approach it, even if it is designed as a professional machine. Due to its novelty and selling price closer to already existing products, the company has estimated that it will bring to an increase around $7,5\%$ of profits next year. In addition, according to their forecasts its production will cannibalize two other machines in future years, further increasing its demand and allowing the creation of a whole range of products with the same characteristics.
According to the company, this product will be produced with high frequency and medium volumes in next periods, and a series of opportunities and threats related to the launching of a new product can occur in the immediate future.
The analysis of the supply chain agility level of this product has been performed following the framework shown in Figure 5.1. It is based on 6 steps.

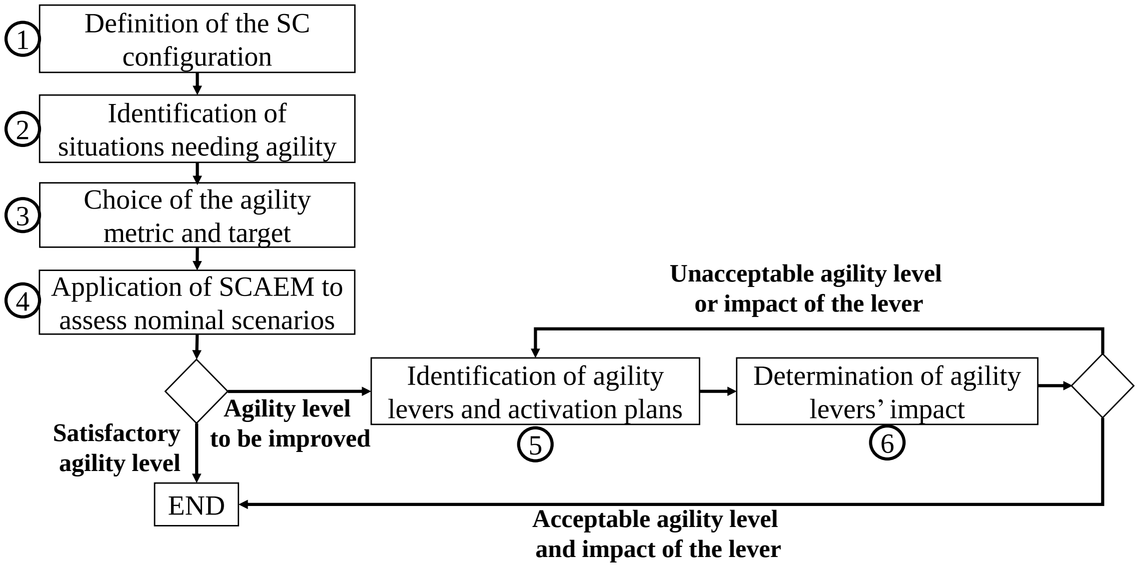

Figure 5.1. Case study methodology

1. Definition of the SC configuration

The first step has been the definition of the SC configuration and the gathering of the necessary data to apply the simulation model.
This phase has involved various sectors of the company, and it allowed to understand which are the main components needed to produce one unit of final product, its markets, the location of suppliers, their lead times and frozen periods.
According to the purchasing department and the production division, to assembly one unit of final product 8 groups of sub-components are required. Some of them need to be processed through manufacturing operations once received by suppliers, and these phases are performed internally the plant.
Raw materials are purchased mainly onshore, even if engines and the hydraulic groups for the transmission are bought directly from the producer, respectively in China and Japan. These latter are supplied by boat, while road transportation is preferred for all the other components. The purchasing department confirmed the assumption of ample capacity of transportation activities, stating that they have never had capacity limitations imposed by the transportation modes adopted.
The sales office provided information related to the markets where this product is planned to be sold, the total average demand expected and its proportion in each market, the transportation means adopted by BCS to ship its products and the corresponding lead times. It is reported in Appendix C.
According to their market analysis, around the 20% of the produced machines are intended for the North-American market, the 30% for the Italian one and the 50% for the rest of Europe. There is not a prioritization of such channels, indeed they are served according to an order proportional allocation policy. Road transportation is preferred for continental deliveries while ship is used for out-of-Europe transports.
The company adopts a backlog policy, indeed in most of cases its clients are willing to wait for products for a certain time in case of stock-out situations.

2. Identification of situations needing agility

This step can be done either proactively or reactively, in order to mitigate potential situations or after the occurrence of a threat or opportunity.
As explained in Chapter 1, the evaluation and improvement of SC agility should start from an analysis of the internal and external context in which the network evolves.
From the interviews performed to the sales departments it emerged that one main situation needing agility concerns the company.
It is related to the marketing campaign that is scheduled for the promotion of the product. The sales department estimates that it could bring to an increase of demand up to the 50% for the American market, where the product is already gaining good consensus. Nonetheless, the assembly line has been built with a finite capacity to guarantee the production of 40 units/week, which could be incremented up to 50 units/week if the market would require it. As a result, large demand variations may not be met.

3. Agility metrics and targets

After having identified the situations needing agility, appropriate metrics should be chosen to calculate their impact.
Considering the KPIs presented in Section 3.2, their selection depends on whether the occurrence of the situation is sudden or if it can be detected sufficiently in advance.
The organization can define an agility target depending on data available, and it is related to customer requirements, enterprise marketing strategy, to competition compulsions, legislation or internal strategies and policies.
The acceptable time range to satisfy customers demand without losing major sales has been set to 4 weeks. As it is a situation which effects can be anticipated proactively, the SCAPM has been chosen to evaluate the impact of such situation and schedule activities properly. Then, the SCARM of the SC is analysed to investigate which actions could be undertaken in case of reactive response.

4. Application of SCAEM

After having collected the data about the SC configuration and the situations needing agility to analyse, it is possible to apply SCAEM. It allows to evaluate the impact of the situations on the system providing the nominal scenarios to which, in case of unsatisfactory agile performance, apply levers.
After calculating the selected metrics, the agility level of the supply chain corresponding to the each situation is compared to the target fixed. If it is satisfied the process comes to its end, otherwise agility levers can be applied to improve it.

