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Unlocking the power duo: Exploring the interplay of supply chain sustainability and resilience through a composite indicator

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ABSTRACT

Supply chain sustainability and resilience have gained the interest of academic and industrial communities, and increasingly represent top priorities in organizations' agendas. This article aims to measure the key dimensions driving sustainability and resilience in supply chains and their interrelationships. We propose a new composite indicator for their joint assessment through the application of a robust composite indicator development framework, and the integration of secondary data with primary data gathered from a survey in the Italian industry. Results show no evidence of a trade-off between supply chain sustainability and resilience and instead highlight a potentially important cross-fertilization from sustainability to resilience through supply chain collaboration when these transcend the internal boundaries of the firm. This is a significant contribution to the existing debate in the literature on the relationship between sustainability and resilience in the supply chain, thanks to the development of an integrative composite indicator and a quantitative approach to the explanation of this relationship. By fostering a deeper understanding of supply chain sustainability and resilience, this investigation informs decision-makers on potential avenues to concurrently build and sustain their firms' supply chain sustainability and resilience.

1. Introduction

Sustainability and Resilience are two topics that have gained the interest of academic and industrial discussions on the supply chain (Negri et al., 2022; Fahimnia et al., 2019). Recent events, such as Russia's invasion of Ukraine, Brexit, the Covid-19 pandemic, interruption of flows through the Suez Canal, and environmental disasters are few examples that have raised debate on the need for more resilient supply networks (Ferrari et al., 2023; Chowdhury et al., 2020; Drozdibob et al., 2022). Concurrently, environmental disasters recall the long-term phenomenon of climate change and its effects on the planet and the perspective of deteriorating environmental conditions. Along with stakeholder pressure, environmental responsibility, polluting emissions, human rights and safety in the workplace, these elements highlight the undeniable importance of sustainability in the management of supply chains (Marttinen et al., 2023).

Only recently has the scientific community started to address the two aspects jointly (Carissimi et al., 2023; Sonar et al., 2022), as there is evidence that the concurrent development of sustainability and resilience within organizations and supply chains leads to enhanced performance for firms (Carter & Washispack, 2018; Edgeman & Wu, 2016). Some authors, though, describe a potential trade-off between the two concepts, leading to improving one at the expense of the other (Edgeman & Wu, 2016; Ivanov et al., 2019; Perrings, 2006). From the typically qualitative or conceptually oriented existing contributions (e.g., Soni et al., 2014; Hosseini et al., 2019), examples of synergic outcomes related to actions that foster sustainability and resilience emerge alongside detrimental ones (Sarkis et al., 2020). Organizations allocate the same priority to better sustainability and resilience, however, these two concepts do not always seem to go hand in hand (Rajesh, 2018).

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These mixed messages derive from a lack of theoretical clarity regarding the interpretations of the two concepts and related interrelationships. Some authors regard sustainability as a driver of resilience (e.g., Bag et al., 2019; Gouda & Saranga, 2018; Jain et al., 2017), others instead state that resilience is an antecedent of sustainability (e.g., Brinkley, 2018; Eltantawy, 2015; Shin & Park, 2019), essential to design business models and supply chains able to pursue environmental strategies and objectives (Shashi et al., 2020). The same lack of clarity on the interrelationship between sustainability and resilience emerges also from the industrial community, as indicated by Cotta et al. (2022) who, in their qualitative work, reported conflicting perceptions of supply chain managers in this respect.

Measurement is needed to solve the problem of these mixed messages and to support theory and practice in better understanding the interrelationship between supply chain Sustainability and Resilience to ultimately improve firm's performance (Neri et al., 2021). It would be necessary to jointly measure sustainability and resilience in an integrative framework, assessing the relative weight of these concepts and their dimensions along with the interrelationships between them. In fact, the existing literature has produced several attempts to provide a measure of sustainability and resilience performance in a supply chain but providing separate measurements that, if on one side are able to quantify the investigated performance (resilience or sustainability), on the other fail in providing an integrative and exhaustive view of the joint effect of sustainability and resilience in a supply chain. Especially, while the literature is fairly rich in examples of economic and environmental sustainability measurement (e.g., typically through established frameworks such as the Green House Gases – GHG protocol or the Global Logistics Emissions Council – GLEC framework), the quantitative measurement of social sustainability or resilience are less developed and are in need of further elaboration.

To address the complexity of the interrelationships among the dimensions composing the investigated concepts and the relative weights in the relationship, some authors have proposed the use of the Composite Indicators (CI) methodology that aggregates metrics to address the multi-dimensional and complex interrelationships of potentially conflicting dimensions (Azevedo et al., 2013). The existing CI measurement endeavours are complex, requiring a large amount of data and not always transparent about methods and algorithms (Ramezankhani et al., 2018). This affects the replicability and reliability of the proposed tools (Aguinis and Solarino, 2019). Furthermore, there is no clarity on the measurement dimensions to be considered, nor has a unique framework of sustainability and resilience been proposed. Some contributions, in fact, focus only on some elements of sustainability or resilience (e.g., Azevedo et al., 2016; Sen et al., 2018).

Thus, there is still a need for a framework that assesses the degree of Sustainability and Resilience of the supply chain. This framework would help firms to identify to the benefit of organizations.

The objective of the present article is to show organizations' performance by concurrently leveraging supply chain sustainability and resilience, unveiling the dimensions of these two concepts and the interrelationships between them. We strive to achieve this objective through a composite indicator of Sustainability and Resilience of firms' supply chain, named Sustainability and Resilience Index – or "Resist-I".

We defined the following research questions: RQ1) What are the composite indicator's key dimensions and what is the aggregation of metrics required to jointly measure the Sustainability and Resilience of the supply chain? And RQ2) What interrelationships do exist between the Sustainability and Resilience of a supply chain?

We present an empirical investigation with data collected through a survey from the Italian manufacturing, retail, and energy supply industries. This is a significant application field, since Italy is part of the Group of Seven (G7), the world's ninth-largest economy, the second most important country in Europe in terms of manufacturing, and the fifth worldwide (Italian Trade Agency, 2022).

The remainder of this paper is organized as follows. Section 2 describes the theoretical background, while Section 3 presents the adopted Methodology. Section 4 describes the results, and in Section 5 we discuss the findings. Section 6 provides concluding remarks and future research directions.