5. Identification of agility levers and activation plans

The first step to improve agile performance is the identification of applicable agility levers and their implementation actions.
This phase has been performed through interviews to the purchasing department, the production division and the sales office. It emerged that the main techniques through which the company is disposed to increase its SC agility level are:

- Reduce the frozen planning periods required by the company in case of extreme urgent situations. The company has a planning production horizon of 4 weeks, which could be reduced up to 0 to not lose important sales.
- Reduce lead times by exploiting faster transportation means in case of offshore supplies or deliveries. Air transportation allows to reduce the time needed to receive or ship product to 1 week.
- Increase the production capacity of assembly operations by enhancing the workforce utilisation through overtime or pivoting employees towards bottleneck operations. As already said, the assembly line is designed to have a throughput around 40 units/week, which can be increased up to 50 units/week due to physical constraints.

The sustainable evaluation of this levers can be performed using the agility cost model and the theoretical framework proposed in Chapter 4.
The company has chosen to not give detailed information related to costs, stating that the change of transportation means is performed only in exceptional cases. On the other hand, the enhancement of workforce utilisation is widely exploited.

6. Determination of the agility levers' impact

Once identified the agility levers that the company could apply to increase the agile performance of each scenario, it is possible to apply SCAEM to simulate their impact. In this phase it has to be considered the activation time and the duration of each lever implemented.
Besides the impact on agile performance, the agility cost model and the theoretical frameworks proposed in Chapter 4 allow to evaluate also the sustainability of selected actions. In this way, it is possible to determine the actions that maximize the agility level with the minimum sustainable impact.
Once estimated the impact of the agility levers applied, the updated value of the chosen agility metric is analysed. If the agile performance is adequate to the requirements of the company and the impact on economic, environmental and social sustainability are acceptable, the process ends. On the other hand, if the activation plan of agility actions is not feasible different agility levers or a different combination of them should be identified and applied, steps 5 and 6 are repeated.

5.4 Analysis and results

The first step to analyse the impact of the situation needing agility on the SC of the product has been the representation of its configuration. For the sake of simplicity, its simplified scheme is reported in Figure 5.2 while in Appendix C data are embedded. The 8 groups of suppliers represent the sources of raw materials, and some of them are processed inside the plant and then assembled on the assembly lines.
Considering stock points from 1 to 8, they respectively represent the sheets metal, gears raw-materials, crankcases, parts for clutches, hulls, wheels, hydrostatic group and engines. Only the last two are purchased offshore directly from the manufacturer and are shipped by boat, while the ones located in Italy and transported by trucks.

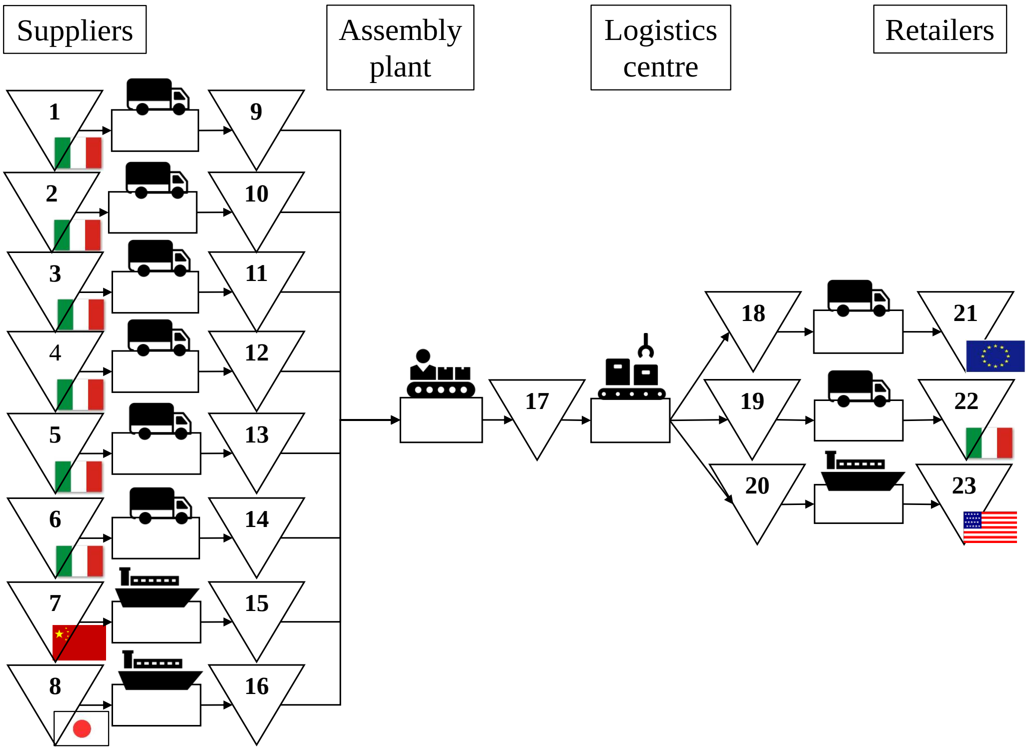

Figure 5.2. Representation of the product's SC configuration

Similarly, the final product is distributed by truck in the Italian and European markets, while boat transportation is preferred for shipments in the USA. It is reminded that the Italian market accounts for the 30% of the overall demand of the product, the European for the 50% and the North-American for the remaining 20%.
The company has visibility only on its immediate upstream and immediate downstream levels, therefore no information has been provided regarding the manufacturing operations of the suppliers or the distribution operations of retailers.
All the data used to implement SCAEM and to initialise the model are reported in Appendix C.

5.4.1 Application of the model

As the increase of the USA market's demand should derive from a promotional campaign, the company could proactively anticipate it to not have any backorder.
It is worthwhile to notice that the increase of demand of a distribution channel provokes a reduction of service levels in all markets if the system is not able to face it immediately and a proportional stock allocation policy is adopted. Indeed, to each channel is allocated a fraction corresponding to the proportion it ordered with respect the total order coming at each period.
Nonetheless, the SCAPM metric represents the detection time needed by the whole SC to not have any reduction of service level. Therefore it accounts for the channel that requires a largest anticipation time to not be affected by the disruption.
The simulation of the nominal scenario showed that 18 weeks would be needed to re-acquire performance levels, highlighting an unsatisfactory level of agility. Accord-

ingly, an investigation has been performed to observe the detection time to achieve the maximum acceptable SCARM targeted by the company and the SCAPM value. $\Delta_{detection}$ represents the number of weeks needed to anticipate the disruption before its occurring and obtain the associated SCARM. Table 5.1 reports the results.

Table 5.1. Detection interval needed to achieve the targeted SCARM

$\Delta_{detection}$ $[wk]$	SCARM $[wk]$
0	18
-1	17
-2	15
-3	14
-4	12
-5	11
-6	9
-7	8
-8	7
-9	5
-10	**3**
-11	2
-12	**0**

Therefore, the company has to account for the variation of demand at least 12 weeks before its occurring to not have reduction in performance levels or at least 10 weeks before to respect the targeted SCARM = 4 weeks.
Nonetheless, these simulations have been performed accounting that the company is momentarily not keeping any stock of end-product, as the ones produced are already sold and they are still trying to understand the machine's reachability on the market. However, in Section 3.4.5 the variation of target stocks is addressed as the only exclusively proactive agility lever. Therefore, an analyses has been carried out to investigate how a buffer stock in the logistics centre could reduce the detection interval needed to achieve the targeted SCARM and the SCAPM.

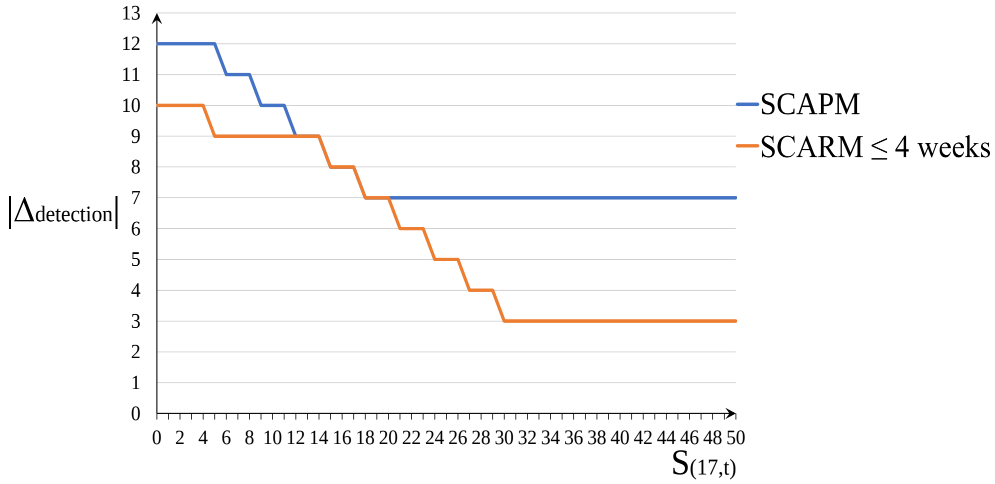

Figure 5.3. Impact of stock levels in reaching the targeted SCARM

Figure 5.3 shows that increasing proactively the target stock of the logistics centre can help reducing the detection time needed both to not have any reduction in service levels and to have a SCARM equal or smaller than the targeted one.
Accounting that larger detection and plan intervals may generate complexities to the company, it is investigated the quantity that should be kept in node 17 to minimize the required number of anticipation weeks to have SCARM $\leq$ 4 weeks.
The analyses allows to investigate which is the quantity that should be kept in stock to not have performance reductions, and it provides indication about how many weeks of anticipation should be accounted relating to the quantity kept. As a result, managers can decide which is the most suitable solution in terms of stock holding costs and potential penalty fees to proactively plan the distribution of the product in the three markets. Moreover, it should be accounted that increasing proactively stock levels may be a risk for the company in case the demand would not actually increase.
Observing Figure 5.3 it is possible to notice that if up to 4 machines are held in stock 10 weeks of anticipation are needed to have an acceptable performance reduction. Increasing the target stock allows to gradually reduce the detection horizon. However, at least 3 weeks of anticipation are needed to have the SCARM $\leq$ 4 weeks independently from the quantity kept, as 7 weeks elapse from the logistic centre to the retailers due to the sum of lead times. It can be observed also considering the SCAPM, indeed to not have any reduction in service levels at least 7 weeks before the machines have to be launched.
The company might decide to respond to this demand variation also reactively, by implementing the levers explained in Section 5.3. An analyses has been performed to investigate which are the actions or their combination that could allow the SC to achieve the targeted SCARM.
It emerged that the company would give priority to the levers related to its internal management, therefore increasing the production capacity by pivoting workers on the lines and working overtime or reducing its frozen planning period. Besides, the purchasing and sales departments stated that in case of extreme urgency the ship transportations might be performed by flight, even if it should be reduced to the minimum because of costs.
Respondents chose to not give detailed information related to the cost of implementation of the different levers, but they affirmed that the improvement of production capacity and the reduction of frozen planning period should have to be maximized trying to minimize the usage of other transportation means. This choice is related to the economic impact of transportation modes, as social or environmental aspects are not taken into account in their decision-making process.
The results of the analyses are reported in Appendix C. It can be observed that either the reduction of the company's frozen planning period nor the improvement of production capacity are sufficient to bring the SCARM $\leq$ 4 weeks. Similarly, the selection of faster transportation means in supply or delivery activities does not allow to reach the target.
Therefore, it has been chosen to investigate the combination of these levers and their activation plans that could satisfy the service level requirement. Each lever is associated to the duration of its implementation and the time of its activation.
The simulations performed have been aimed to minimize the duration of each lever, minimizing also the exploitation of air transportation. Among the scenarios analysed,

it has been noticed that the exploitation of air transportation for 2 weeks and the nullification of the company's frozen planning period when the disruption occurs are necessary to reduce the SCARM of the system to 4 weeks, respecting the needs of the company. These levers should be combined with an increase of the production capacity in order to meet the total demand in the time interval chosen.
In Appendix C is considered an increase of capacity of the 25%, as the plant manager stated that the line could reach the 50 units/week produced with respect to the current 40 units/week. Nonetheless, referring to the framework proposed in Chapter 4, the solutions adopted to enhance the agility level of the SC would have both a negative environmental and social impact. Indeed, the adoption of faster and more pollutant transportation means would be selected to decrease the lead time, while overtime working hours could be used to enhance the throughput.
In order to improve the economic, environmental and social sustainability of the application of these levers it has been investigated the minimum necessary production capacity to achieve the targeted SCARM.
Table 5.2 reports the results of some of the scenarios analysed.