2. Supply chain sustainability and resilience and related composite indicators

2.1. Supply chain resilience

Supply chain resilience has been traditionally defined as the ability to restore the state of operations after a disruption (Ribeiro and Barbosa-Povoa, 2018). However, recent contributions have broadened this view, recognising resilience as not only the capacity to recover but also to adapt and transform in response to environmental changes (Wieland and Durach, 2021). They propose that resilience should not merely be viewed through an equilibrium lens but rather as an emergent property resulting from the interactions of various actors within the supply chain. Davoudi (2012) discusses three views on resilience: engineering resilience as the ability of a system to return to an equilibrium after a disturbance; ecological resilience, which proposes the existence of multiple equilibria; and evolutionary resilience, which moves away from the concept of equilibrium and affirms that systems might change over time with or without an external disturbance. Davoudi (2012) proposes resilience as the capacity to adapt to all types of changes in a continuous way, since today's world is seen as chaotic and uncertain. Wieland and Durach (2021) apply these resilience concepts to supply chains, concluding that the study of supply chain resilience should not discard the engineering view, which measures resilience in terms of time to recovery and time to survive, and helps confronting risky events in the short term. However, this view needs to be enriched with the social-ecological perspective that empowers organizations to adapt and transform in the long term (Wieland and Durach, 2021). This dual perspective is crucial in a world where disruptions are not only more frequent but also more complex (Walker, 2020). The social-ecological approach embraces different phases: prepare, respond, recover and maintain, emphasizing the importance of proactive preparation (anticipating risks) and maintenance (intended as long-term adaptability), which equips organizations to handle unexpected events effectively while planning for future uncertainties. Hence, the concept of supply chain resilience needs to combine proactive/anticipating actions with continuity plans and programmed steps (Ribeiro and Barbosa-Povoa, 2022; Colicchia et al., 2019), which can foster the development of adequate supply chain resilience capabilities also in case of unexpected events (Faruquee et al., 2023, Munir et al., 2022). Alvarenga et al. (2023) emphasize the need for organizations to leverage past experiences to better manage future disruptions. Recent research also emphasizes the importance of understanding resilience at different scales, highlighting the interplay and interconnectedness between individual organizations and recognising supply chains as continually evolving systems. The resilience of individual organizations contributes to the overall resilience of the supply chain, but resilience at the firm level is not a synonym for supply chain resilience. As such, strategies to enhance resilience should address the complexities of interorganizational relationships and their implications for risk management and recovery (Faruquee et al., 2023; Novak et al., 2021). In this sense, Aslam et al. (2024) argue that organizations with strong social networks are more adept at managing risks and recovering from disruptions. The collaborative relationships formed within supply chains can lead to improved communication and coordination, which are essential for effective disruption management.

2.2. Supply chain sustainability

Supply chain sustainability refers to the management of material, information, capital flows, and relationships between companies supplying goods from upstream to downstream in ways that address all three dimensions of sustainable development, i.e., economic, environmental, and social (Seuring & Müller, 2008; Carter & Rogers, 2008). This is called the "triple-bottom line" of sustainable development. While traditional literature has focused on the triple-bottom line elements separately (Wu et al., 2021), firms are now under pressure to incorporate the triple-bottom line into operations and supply chain management (Carvalho et al., 2022). Despite recent crises and disruptions, it is possible to notice an upward trend in research publications on supply chain sustainability, which signifies a growing recognition of the importance of sustainability in supply chains. This trend reflects a broader understanding that sustainable practices are crucial for mitigating risks and ensuring operational continuity in times of crisis (Carissimi et al., 2023). The role of sustainability in supply chains is also reflected in the increasing emphasis on social responsibility. Aliahmadi et al. (2022) point out that the shift towards sustainability is not merely a response to regulatory pressures but is driven by consumer preferences for products that align with their values. Qu and Ji (2023) argue that sustainable supply chain development is integral to the overall success of enterprises, encompassing all aspects of supply chain management, including the social side of sustainability. As such, organizations must prioritize sustainable practices to remain competitive and relevant in the market (Qu and Ji, 2023). There is in fact a wide consensus on the fact that greater social and environmental responsibility can improve firm performance (Porter and van der Linde 1995; Zhou et al., 2023). This has recently been seen in the light of improving the possibility of accessing funding and credit lines from financiers thanks to the adoption of the ESG principles, which merge Environmental, Social and Governance aspects (Marttinen et al., 2023; Rajesh, 2021).

2.3. The interplay between supply chain sustainability and resilience

The interplay between supply chain sustainability and resilience has garnered significant attention in recent academic discourse, particularly as organisations navigate the complexities of modern supply chains amid increasing disruptions and environmental concerns (Burkhart and Bode, 2024; Cotta et al., 2022). Recent studies indicate that sustainability and resilience are multidimensional and intertwined (Carissimi et al., 2023; Neri et al., 2021). While pursuing sustainability, a firm may look beyond the short-term financial results and understand what risk factors could harm their supply chain. In doing so, an increasing number of sustainability issues might be considered as sources of risk (Dobler et al., 2014). Shrivastava (1995) argues that a company's proactive engagement with sustainability practices lowers the risk of facing new and costly regulations, with a positive causation from sustainability to resilience. Le et al., (2021) described how inter-firm collaboration is necessary to achieve sustainability; collaboration is considered a supply chain resilience aspect (Carvalho et al., 2013; Kamalahmadi & Parast, 2016; Pettit et al., 2013). Furthermore, Singh et al. (2019) consider sustainability as one of the 17 dimensions composing resilience. Some authors (e.g., Koh et al., 2016) observe that efficiency and minimal use of resources to reach a target, may pose risks if there are adverse changes in the environment: the pursuit of efficiency often causes a thinning of buffers, which are important tools needed to recover from disruptions. For instance, the push towards centralized networks to minimize transportation and the minimization of inventories to reduce waste become hurdles to supply chain resilience (Heckmann et al., 2015): redundancies lead to increased resource consumption, which affects the efficient use of supply chain resources (Roostaie et al., 2019). The role of environmental risks in shaping the nexus between resilience and sustainability is further explored by Hsieh (2023). This study emphasizes that organizations must prioritize resilience to effectively manage internal and external environmental risks. By integrating resilience into their operational strategies, firms can enhance their agility and responsiveness, ultimately leading to improved performance outcomes. This interplay suggests that a resilient supply chain is better equipped to adapt to environmental changes, thereby reinforcing its sustainability objectives. While certain practices, such as the sustainable use of resources, can contribute to building resilience, some authors discuss how resilience can bolster sustainability. Cui et al. (2022) provide empirical evidence supporting the notion that supply chain resilience influences sustainability performance across economic, environmental, and social dimensions. This finding underscores the importance of preparing for disruptions through sustainable practices, which can lead to improved performance across multiple sustainability metrics. Such measures include the adoption of renewable resources, waste reduction initiatives, and sustainable sourcing practices, which not only enhance resilience but also contribute to the overall sustainability of supply chains. Disruptions can be caused by conflict and geopolitical tensions and Srai (2023) discusses how these pressures necessitate the reconfiguration of supply chains. The need to unhook from conflict zones illustrates the importance of resilience in maintaining sustainable operations.