Table 5.2. Results of the simulations when combining agility levers

Scenario	**Levers**	**SCARM** $[wk]$
S0	No levers activated	18
S1	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C = 1$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L = 2$ wk $F_{(9,t_{situation})} = 0$ wk	4
S2	$C_{(9,t_{situation})} = 45$ h/wk, $\Delta C = 1$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L = 2$ wk $F_{(9,t_{situation})} = 0$ wk	**4**
S3	$C_{(9,t_{situation})} = 44$ h/wk, $\Delta C = 1$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L = 2$ wk $F_{(9,t_{situation})} = 0$ wk	5

Therefore, the same agility improvement can be achieved also by increasing the production capacity of $12,5\%$ instead of 25%. On the other hand, a smaller capacity would not be able to assure to achieve the targeted SCARM.
According to the company, the increase of production capacity may be obtained either through overtime working hours or pivoting workers to the assembly line to increase the production rate. Even if these methods provide the same output in terms of agile performance, they have different impacts considering sustainability.
Under an economic perspective, the plant manager stated that the pivoting of workers would have a smaller impact on costs, above all in periods of low seasonality. Moreover, observing Table 4.2 the training of workers to several tasks can enhance agile capabilities with positive effects on individuals. On the other hand, overtime working hours would have a negative impact on workers, as well as a reduction of the environmental sustainability of the SC due to longer working hours' emissions.
As a result, the tool has provided a scenario that has been considered feasible by the company, both in terms of agility level reached and impact of the levers.

5.5 Conclusions

This chapter is aimed to show the applicability of the model and the decision-making tool presented in chapters 3 and 4 to real organizations. As already seen in Section 2.3, the real case study methodology is a technique used by authors to validate proposed theoretical models. Therefore, it has been chosen to carry out an investigation about the agility of a multi-national company operating in the field of agricultural machines. In order to perform the research a questionnaire has been developed and proposed to professional figures belonging to different departments inside the company. The lack of a SC manager forced to gather the data related to the activities taking place across the network directly from those who manage them through one-to-one interviews.
These latter have had a mean duration of 30 minutes, plus the time needed to introduce the topic and the target of the research to each correspondent. Notes and recordings have been then used to reconstruct the configuration of the SC under study. The methodology adopted to carry out the investigation is presented in the framework in Section 5.3, and it can be exploited to inquire into agility of generic organizations. Indeed, the nature of the framework allows to replicate the case study performed also to other types of product supply chains.
It should be highlighted that the simulation of the different scenarios has been a time-consuming activity. The company did not require to observe the impact of a situation needing agility and verify whether certain levers could have had a positive effect on its mitigation, but to investigate which levers and activation plans might be helpful to achieve the targeted service level among the ones proposed. Therefore, the research has been focused on the investigation of proactive and reactive actions to mitigate an increase of demand keeping into account the requirements of the organization, both in terms of targeted agility level and managerial constraints. As a result, several simulations have been performed.
It should be considered that in this case study the focus has been given to a single product SC, and the visibility of the company was limited to its immediate upstream and downstream levels. On the other hand, some organizations may require to investigate the agility level of multi-product supply chains with several levels and potential levers. In this case a large number of investigations would be required, as varying the activation plan or the agility levers applied to one stage may vary the bottleneck of the overall system or generate unfeasible solutions. Therefore, the more complex the configuration and the higher the number of actors involved, the more time-consuming the comparison of scenarios and the number of simulations.
Nonetheless, it is possible to observe that the mathematical and simulation models developed can be applied to real supply chains and generate realistic solutions. It is trivial that the higher detail of data used to simulate the behaviour of the system, the more accurate the results of simulations.
In conclusion, the decision-making tool designed allows to investigate the impact of situations needing agility and selected levers on the performance of the system, deciding the most suitable ones to implement accounting the trade-off between sustainability and performance. As a result, the methodology developed represents a contribution to the state of the art in Supply Chain Agility, providing a model that can consider the heterogeneity of situations and levers to improve the performance of networks.

Conclusions

This thesis investigates the role of SC agility in achieving competitive advantage. Its academic relevance is due to the subject itself, as several articles highlighted the role of agility in mitigating disruptions and seizing opportunities, defining it as an antecedent of SC resiliency (Aslam, Khan, et al., 2020).
Because of its multidisciplinary nature (D. Gligor, Holcomb, and Stank, 2013), agility is recognized in literature to be a fragmented concept (Al Humdan et al., 2020). A gap has been identified between theoretical studies on the benefits deriving from the adoption of agile practices and the definition of quantitative models to improve it.
In order to provide a comprehensive view of the SC agility paradigm, a research about its pillars has been performed. This exploration phase allowed to build the agility framework shown in Figure 1.1, providing an indication of the main elements that should be considered when dealing with agility in networks.
It emerged that authors investigated the factors that can lead organizations to develop agility and the specific events that require agile capabilities. The former have been addressed as agility drivers, as they drive companies towards agility, while the latter as situations needing agility (Boubaker, Jemai, et al., 2019b). These concepts are related to the risks that organizations have to face, which derive from pressures and changes in the SC business environment (Sharifi and Z. Zhang, 1999).
Some authors focused on the determination of actions that can be implemented to mitigate such risks and enhance the agility of networks, defined agility levers. These latter have been addressed as reactive, proactive and both reactive and proactive, depending on whether they can be activated before or after the occurring of a situation needing agility (Al Humdan et al., 2020). Scholars investigated them studying different types of networks, and the bibliographical research performed highlighted the heterogeneity of situations and levers that can respectively afflict and improve the agility of supply chains.
Among levers, researchers recognised the central role of information sharing capabilities and top management commitment to enhance agile attributes, and some of them underlined that the lack of these elements generates barriers toward the achievement of competitive advantage, therefore to lower performance levels.
Agile capabilities have been associated to the improvement of performance both in terms of environmental (Yusuf et al., 2020) and economic (Al Humdan et al., 2020) sustainability. Nonetheless, some authors argued that not all products' supply chains may take advantage from the enhancement of agility, highlighting that it helps to reach the SC fit mainly in case of innovative products dominated by dynamic and uncertain markets (D. M. Gligor, 2016; Gyarmathy et al., 2020).
Despite the growing attention towards this topic, the systemic literature review per-