While links between sustainability and resilience in SCs have been drawn, clarity needs to be provided on the interplay between these two concepts (Negri et al., 2022). It has been argued that better sustainability and resilience improve the economic performance of organizations (Ahmed et al., 2020). However, little is known about the potential outcomes of the concurrent implementation of Sustainability and Resilience practices (Fahimnia et al., 2018). In fact, managers recognize the complementarities between these two dimensions, suggesting that effective management of financial, material, and information flows can enhance both resilience and sustainability (Cotta et al., 2022), but this recognition is linked to how they perceive the relationship between resilience and sustainability practices. However, companies risk undermining their business performance if they adopt practices without thoroughly understanding their combined impact, highlighting the importance of a decision-making process supported by compelling evidence driven by measurement-based frameworks and data analytics tools to facilitate data collection, which in turn enhance supply chain resilience by improving responsiveness and facilitating innovation (Nakandala et al., 2023).

2.4. Composite indicators for measuring supply chain sustainability and resilience

By leveraging composite indicators, organizations can enhance their understanding of the interplay between sustainability and resilience, ultimately leading to improved operational effectiveness and long-term success. Dočekalová & Kocmanová (2016) developed a composite indicator integrating environmental, social, and economic sustainability with Corporate and Governance (CG). Environmental metrics include consumption of both recycled and raw materials, fuel consumption, and waste production. Social metrics include the percentage of employees covered by a collective agreement, wage discrimination, and occupational diseases, while economic metrics consist of cash flow and return on assets. Corporate governance metrics include the percentage of women in CG roles, the percentage of achieved strategic goals, and the total number of sanctions for noncompliance with laws and regulations. However, their approach lacks clarity on some methodological steps, such as the weighting and aggregation methods used to calculate the indicator, and they omit essential processes like sensitivity and robustness analyses.

Azevedo et al. (2013, 2016) developed the Ecosilient index and the LARG index to measure the resilience and environmental sustainability of companies. The authors identified the most widespread practices that were deemed to create either resilience or environmental sustainability. Firms from the upstream Portuguese automotive supply chain were asked to self-assess the implementation level of resilience and ecological responsibility practices on a Likert scale (1–5), and the results were then used as component metrics. The weights were then determined through the Delphi technique: a panel of experts was used for three rounds. The results showed some that all companies interviewed had ISO 14001 certifications, since automakers often require it of all their first-tier suppliers. They also showed a very high level of implementation of resilient practices; for example, with a very high level of strategic inventories to overcome potential material shortages.

Sen et al., (2018) based their work on the Ecosilient index by Azevedo et al. (2013), but turning the composite indicator into a fuzzy composite indicator. To rank various performance indicators, the concepts of fuzzy performance importance index and of Degree of Similarity were applied. The relationships among the component metrics were established through interpretive structural modelling (ISM). In line with the evaluations measured on a Likert scale, the fuzzy theory classifies the KPIs into several distinct categories. Mari et al., (2014) also worked on the Ecosilient index by Azevedo et al. (2013) to balance (i.e., optimize) a garment manufacturing supply chain's degree of Sustainability and Resilience, also finding that, in fact, Sustainability and Resilience move hand in hand.

Ruiz-Benitez et al., (2017) worked on the LARG index by Azevedo et al., (2016) to measure the environmental benefits of resilient supply chain practices in the Spanish aerospace sector. Based on the ISM approach, 15 experts from the aerospace manufacturing sector were consulted regarding the importance and degree of implementation of lean, green, and resilient supply chain practices and their expected impact on environmental performance.

These papers offer instruments that use composite indicators for measuring supply chain resilience, greenness, leanness, and agility: we can see three main gaps. First, they do not consider the concept of sustainability in its broadest sense, neglecting the economic and social issues. Second, the authors do not clearly define the concepts of Sustainability and Resilience. So, they miss supply chain 'risk management' and adaptation, with no reference to anticipation of the disruptions, business continuity and long-term transformation, redundancy of network nodes (manufacturing facilities and suppliers), and there is no assessment of transportation impact on environmental sustainability. Third, the process followed to develop the composite indicator is not always sufficiently clear, including data inputs-outputs, and the validation process. The research by Sen et al., (2018), Ruiz-Benitez et al., (2017), Mari et al., (2014) represents extensions and important applications of Azevedo et al.'s (2013, 2016) work, but the authors do not overcome the limitations of the original endeavour.

Fahimnia et al. (2018) and Jabbarzadeh et al. (2018) on the other hand, include the social and economic dimensions in the sustainability performance of 9 suppliers of 4 manufacturing companies in the plastic pipes sector in Golpayegan Industrial Park (GIP), Iran. They used a layered approach to analyse Sustainability and Resilience. After a resilient configuration is set, sustainability is optimized, or if a sustainable configuration is set, resilient practices can be explored, whilst simultaneous measurement of sustainability and resilience remain pending.

3. Methodology

The literature gap and research questions were addressed with a composite indicator, developed with an established methodology. This new supply chain "Sustainability and Resilience Index" (Resist-I) is used for the joint assessment of Resilience, Sustainability, and their interrelationship.

Resist-I is built on 2 sub-indexes, Sustainability and Resilience which are built on 11 pillars: adaptive risk management, collaboration, redundancy, and agility belong to the Resilience sub-index; environmental sourcing, sustainable supply chain and logistics practices, environmental commitment, socially responsible sourcing, internal supply chain and external stakeholders belong to the Sustainability sub-index. The Resilience sub-index has 11 sub-pillars, while the Sustainability sub-index has 16 sub-pillars. Resist-I aggregates a total of 52 indicators, 24 from the Resilience sub-index, and 28 from the Sustainability sub-index, for an overall balanced contribution between the Resilience and the Sustainability sub-indexes. A new tool, COINr, was implemented to facilitate the composite development and visualization (Becker et al., 2022).

The methodology draws on the guidelines for Constructing Composite Indicators of the OECD and the Joint Research Centre of the EU Commission, JRC-EU (OECD-JRC, 2008). The JRC-OECD methodology is used worldwide for building Composite Indicators with 118 Indexes and 25 Scoreboards being developed around the world (European Commission, 2022).

According to the above adopted guidelines a reliable CI is developed in 10 steps, grouped in four phases: 1. scoping, framing and selection; 2. data collection and treatment; 3. composite building; and 4. analysis and benchmarking. Each research phase allows an Advisory Board (AB) of experts and stakeholders, with varying backgrounds in SC Sustainability and Resilience, to steer the research with reviews, validating the progress to the following research phases. Our AB was composed of 8 experts with various backgrounds in supply chain Sustainability and Resilience, including two research professors in supply chain security and resilience, a director of a logistics company, a director of a retail company, a board member of a business continuity institute, a director of a large retail company, a director of a manufacturing company, the CEO of a supply chain consultancy for the Fast-Moving Consumer Goods (FMCGs), Retail and Wholesale, and energy sectors, and a representative of the innovation department of a global FMCGs manufacturer. Table 1 synthesises the Resist-I development process.