formed has shown that only a few authors dealt with the development of mathematical models to evaluate and enhance the agility level of networks.
It has been noticed that most of papers deal with expert's subjective evaluations of SCA, which is assessed as a reflection of the degree of implementation of specific attributes related to agility. Only 16% of the analysed papers proposed quantitative models, which mainly focused on the design of networks selecting suppliers that optimize service levels and costs. Besides, most of them considered only demand variations as potential situations needing agility.
Due to the lack of quantitative models that could evaluate the agility level of an existing SC network and improve it considering the heterogeneity of situations and levers, it has been developed a discrete-event simulation model aimed to replicate the behaviour of open-loop supply chains when impacted by these elements.
Through the modelling of a set of operations that may take place in real networks and the definition of a mathematical model to describe the information and material flows typical of any SC (Mentzer et al., 2001), it is created a decision-making tool. It allows to evaluate the impact of a situation needing agility on the system and apply levers to counteract it, either proactively or reactively.
These levers are related to the physical flow of the network, and the tool permits to compare different scenarios selecting actions to improve the agile performance of the SC by varying their time of application, duration and the entity of the variation they bring to the system's parameters.
The VBA application developed offers an interface with Microsoft Excel that allows to model different SC configurations by entering their parameters, presenting the results related to their agility evaluation.
To evaluate quantitatively the SC agility level, three metrics are considered: the Supply Chain Agility Preparation Metric (SCAPM), which represents the time of anticipation needed by the SC so that the occurrence a situation does not impact the final customers; the Supply Chain Agility Response Metric (SCARM), which is the time required by the SC to respond to an unpredicted situation; the Supply Chain Resiliency Evaluation Metric (SCREM), that accounts for the time to re-achieve targeted inventory levels after a disruption has occurred.
In order to show the mechanism of the developed model, an illustrative case study is presented. It is considered the impact of proactive and reactive levers to face a temporary increase of customer's demand, and it is highlighted the importance of information sharing capabilities in improving the SCARM of supply chains. Specifically, it is shown how a lag time in communicating the occurring of disruptions to partners can lead to a reduction of agile performance (Dubey, Altay, et al., 2018).
Each agility lever can be activated in different modes, and each of them can generate different costs. In Chapter 4 the cost of agility is defined as the total cost incurred to enhance the agility level of a scenario.
A cost model is proposed to determine the economic impact of the agility levers' application, in order to observe the trade-off between agile performance and cost of agility. In this way, an evaluation regarding the economic sustainability of selected actions is permitted in the decision-making process and two problems can be addressed: identify the levers to be activated that maximize service levels under budget constraints or identify the ones that allow to reach a targeted service level at the minimum cost.
Besides the economic impact of agility levers, Chapter 4 investigates also their ef-

fects on environmental and social sustainability. Actions that can be undertaken to implement each agility lever have been identified through a literature review, and a theoretical framework is proposed in order to allow considering also green and social aspects in the decision-making process.
The case study methodology is exploited to validate the proposed model, showing its practical applicability. A leader company in the production of agricultural machines is selected as unit of analysis, and interviews based on a questionnaire have been performed to gather data related to the SC of an innovative product they are introducing to the market. It is presented the methodology adopted to analyse and improve their SC agility level with respect to an increase of external demand, applying and proposing different levers that can help reaching the targeted agility.
The results obtained show that the developed tool supports the decision-making process, and provides solutions to improve the agility level of networks. Figure 5.4 shows its constitutive elements, inputs and the methodologies used to investigate and develop each of them.

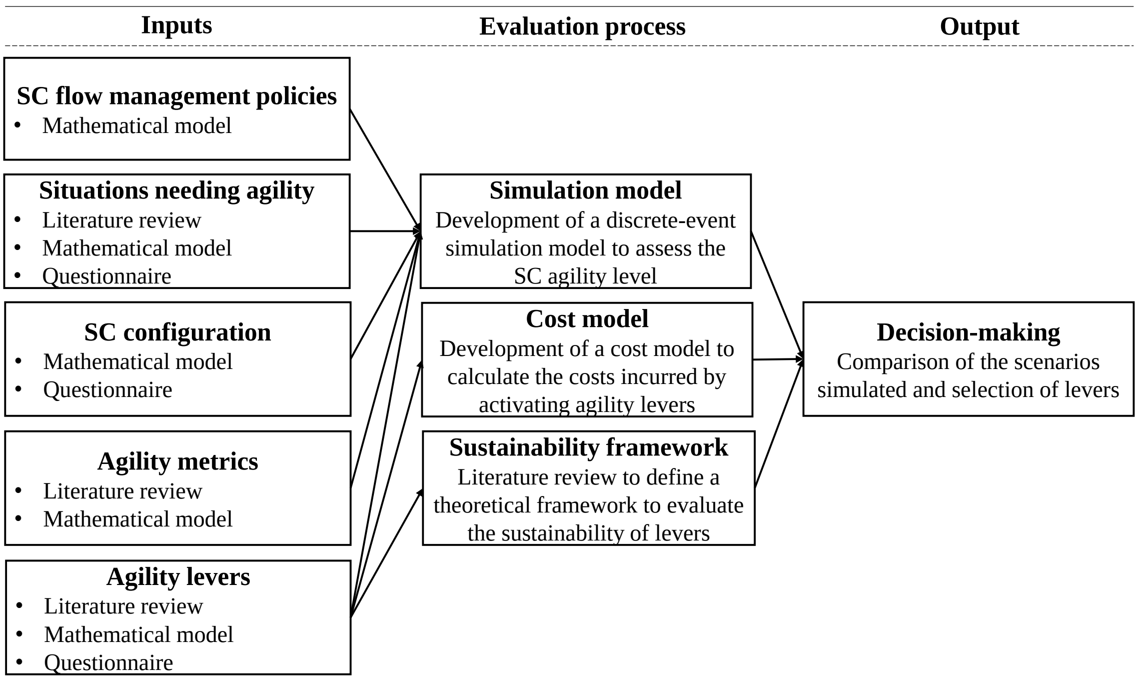

Figure 5.4. Elements of the decision-making tool developed

It is possible to observe that some elements have been addressed using different research techniques. For example, agility levers have been investigated through a literature review in Chapter 1, then mathematically modelled to develop the discrete-event simulation tool in Chapter 2, finally explored using a questionnaire in Chapter 5 to perform the real case study.
This work presents also some limits and perspectives. As instance, it is reported that the use of ICT systems are crucial in information sharing and to develop alertness within supply chains (Centobelli et al., 2020). The illustrative case study shows that an imperfect alerting system has a detrimental impact on agility, as it does not allow to take countermeasures quickly. Therefore, it could be of interest to investigate the impact of these technologies on SC agility using the real case study methodology.