To detail Table 1 above, Phase I includes steps 1 and 2 of the OECD-JRC Methodology, i.e., development of the CI theoretical framework and selection of the indicators. Our literature review sets the boundaries of the research, isolates the key concepts, and defines the conceptual framework (step 1), along with the identification and selection of relevant indicators and the survey questionnaire design (step 2) (see Table 2-Resist-I Framework). Phase 2 includes steps 3, 4 and 5, respectively data treatment, normalization and weighting. Phase 3 includes steps 6, 7 and 8, respectively data aggregation, coherence, and robustness and sensitivity analysis. Phase 4 consists of steps 9 and 10, i. e., data sensemaking and visualization of the composite indicator building.

3.1. Phase 1 scoping and framing

Step 1, the conceptual framework, is the first step of the development of composite indicators. The scope of the literature review is related to Sustainability and Resilience in the supply chain and related indicators.

Table 1
10 steps to build a composite indicator, research phases, and Advisory Board contribution.

Research phases	Composite indicators building – 10 steps	Advisory board contributions	Research contributions
1.Scoping and framing	1. Conceptual framework 2. Selection of indicators	−Framework, indicators, and survey questionnaire validation	−Firm level data
2.Survey and data treatment	3. Data treatment 4. Normalisation 5. Weighting	−Validation of the survey sampling and data treatment	−Survey for data collection
3.Composite building	6. Aggregation 7. Statistical coherence 8. Robustness and sensitivity	−Validation of indicators grouping, sub-pillars, pillars, and sub-indices	−Use of R package for composite building: COINr
4.Results: Analysis and benchmarking	9. Data sensemaking 10. Data visualization	−Results validation and insights for future research	−Theoretical and managerial implications

Table 2
Resist-I Theoretical Framework and related main references.

PILLAR (Label)	SUB-PILLAR	INDICATOR	Description	Survey question*	Main References	
		SUB-INDEX: RESILIENCE				
Agility (Agility)	Adaptability & Velocity	Transportation & Warehousing Flexibility	Evaluates the flexibility in terms of extra time and extra cost sustained in case of sudden switch of logistics provider, of volume changes or of sudden needs of deliveries.	1.1	Ponomarov and Holcomb, 2009; Stevenson and Spring, 2007; Jain et al., 2017; Pettit et al., 2013; Soni et al., 2014; Zavala-Alcívar et al., 2020; Christopher and Peck, 2004	Carvalho et al., 2012; Pettit et al., 2010
		Transportation Mode Flexibility	Evaluates the flexibility in terms of extra time and extra cost burdened in case of sudden need of a change of transportation mode	1.2		Carvalho et al., 2012; Pettit et al., 2010
		Workforce Flexibility	Level of workforce flexibility in terms of variety of tasks performed	1.6		Azevedo et al., 2013; Kamalahmadi & Parast, 2016
	Responsiveness & Recovery	Production Volumes Flexibility	Measures the plants' capabilities to increase production volumes in order to recover from disruptions	1.4	Carvalho et al., 2013; Pettit et al., 2013; Levin and Lubchenco, 2008; Ivanov et al., 2017; Kamalahmadi and Parast, 2016; Rajesh, 2018; Namdar et al., 2021	Azevedo et al., 2013 ; Azevedo et al., 2016
		Use of Small Minimum Batch Size from Supplier	It measures how small, relative to the average batch sizes, is the minimum batch size purchased from suppliers. This strategy shows a superior attention to flexibility rather than to economies of scale	1.7		Azevedo et al., 2013; Azevedo et al., 2016
		Use of Small Minimum Batch Size toward Customers	It measures how small, relative to the average batch sizes, is the minimum batch size produced. This strategy shows a superior attention to flexibility rather than to economies of scale	1.8		Azevedo et al., 2013; Azevedo et al., 2016
	Flexibility in Sourcing & Order Fulfilment	Production Systems Flexibility	Measures the plants' capabilities to manufacture different products on the same line with no substantial changes in production quality, cost and time	1.3	Rajesh, 2018; Chowdhury et al., 2020	Azevedo et al., 2013; Azevedo et al., 2016
		Supply Base Flexibility	Evaluates the flexibility of the supply base: how quickly and easily the sourcing can switch from one supplier to another	1.5		Carvalho et al., 2012; Pettit et al., 2010, 2013; Sen et al., 2018
Redundancy (Red)	Inventory Mgmt & Dispersion	Safety Stock Implementation	Evaluates the use of products held at stock to face unexpected events	1.9	Tukamuhabwa et al., 2015; Behzadi et al., 2017; Kochan and Nowicki, 2018; Hosseini et al., 2019 ; Rice and Caniato, 2003; Iakovou et al., 2007; Tomlin, 2006	Carvalho et al., 2012; Pettit et al., 2010
		SC Density	Measures the level of concentration of manufacturing nodes (production facilities)	1.11		Hosseini et al., 2019; Cabral et al., 2012
	Capacity	Production Capacity Saturation	Measures the level of free production capacity which can be leveraged in case of disruptions	1.10	Pettit et al., 2010; Azevedo et al., 2013	Pettit et al., 2013
	Supply Base	Use of Dual/Multiple Sourcing for Raw Materials	Evaluates the existence of active linkages besides the main one for the different raw materials purchased	1.12	Rajesh, 2018; Ivanov et al., 2019; Rice and Caniato, 2003; Namdar et al., 2021	Pettit et al., 2013; Ivanov et al., 2017
		Use of Dual/Multiple Sourcing for Finished Products	Evaluates the existence of active linkages besides the main one for the different finished products purchased	1.13		Pettit et al., 2013; Ivanov et al., 2017
		Use of carriers Multisourcing	Evaluates the existence of active linkages besides the main one for the provision of transportation logistics services	1.14		Pettit et al., 2013
		Use of Logistics Multisourcing	Evaluates the existence of active linkages besides the main one for the provision of storage logistics services	1.15		Pettit et al., 2013
Adaptive Risk management (ARMan)	Security & Robustness	Data Storage Backup System	Existence of backup systems and servers for the storage of data, information, and knowledge	1.16	Pettit et al., 2013; Rice and Caniato, 2003; Manuj and Mentzer, 2008; Karl et al., 2018; Brandon-Jones et al.,	Azevedo et al., 2013; Azevedo et al., 2016

(*continued on next page*)

Table 2 (*continued*)