Regarding the quantitative evaluation of agility, the metrics proposed permit to take into account different types of situations needing agility which imply quantity and mix variations or change in planning. Nonetheless, the quantitative modelling of situations such as weather change or cyber attacks is not obvious and intermediate mathematical models can be used to quantify their impact on the SC's flows.
Furthermore, the cost model presented permits to have an evaluation of costs incurred to implement agility levers but it does not allow a calculation of costs related to the specific operation performed or the evaluation of stock-out penalties. Therefore, it could be interesting to embed these elements inside SCAEM and investigate the connection between agile and financial performance, profitability.
In (Ciccullo et al., 2018) it is argued that only a few researches related to the connection between agility and social sustainability are present in literature, and this trend has been verified while developing the agility levers' sustainability framework. It may be of interest to empirically validate this framework and investigate deeper the impact of the proposed levers on sustainability. Besides, the development of a quantitative model to calculate the environmental impact of levers can be useful to account for current regulations on carbon emissions.
In the end, the developed discrete-event simulation model allows to investigate the impact of selected actions on the state of the system by comparing different scenarios, while it does not allow to find the optimal solution.
Supply chains deal with a large number of products and components, therefore the future development of an optimization model can be of useful to select agility levers and their optimal activation plan to enhance performance under different constraints.

Appendix A

Minimum Planning Horizon

The mathematical model presented in Chapter 3 is based on the definition of a planning horizon $U_{(n,t)}$ for each connection of the supply chain.
This interval is modelled as a time-dependent parameter, as a situation needing agility might happen suddenly varying some parameters of the system (lead times, frozen periods) that are at the basis of its definition.
$U_{(n,t)}$ defines the length of the planning horizon adopted in each stock point to plan and calculate the net requirement to order at upstream suppliers. It allows the sharing of information among consecutive different levels of the network.
Ideally, it could not have an upper bound. Considering a rolling horizon $i \in [0, \ldots, U_{(n,t)}]$ of a generic Stage n, $i = 0$ represents the current period at which variables are actually defined, while values for $i > 0$ represent estimations of upcoming events. However, it is limited by the simulation time T chosen.
On the other hand, the model requires a minimum planning horizon at each stage to not lose any information. This minimum amount of information represents the smallest time required by the information flow to cross the whole supply chain from the stage under consideration until the raw-material level. It accounts for lead times and relevant frozen periods of the network.
In the most simple case, the minimum horizon of a Stage n is given by the sum of its lead time and all the lead times of its upstream operations until the raw-material level. However, its calculation is not trivial when frozen periods of stages are different from zero and determine an enlargement of frozen planning horizons.
In the presented model, Algorithm 3 is deployed to calculate the minimum planning horizon $U_{(n,t)}$ of each stage $n \in [1, \ldots, N]$ at the beginning of each time t.
It allows to not lose information between levels and to minimize the time consumption of each simulated scenario under evaluation.

Algorithm 3 Algorithm to define the minimum planning horizon of each stage n

for $n = 1$ *to* N **do**
  for $k = 1$ *to* K **do**
    if $Predecessors(k) = \{\}$ **then**
      $\forall k_s \in Successors(k)$
      if $k \in Inputs(n), k_s \in Outputs(n)$ **then**
        $U_{(k,t)} = F_{(n,t)}$
        $U_{(k \to k_s,t)} = L_{(n,t)} + F_{(n,t)}$
        if $U_{(k \to k_s,t)} > U_{(k_s,t)}$ **then**
          $U_{(k_s,t)} = U_{(k \to k_s,t)}$
        end if
      end if
    else
      $\forall k_s \in Successors(k)$
      if $k \in Inputs(n), k_s \in Outputs(n)$ **then**
        if $F_{(n,t)} > U_{(k,t)}$ **then**
          $U_{(k \to k_s,t)} = L_{(n,t)} + F_{(n,t)}$
        else
          if $U_{(k,t)} + L_{(n,t)} > U_{(k_s,t)}$ **then**
            $U_{(k \to k_s,t)} = L_{(n,t)} + U_{(k,t)}$
          end if
        end if
        if $U_{(k \to k_s,t)} > U_{(k_s,t)}$ **then**
          $U_{(k_s,t)} = L_{(n,t)} + U_{(k,t)}$
        end if
      end if
    end if
  end for
end for
for $n = N$ *to* 1 **do**
  for $k = K$ *to* 1 **do**
    $\forall k_s \in Successors(k)$
    if $k \in Inputs(n), k_s \in Outputs(n)$ **then**
      $U_{(k,t)} = U_{(k_s,t)} - L_{(n,t)}$
      $U_{(n,t)} = U_{(k_s,t)}$
    end if
  end for
end for

Appendix B

Questionnaire

The questionnaire reported in Table B.1 has been used to gather information related the SC configuration and the other elements needed to apply the model presented in Chapter 3.

Table B.1. Questionnaire used to gather data

	Questionnaire
1	With respect to the range of products offered by your company, could one of them require agility (because of mean demand variation, issues in the supply systems, etc.)?
2	Which operations do take place across the SC of this product from the raw materials to the finished product?
3	The suppliers are located only in Italy or also abroad? Where?
4	Is the choice of suppliers based only on economic/production aspects or does it account also for environmental and/or social sustainability? Why?
5	How do you plan the purchasing to your suppliers?
6	Do your suppliers impose you limitations on the quantities you can ask? Why?
7	Are the supplying transportation modes you use characterized by finite capacities? Why? Why did you choose such transportation modes?
8	How much time does it take to complete each operation involved in the SC?
9	Which is the strategy you adopt with respect to inventory levels across the SC? Why?
10	Is the product distributed in one or more markets? If one, how many distribution channels do you have? To which proportion of the total demand each of them accounts for? If more markets, to which proportion of demand each of them accounts for?
11	How long does it take to deliver your products? Do you impose a planning period to your customers? Why?
12	Are you facing any phenomenon that is decreasing the service level of the SC? Why? How long is it lasting?
13	Do you think that you will have to face any situation that may decrease the service level of the SC in future? Why?
14	These variations are induced by external factors (e.g. the pandemic) or by managerial decisions (e.g. promotional campaigns)?

	Questionnaire
15	In your opinion, could the SC bear these variations in terms of costs and service levels?
16	In your opinion, the SC has a proper level of agility or should it be improved? Why?
17	In your opinion, which would be the best actions to enhance such level? Why? How would they impact the SC?
18	Among these actions, which ones would you prioritize? Approximatively, how much would it cost to implement them?
19	Would you keep into account environmental and social sustainability issues related to the implementation of these actions? Why?

Appendix C

Numerical data of the case study

Figure C.1 below reports the SC configuration with the parameters defining the system.

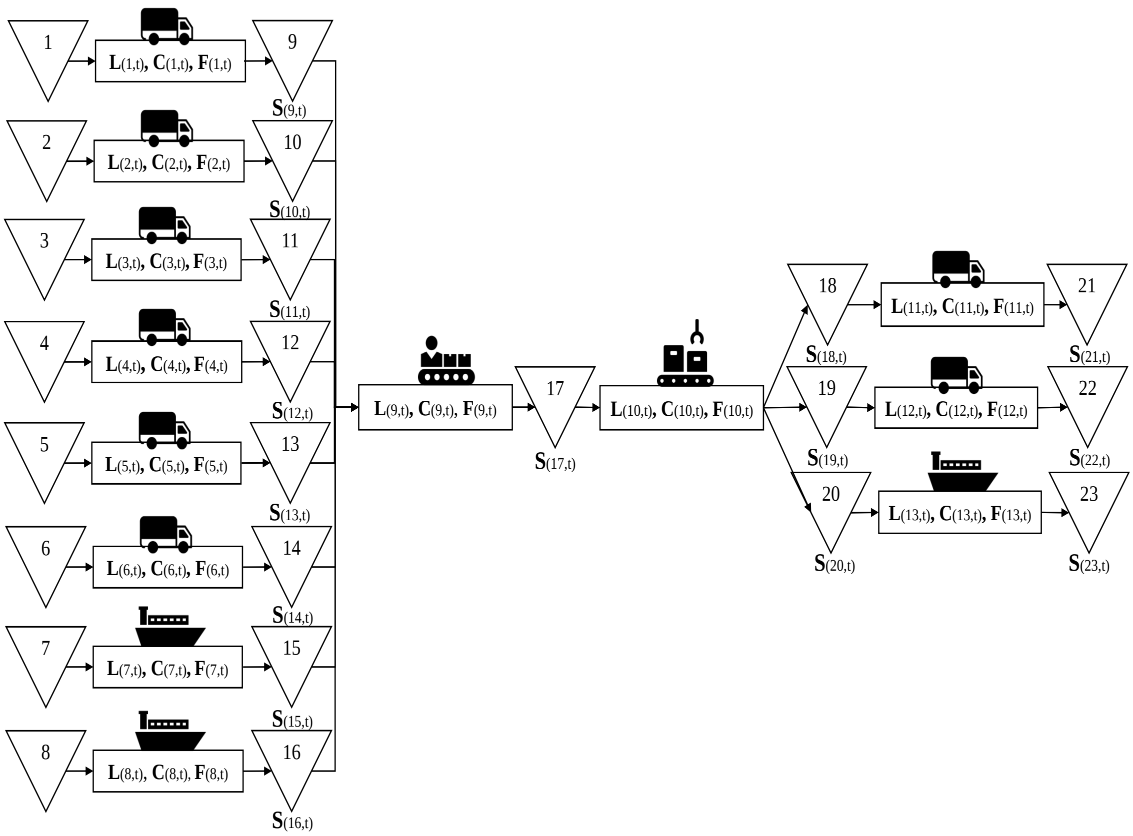

Figure C.1. Case study's SC configuration

Data used to perform the case study are reported in the tables below.
It is highlighted that the company is not keeping target stocks of finished products for the moment, because it is a new device and they are still analysing its reachability in the market.
It is reminded that stock points in the most upstream level are considered with ample stock at all times, therefore they are not initialised. Any other stock point is initialised to have a steady-state system at the beginning of the simulation.

Table C.1. Initialisation of inventory levels and target stocks

Stock point k	Target stock $S_{(k,t)}$ $[units]$	Inventory level $IN_{(k,0)}$ $[units]$
9	120	120
10	210	300
11	120	120
12	210	300
13	30	30
14	30	30
15	120	840
16	120	840
17	0	180
18	0	16
19	0	8
20	0	6
21	0	16
22	0	8
23	0	36

From the data gathering it emerged the forecasted yearly total demand for the product under consideration. It is considered that in one year (48 weeks) 1400 units will be produced to be sold with a pace of 30 units/week. Therefore, accounting for the market analyses of the company an average demand of 8 units/week deriving from the Italian market (30%), 6 units/week from USA (20%) and the remaining 16 units/week from the rest of Europe (50%) is expected.
Regarding the parameters proper of the operational stages composing the network, data have been provided by the interviews performed to the divisions of the company. They are reported in Table C.2.
It is reminded that transportation operations are supposed to be always able to transport required quantities, and the company confirmed this assumption.