PILLAR (Label)	SUB-PILLAR	INDICATOR	Description	Survey question*	Main References	
		Suppliers Financial Robustness	Evaluates the average financial situation of suppliers and the related insolvency risk	1.20	2014; Axon and Darton, 2021; Shishodia et al., 2021	Zavala-Alcívar et al., 2020
	Risk Mgmt Culture & Business Continuity	Risk Metrics Use	Measures the extent to which risk metrics are used and considered in SCM	1.17	Karl et al., 2018; Li and Zobel, 2020; Klibi et al., 2010; Singh et al., 2019; Namdar et al., 2021	Manuj & Mentzer, 2008
		Business Continuity Plans	Evaluates the existence and degree of development of business continuity plans, ensuring the continuous run of operations in case of disruption	1.19		Azevedo et al., 2013, 2016; Rice & Caniato, 2003
	Reliability	Presence of Nodes in High Risk Areas	Evaluates the supply chain exposure to social, political, and economic risks by investigating the level of involvement with more risky countries	1.18	Hosseini et al., 2019; Ivanov et al., 2019; Karl et al., 2018; Lotfi et al., 2021	Adenso-Diaz et al., 2012; Soni et al., 2014
Collaboration (Collab)	Visibility & Collaboration Practices	External Stocks and Downstream Demand Visibility	Measures the degree of both downstream and upstream stocks on which the company has visibility. Evaluates to which degree supply chain partners let the company access demand forecasts, and leverage ICT systems to allow an easy and prompt preparation of production schedules	1.21	Rajesh, 2018; Pettit et al., 2013; Blackhurst et al., 2011; Pereira et al., 2014; Iakovou et al., 2007; Karl et al., 2018; Papadopoulos et al., 2017; Jain et al., 2017; Taghizadeh et al., 2021; Shen and Sun, 2021	Azevedo et al., 2013, 2016; Pettit et al., 2013
		Collaborative Forecasting Level	Measures the collaboration level of the company with external suppliers to jointly perform demand forecasts	1.22		Pettit et al., 2013
	Communication & ICT Skills	SC Information Sharing Quality	It evaluates how quicky and accurately information regarding disruptions and incidents is shared throughout the supply chain	1.23	Rajesh, 2018; Hosseini et al., 2019; Soni et al., 2014; Jain et al., 2017; Pettit et al., 2013; Carvalho et al., 2012; Pereira et al., 2014	Kamalahmadi & Parast, 2016; Pettit et al., 2013
		Collaborative Communication Level	Evaluates the level of communication and information sharing with suppliers and partners	1.24		Carvalho et al., 2013; Pettit et al., 2013
		SUB-INDEX: SUSTAINABILITY				
Environmental Sourcing (ESource)	Suppliers Env. Certification & Green Procurement	Certified Suppliers Share – Environmental	Measures the (rough) percentage of suppliers having an ISO14000 certification or others recognized Environmental Management certifications	2.1	Epstein and Wisner, 2001; Hassini et al., 2012; Zhu et al., 2008; Bala et al., 2008; Govindan et al., 2015; Rao and Holt, 2005; Küchler and Herzig 2021; Chirra et al. 2021	Seuring & Müller, 2008; Govindan et al., 2013; Zhu et al., 2008
		Green Procurement Consideration	Investigates the level of consideration for environmental factors (i.e., environmental performances, level of environmental compliance, environmental responsibility and proactivity) when evaluating suppliers	2.2		Srivastava, 2007; Carter & Rogers, 2008; Miemczyk and Luzzini, 2018
	Env. Supply Visibility	Second-tier Environmental Sustainability Assessment	Assesses the level of visibility and of investigation performed on second-tier suppliers' environmental performances	2.3	Epstein and Wisner, 2001; Hassini et al., 2012; Govindan et al.. 2013	Zhu et al., 2008; Miemczyk and Luzzini, 2018
Sustainable Supply Chain and Logistics Practices (SLog)	SC Design & Transportation Mode	Modal Transportation	Measures the (rough) distribution of transportation loads along road, train, sea, and air transportation	2.5	Dekker et al., 2012; Hassini et al., 2012; Carter and Easton, 2011; Lin et al., 2018	Carter & Rogers, 2008; Rao & Holt, 2005; Seuring, 2013; Hervani et al., 2005
		Suppliers Dispersion	Measures the geographical concentration of nodes in the SC	2.4		Lin et al., 2018; Balcik et al., 2010
	Energy Use	Renewable Energy Use in Production and Storage facilities	Assesses the percentage of energy used coming from renewable sources rather than from fossil fuels	2.6	Rao and Holt, 2005; Dekker et al., 2012; Kumar et al., 2020	Srivastava, 2007; Carter & Rogers, 2008; Rao & Holt, 2005; Hervani et al., 2005
	Waste Recyclability & Reuse, Recycling and Remanufacturing	Production Wastes Quality	Evaluates the degree of theoretical recyclability of the production scraps and wastes coming from production and storage processes; as already mentioned, this indicator also	2.9	Hervani et al., 2005; Zhu et al., 2008; Carter and Easton, 2011; Florida and Davison, 2001; Tsai et al., 2021	Srivastava, 2007

(continued on next page)

Table 2 (*continued*)

PILLAR (Label)	SUB-PILLAR	INDICATOR	Description	Survey question*	Main References	
			implies an environmentally responsible design of products			
		Recycling, Remanufacturing and Reuse	Measures the actual implementation of recycling, remanufacturing and reuse of scraps and wastes coming from both production and storage activities	2.10		Carter & Rogers, 2008; Rao & Holt, 2005; Seuring, 2013; Srivastava, 2007
	Waste Production & Water Use	Total Waste Production	It evaluates the efficiency of production processes in terms of production scraps	2.8	Florida and Davison, 2001; Rao and Holt, 2005	Govindan et al., 2013
		Total Water Use	Evaluates the degree of water-intensity of production processes	2.7		Govindan et al., 2013; Hervani et al., 2005
Environmental Commitment (ECom)	Company's Commitment & Packaging Recyclability	Packaging Recyclability	Measures the degree to which the packaging used for finished products is recyclable	2.11	Walker et al., 2008; Yontar and Ersöz, 2021	Dekker et al., 2012; Rao & Holt, 2005; Srivastava, 2007
		Environmental Roles Diffusion	Assesses the diffusion within the company of job roles having clear environmental responsibility roles	2.14		Hervani et al., 2005
		Environmental Impact Self-Assessment	Evaluates how often the company undertakes a self-assessment of its own environmental impact, looking at the consumption of natural resources and emissions	2.12		Hervani et al., 2005; Zhu et al., 2008
	Env. Certification Use & Environmental Relevance in SCM	Environmental Impact in SCM Performance Evaluation	It evaluates the relevance of environmental performances in the overall evaluation of company's and supply chain's performances	2.13	Hervani et al., 2005; Govindan et al., 2013; Younis and Sundarakani, 2020	Govindan et al., 2013; Hervani et al., 2005; Seuring & Müller, 2008; Srivastava, 2007
Socially Responsible Sourcing (SRes)	Socially Responsible Procurement & Soc. Supply Visibility	Certified Suppliers Share – Social	Evaluates the number of company's suppliers which hold a social responsibility certification; it is a measure of the attention the company gives to selecting socially responsible partners	3.1	Epstein and Wisner, 2001; Santiteerakul et al., 2011; Baba et al., 2019; Wang et al., 2023; Khan et al. 2021	Hervani et al., 2005; Miemczyk and Luzzini, 2018
		Second-tier Social Sustainability Assessment	Assesses the level of visibility and of investigation performed on second-tier suppliers' social performances	3.2		Hassini et al., 2012; Krasnikov & Jayachandran, 2008; Seuring & Müller, 2008
Internal Supply Chain (InSC)	Working Conditions & Employees Satisfaction	Employees Satisfaction Measurement	Assesses the company's frequency in measuring employees' job and training satisfaction	3.3	Baba et al., 2019; Walker et al., 2008; Dekker et al., 2012; Carter and Easton, 2011; Khan et al. 2021	Carter & Rogers, 2008; Hassini et al., 2012
		Health and Safety Practices Implementation	Evaluates how broadly the company implements health and safety programs and practices in the supply chain (e.g., support to 84employees having physical tasks, to employees working in cold environments, safety on production sites)	3.4		Carter & Rogers, 2008; Seuring & Müller, 2008
	Equity, Diversity and Inclusion & Gender Equality	Gender Equality Employment	Measures the gap, if there is any, between male and female workers	3.9	Baba et al., 2019; Narimissa et al., 2020; Benjamin et al., 2020	Govindan et al., 2013
		Inclusivity, Equity and Diversity Practices	Measures the diffusion and frequency of implementation of programs and practices aimed at creating an inclusive, equal and diverse environment within the company and supply chain	3.5		Govindan et al., 2013; Hutchins and Sutherland, 2008
	Social Sust. Relevance in SCM	Social Impact in SCM Performance Evaluation	It evaluates the relevance of social responsibility performances in the overall evaluation of company's and supply chain's performances	3.6	Baba et al., 2019; Thies et al., 2021	Santiteerakul et al., 2011
External Stakeholders (EStake)	Community Involvement Initiatives	Community Initiatives	Assesses the company's involvement with local communities through contributions to the local	3.7	Govindan et al., 2013; Baba et al., 2019	Hervani et al., 2005; Santiteerakul et al., 2011

(*continued on next page*)

Table 2 (*continued*)

PILLAR (Label)	SUB-PILLAR	INDICATOR	Description	Survey question*	Main References	
			economy, ensuring local wealth and skills, and implementing programs for the development of local issues			
Financial Management (FMan)	Profitability & Growth	EBITDA Margin	It assesses the level of margin the company has, without considering taxes, interests paid and D&A	Orbis	Ortas et al., 2014; Longinidis and Georgiadis, 2014; de Carvalho Ferreira et al., 2016	Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019
		EBITDA Margin Growth	Measurement of the growth of the EBITDA margin	Orbis		Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019
		Revenue Growth	Measurement of the Turnover growth rate of the last year	Orbis		Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019
	SC Finance	NWC/Turnover	This indicator helps evaluate the management of the main leverages, i.e. inventories, payables and receivables.	Orbis	Ortas et al., 2014; Longinidis and Georgiadis, 2014; de Carvalho Ferreira et al., 2016	Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019
	Short & Long Term Solvency	Current Ratio	Evaluates the short-term solvency of the company by comparing the most liquid assets with the closest liabilities	Orbis	Ortas et al., 2014; Longinidis and Georgiadis, 2014; de Carvalho Ferreira et al., 2016	Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019
		D/E	Evaluates the long-term financial robustness of a company	Orbis		Camerinelli, 2009; Lekkakos & Serrano, 2016; Manning & Soon, 2016; Zhu et al., 2019

* See appendix III.

To define the conceptual framework leading to the structure of the composite indicator (in terms of pillars and sub-pillars) and linked indicators, a top-down/bottom-up approach was used.

The top-down approach consisted in the identification of the dimensions of supply chain Sustainability and Resilience to define pillars and sub-pillars of the index. An open focused literature search (Dey, 2014) was carried out on supply chain Sustainability and Resilience by interrogating the Scopus and the Web of Science (WoS) databases. The keywords used for this search revolved around "supply chain resilience" and "supply chain sustainability", plus keywords such as "dimension", "concept", "pillar", "framework", "taxonomy", "category" to narrow the focus of the search. The task was then complemented by a forward/backward citation snowball search (Thomé et al., 2016). Papers were analysed through a coding process (Gioia et al., 2013), carried out by three researchers independently and concurrently, and the key dimensions of Sustainability and Resilience were identified. Meetings were arranged to reconcile divergencies and reach a final consensus. 4 pillars for supply chain resilience, and 7 pillars for supply chain sustainability were obtained, plus 11 sub-pillars for supply chain resilience and 16 for supply chain sustainability (see Table 2).

The bottom-up approach was based on the Systematic Literature Review (SLR) (Denyer & Tranfield (2009) to identify indicators through a more focused review. The SLR used the following research strings: ((("resilienc*" OR "resilient") AND ("indicator*" OR "metric*" OR "index" OR "indice*") AND "suppl* chain")); ((("sustainable supply chain*" OR "supply chain sustainability") AND ("indicator*" OR "metric*" OR "index" OR "indice*"))). The SLR used the Scopus and WoS databases again. We included papers in peer-reviewed scientific journals, written in English, containing the keywords of the search strings in the title, abstract or keywords, with no restriction on the publication year. Removing the duplicates, we obtained 242 papers for supply chain resilience, and 318 for supply chain sustainability. By applying exclusion criteria (i.e., non-affiliated fields, and papers not focusing on the measurement of Sustainability and Resilience) through title analysis, scrutiny of the abstract, and full text analysis (plus a forward/backward citation snowball search), we obtained a final sample of 87 papers.

The retrieved indicators were coded to develop relevant categories of items (Gioia et al., 2013). The same coding procedure as above was adopted. Consensus was reached around 94 indicators extracted from the literature, and provisionally assigned by the researchers to the previously defined sub-pillars.

The set of 94 assigned indicators was submitted to the Advisory Board (AB). The AB provided different opinions, leading to an acceptable, robust, legitimate, and balanced framework regarding its dimensions and indicators (Becker et al., 2019; Okoli & Pawlowski, 2004)).

Step 2 refers to the indicator selection. The AB validated a criterion to select indicators based on: 1) difficulty or data privacy concerns for retrieving data; 2) difficulty in operationalizing absolute values (e.g. amount of CO2 emissions in a period of time by a business unit) in a survey; 3) the less meaningful of two similar indicators; 4) too advanced indicator (e.g. use of next-generation green vehicles) for the Italian context; 5) non-applicable to all sectors involved; 6) high likelihood of a lack of awareness of the value of the metric by the companies (e.g. energy consumption of outsourced logistics facilities).

Out of the 94 initial indicators, 52 were retained and included in the conceptual framework (Table 2).

In this same phase, the survey questionnaire was developed and later reviewed and validated with the AB.

3.2. Phase 2 survey and data treatment

This phase includes the data gathering, data treatment, data normalization and weighting. Data gathering integrates secondary and primary data sources. The secondary data originated from the Orbis Bureau van Dijk database, and includes business statistics such as industry classification, number of employees, revenues, financial data, and headquarters location. The primary data originated from a survey questionnaire (see appendix III) the aim of which was to obtain information to measure supply chain Sustainability and Resilience.