Table C.2. Data related to the stages composing the product's SC

Stage n	Type of operation	$L_{(n,t)}$ $[wk]$	$F_{(n,t)}$ $[wk]$	$C_{(n,t)}$ $[h/wk]$
1	Transportation	4	0	/
2	Transportation	7	0	/
3	Transportation	4	0	/
4	Transportation	7	0	/
5	Transportation	1	2	/
6	Transportation	1	3	/
7	Transportation	4	24	/
8	Transportation	4	24	/
9	Assembly	2	4	40
10	Distribution	1	0	40
11	Transportation	1	0	/
12	Transportation	1	0	/
13	Transportation	6	0	/

The production line has been designed to produce approximately one unit of final product every hour, therefore the throughput in node $k = 17$ is assumed to be $\boldsymbol{r}_{(17,t)} = 1$ unit/h, and it represents the bottleneck of the system. On the other hand, the manager of the logistics centre stated that the packaging and distribution operations have never been the limiting factors of the company, as they are able to manage around 6 machines per hour also in case accessories should be shipped with the machine. Therefore, it has been considered $\boldsymbol{r}_{(k,t)} = 2$ units/h for $k = 17, 18, 19$. In order to observe the impact of reactive agility levers, different scenarios have been simulated and for each of them sub-groups related to their duration have been analysed. The scenarios considered are:

- S0: nominal scenario, no levers activated.
- S1: Increase of Stage 9's production capacity from 40 to 50units/week.
- S2: Decrease of Stage 9's frozen planning period from 4 to 2 weeks
- S3: Decrease of Stage 9's frozen planning period from 4 to 1 week
- S4: Decrease of Stage 9's frozen planning period from 4 to 0 week
- S5: Decrease of Stage 13's lead time from 6 to 1 week.
- S6: Decrease of stages 7 and 8 lead times from 4 to 1 week.

The results obtained are reported in Table C.3. Bold results represent the overall SCARM of the system in each scenario and for each sub-scenario considering the duration of activation of the lever.

Table C.3. Results of the simulations

Scenario	**SCARM** $[wk]$	**Duration of activation of the lever** $[wk]$										
		0	1	2	3	4	5	6	7	8	9	10
S1	SCARM(21)	13	13	13	13	13	11	10	10	10	10	10
	SCARM(22)	13	13	13	13	13	11	10	10	10	10	10
	SCARM(23)	**18**	**18**	**18**	**18**	**18**	**17**	**15**	**15**	**15**	**15**	**15**
S2	SCARM(21)	13	10	10	10	10	10	10	10	10	10	10
	SCARM(22)	13	10	10	10	10	10	10	10	10	10	10
	SCARM(23)	**18**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**	**15**
S3	SCARM(21)	13	9	9	9	9	9	9	9	9	9	9
	SCARM(22)	13	8	8	8	8	8	8	8	8	8	8
	SCARM(23)	**18**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**
S4	SCARM(21)	13	9	9	9	9	9	9	9	9	9	9
	SCARM(22)	13	8	8	8	8	8	8	8	8	8	8
	SCARM(23)	**18**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**14**
S5	SCARM(21)	13	11	11	11	11	10	10	10	10	11	11
	SCARM(22)	13	11	11	11	11	10	10	10	10	11	11
	SCARM(23)	**18**	**16**	**16**	**16**	**16**	**15**	**15**	**11**	**11**	**11**	**11**
S6	SCARM(21)	13	13	13	13	13	13	13	13	13	13	13
	SCARM(22)	13	13	13	13	13	13	13	13	13	13	13
	SCARM(23)	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**	**18**

It is notice that the application of these levers cannot allow to meet the targeted SCARM. Therefore, some combinations have been proposed, trying to minimize the usage of air transportation to accomplish the willing of the company.
Table C.4 reports some of the scenarios simulated using a combination of levers. The activation of the levers is assumed to happen at the same instant of the situation needing agility $t_{situation}$, as it has been noticed that by delaying their activation worse results were obtained.

Table C.4. Results of the simulations combining agility levers

Scenario	**Levers**	**SCARM** $[wk]$
S7	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 7$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 7$ wk $F_{(9,t_{situation})} = 0$ wk	4
S8	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 7$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 1$ wk $F_{(9,t_{situation})} = 0$ wk	9
S9	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 6$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 1$ wk $F_{(9,t_{situation})} = 1$ wk	10
S10	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 7$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 2$ wk $F_{(9,t_{situation})} = 1$ wk	10
S11	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 3$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 2$ wk $F_{(9,t_{situation})} = 0$ wk	4
S12	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 2$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 2$ wk $F_{(9,t_{situation})} = 0$ wk	4
S13	$C_{(9,t_{situation})} = 50$ h/wk, $\Delta C_{(9)} = 1$ wk $L_{(13,t_{situation})} = 1$ wk, $\Delta L_{(13)} = 2$ wk $F_{(9,t_{situation})} = 0$ wk	**4**
S14	$L_{(13,t_{situation})} = 2$ wk, $\Delta L_{(13)} = 2$ wk $F_{(9,t_{situation})} = 0$ wk	5

It is noticed that a SCARM ≤ 4 weeks can be achieved if the air transportation is used to deliver machines at least for two weeks, the company can change its production schedule immediately when the disruption occurs and the production capacity is increased at least for 1 week. Scenario S14 is considered the best solution among the ones proposed, as it allows to minimize the duration of each lever while obtaining the targeted agility level.

Acronyms

AHP	Analytic Hierarchy Process
DEA	Data Envelopment Analysis
DEMATEL	Decision Making Trial and Evaluation Laboratory
GHG	greenhouse gas
ICT	information and communication technology
IS	information systems
ISM	Interpretative Structural Modeling
IT	information technology
IVFRN-BMW	Interval-Valued Fuzzy-Rough Numbers Best Worst Method
KPIs	key performance indicators
MADM	multi-attribute decision making
MCDM	multi-criteria decision making
MICMAC	matrix impact cross-reference multiplication applied to classification
MODM	multi-objective decision making
SC	Supply Chain
SCA	Supply Chain Agility
SCAEM	Supply Chain Agility Evaluation Model
SCAPM	Supply Chain Agility Preparation Metric
SCARM	Supply Chain Agility Response Metric
SCOR	Supply Chain Operation Reference
SCREM	Supply Chain Resiliency Evaluation Metric
SNA	Situations Needing Agility
SOQ	Sustainable Order Quantity
VBA	Visual Basic for Applications

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