The survey was administered to a sample obtained from the same Orbis database used to collect secondary data, comprising 3729 firms in Italy operating in the manufacturing, retail, and energy-supply sectors. The number of respondents was 262, which represents a response rate of 6.9 % (See Table 3).

Following concerns of representativeness issues with Orbis datasets (see Bajgar et al., 2020), we performed a sampling bias assessment. According to Eurostat's Structural Business Statistics the Italian industry is highly skewed towards micro (97 %) and retail (41.6 %) establishments, whilst Orbis and consequently the Resist-I sample are much more balanced in terms of firm size and industries (see appendix I). Although there are post-sampling correction methods such as assigning higher weights to emulate the national structural business statistics (Bajgar et al., 2020), the authors, in agreement with the AB, decided to report rather than correct biases. This is also consistent with the exploratory nature of this investigation, which is focused on a new methodological approach to measure Sustainability and Resilience.

Steps 3, 4 and 5 are performed to operationalize the index. The data coverage is 99.2 %, counting 129 missing values. To have a full dataset for our analysis the missing values were treated with the imputation of the unconditional median of each indicator. This estimator (Eq. (1) is more robust compared to the mean.

$$Median = (n+1)/2 \tag{1}$$

Outliers were treated with the winsorization method (i.e., rescaled to the maximum value) to correct the shape of the frequency distribution. After imputation and winsorization, the data was normalized with the min–max transformation [0, 100], to allow for comparability between variables and across pillars, and to aggregate up, to develop the final index (See Eq. (2).

$$I_f = \frac{x_f - x_{min}}{x_{max} - x_{min}} \tag{2}$$

Where f is the firm.

As Table 4 shows, each sub-index, pillar, and sub-pillar was assigned a relative equal weight.[2] The Resist-I has two sub-indices, hence, each received 50 % of the weight. Similarly, the total number of pillars in the Resilience indicator is 11, and given that Agility contains 3 sub-pillars, the assigned weight was 3/11 for Agility, and so on. The weights within each group are normalized to sum to one during the aggregation. Assigned weights are different from effective or final weights, because the weight of an indicator is affected by its own weight and the weights of any aggregate groups to which it belongs, i.e., its parent weights. The latter, is the hierarchical structure contribution of each indicator, sub-pillar, pillar, sub-index to the overall Index in the aggregation process (Becker et al., 2019). We, thus, report below the effective rather than assigned weights for each indicator, sub-pillar, pillar, and sub-index. Effective weights are presented in Table 4, and reported in equations (4), 5, and 6. For instance, while each sub-index, pillar, and sub-pillar were assigned equal weights, the COINr tool modified them. Table 4 shows in parenthesis () the weight, and the last column, ' Weight in Index', indicates the final effective weight of each indicator to the overall Index. The values in equations (4), 5, and 6 correspond to each effective weight from Table 4.

[2] equal weighting is the most common approach and it is used when the scope is to give the same weight to each indicator. Also, experts in practice often assign near-equal weights when asked.

3.3. Phase 3 composite building

Resist-I, is a mathematical hierarchical aggregation of groups of indicators into aggregate values, then those values are aggregated into higher-level aggregates, etc., to arrive at the Resist-I composite index. The aggregation is performed on normalized data if indicators are on different scales, and this averts odd relative influence of indicators. The normalized indicator is multiplied by its weight $w^*_{d,j}$ and then aggregated with the weighted arithmetic average (See Eq. (3), which compared to other methods, e.g. the geometric aggregation, better compensates the weights between indicators and across units of analysis (Becker et al., 2019; OECD-JRC, 2008). In other words, lower values of resilience reflect with higher intensity the relative importance gained by sustainability in the final indicator, and vice versa. Compensability between indicators is important in this investigation, given the lack of clarity of the relationship between Sustainability and Resilience discussed earlier. The COINr package was used for the aggregation procedure (Becker et al., 2022).

$$Resist - I_{p,i} = \sum\nolimits_{i=1}^{n} (X_i W_i) / \sum\nolimits_{i=1}^{n} (W_i) \; \forall p \tag{3}$$

where:

- w_i represents the weight of the pillar or indicator [0;1]
- p represents the pillar(s), e.g., agility, risk management, collaboration, etc. so p = [1,11]

With the statistical coherence analysis, the correct direction and the strength of the statistically significant Pearson correlations among indicators, sub-pillars, pillars, sub-indexes, and index were verified. Correlation measures the degree of statistical dependence between indicators, and most of the time relationships between indicators are linear, except for highly skewed indicators. We look at correlations of each indicator or aggregate with its parents. The sensitivity and uncertainty analysis with consequent 'back to the data' and data visualization followed later. The sensitivity and uncertainty analysis reports the effects on the composite indicator of using alternative normalization, weighting, and distribution methods. Overall, the Resist-I Indicator is robust according to the methodology followed (see appendix II for the full sensitivity and uncertainty analysis).

The final phase, Results: analysis and benchmarking including steps 9 and 10 corresponding to the data sensemaking and visualization of the composite indicator building methodology, is described in the results section following.

4. Results

Results address the dimensions, weights and scores related to the concepts of supply chain Sustainability and Resilience (RQ1) and the interrelationships between Sustainability and Resilience and their dimensions (RQ2).

4.1. The pillars of supply chain sustainability and resilience

The contribution of Sustainability and Resilience to the overall composite index is balanced. Several indicators have relatively high contributions, as evidenced by their width in the outermost ring of Fig. 1. The index is aggregated based on the following relations:

$$Resist - I_i = (0.5Resi_i + 0.5Sust_i) \tag{4}$$

Fig. 1 shows that firms with lower scores in the overall index also have a lower contribution of supply chain sustainability, also showing that sustainability is less developed compared to resilience in terms of performance. This is probably because companies tend to prioritise actions aimed at securing their operations first rather than emphasizing

Table 3
Sampling universe selection.

Orbis global active companies	Orbis Italy active companies	Orbis Italy companies with contact details to June 2019	Companies in the Manufacturing, wholesale, retail, and energy supply	Manual cleaning due to missing data (Sampling universe)	Survey respondents
288,572,957	5,872,120	6,214	3,775	3,729	262

sustainability. High-performing companies have a more balanced approach towards Sustainability and Resilience compared to low-performing companies, which tend to prioritise resilience over sustainability. This is in line with the literature supporting the view that companies tend to intuitively focus on business continuity first (Chowdhury et al., 2020).

The Resilience sub-index comprises four pillars, and their relationships are mediated by their following weights:

$$Resi_i = (0.263ARMan_i + 0.211Collab_i + 0.211Red_i + 0.316Agility_i) \quad (5)$$

Fig. 2 shows that the scores for supply chain collaboration and agility are considerably higher for the most resilient firms. Fig. 3 confirms this finding by showing a larger difference in supply chain collaboration between firms with high, middle, and low Resist-I scores. It seems that low-performing companies tend to struggle, especially in those areas that require capabilities that reach outside the boundaries of their own organization and that require the development of an external network of collaborations across the supply chain. The literature acknowledges that collaboration is part of resilience (Govindan et al., 2015). Agility also represents a part of resilience (Wieland & Wallenburg, 2013), linked to the improvement of supply chain performance according to the literature (e.g., Altay et al., 2018). In fact, from our data it is another area where a significant difference between high-performing and low-performing companies can be detected. Agility, along the same lines as collaboration, is a capability that goes beyond the boundaries of the focal firm, involving (besides internal and organizational processes) also suppliers, contractors, and customers, and that necessitates relationships capable of enabling an agile response and ensuring visibility and good quality of information sharing.

Interestingly, it appears that companies are almost aligned in terms of scores obtained on the risk management and redundancy pillars. It is also worth noting that while companies are aligned around medium–high scores on risk management, they are aligned around medium–low scores on redundancy. This shows that redundancy can be considered a pillar of resilience, but it is also well known that redundancy, for example in terms of extra stocks, “comes at a cost” (Rajesh, 2018), and consequently it cannot be considered as a major contributor to the development of supply chain resilience – as confirmed by our results.

The Sustainability sub-index, comprises seven pillars, and their relationships are weighted as follows:

$$Sust_i = (0.107ESource_i + 0.250SLog_i + 0.143ECom_i + 0.071SRes_i + 0.214InSC_i + 0.036EStake_i + 0.179FMan_i) \quad (6)$$

Figs. 4 and 5 show that the external stakeholders (EStake) and environmental sourcing (ESource) make a difference between firms with low, middle, and high Resist-I scores. Furthermore, external stakeholder (i.e., company contributing to the development of the local community through various initiatives) is the pillar scoring highest for sustainability, despite being the pillar with the lowest weight in the sustainability sub-index. While the economic and environmental sustainability have received more attention in the last few years, the social sustainability side is still acknowledged as a strategic goal for organizations (Janošková and Palaščáková, 2018), and our evidence seems to suggest that companies are ready to leverage this area to improve their sustainability performance. Results show a scant difference between low, middle, and high Resist-I performers, in terms of sustainable financial management practices (FMan). Similarly, there is not much difference between the low and middle Resist-I performers in terms of their sustainable supply chain and logistics practices (SLog), while firms with high Resist-I scores outperform the rest in terms of sustainable supply chain and logistics practices (SLog). These results show that also in terms of sustainability companies tend to give different priorities and develop different areas for the achievement of sustainability in their own supply chain. In fact, while there are established areas that can be managed internally to the focal company (e.g., SLog), the major differences lie in those pillars that again require the ability to go beyond the boundaries of the focal company: external social commitment and environmental sourcing – the development of a set of relationships, initiatives (and potentially collaboration and visibility) with stakeholders and suppliers can foster sustainability performance. This is in line with the literature, which indicates that adoption of certification and audit programs with suppliers are levers for improving the external sustainability side of companies (Govindan et al., 2013). However, supply chain partners might want to adopt the same standards, in order to have a shared understanding and co-align (collaboration and alignment) their practices and performance measurements towards sustainability (Assumpção et al., 2023; Dobler et al., 2014). Common assessment practices and collaboration with suppliers are recognized to have positive impacts on sustainability in terms of environmental and social impacts (Gimenez and Tachizawa, 2012).

Financial management scored a medium value for all companies, showing that the companies tend to work with a good level of economic sustainability but none of them excels, leveraging the financial side to foster sustainability. It seems that financial management is a “must” condition that companies tend to satisfy but it does not represent an actual driver of better sustainability overall. The literature acknowledges the presence of a bidirectional relationship between the sustainable performance of supply chains and their financial performance, but in times of crisis economic and financial issues are prioritized against environmental and social sustainability aspects (Ortas et al., 2014).

4.2. The interrelationship between sustainability and resilience

Fig. 6 presents the interrelationships between the multiple Sustainability and Resilience dimensions. It shows the strength of the Pearson correlation between pillars within and with their sub-index, and between sub-indexes with outside pillars (e.g., Sustainability with Risk Management, Redundancy, etc.).

While the AB validated each indicator, sub-pillar, pillar, and sub-index grouping, as described in the Methodology section, a correlation analysis was implemented to gain nuance regarding the validation and the interrelationships or interdependencies between indicators up to the indicator level, as it is discussed below.

Within the Sustainability sub-index, the Internal Supply Chain (InSC) social commitment and Environmental Commitment (ECom) pillars have the strongest correlation with other pillars and with the sub-index itself. Most of the pillars have a strong correlation within the sub-index, except for Sustainable Supply Chain and Logistics (SLog), which is not correlated with all the pillars, although it is strongly correlated with the sub-index. Financial Management (FMan) is neither significantly correlated with the sub-index nor with other pillars, except for commitment with External Stakeholders (EStake).

Within the Resilience sub-index, three of the four pillars are correlated with each other, except for Redundancy (Red). The sub-index is correlated with Adaptive Risk Management (ARMan) and Redundancy

Table 4
Resist-I Effective weights.

Weight in Sub-Index	Weight in Pillar	Weight in sub-pillar	Weight in Index
RESILIENCE (0.50)			
Agility (0.32)	Adaptability & Velocity (0.33)	Transportation & Warehousing Flexibility (0.25)	1.3 %
		Transportation Mode Flexibility (0.25)	1.3 %
		Workforce Flexibility (0.5)	2.7 %
	Responsiveness & Recovery (0.33)	Production Volumes Flexibility (0.5)	2.7 %
		Use of Small Minimum Batch Size from Supplier (0.25)	1.3 %
		Use of Small Minimum Batch Size toward Customers (0.25)	1.3 %
	Flexibility in Sourcing & Order Fulfilment (0.33)	Production Systems Flexibility (0.5)	2.7 %
		Supply Base Flexibility (0.5)	2.7 %
Redundancy (0.21)	Inventory Mgmt & Dispersion (0.5)	Safety Stock Implementation (0.5)	2.6 %
		SC Density (0.5)	2.6 %
	Capacity (0.25)	Production Capacity Saturation (1)	2.6 %
	Supply Base (0.25)	Use of Dual/Multiple Sourcing for Raw Materials (0.25)	0.7 %
		Use of Dual/Multiple Sourcing for Finished Products (0.25)	0.7 %
		Use of carriers Multisourcing (0.25)	0.7 %
		Use of Logistics Multisourcing (0.25)	0.7 %
Adaptive Risk management (0.26)	Security & Robustness (0.4)	Data Storage Backup System (0.5)	2.6 %
		Suppliers Financial Robustness (0.5)	2.6 %
	Risk Mgmt Culture & Business Continuity (0.4)	Risk Metrics Use (0.5)	2.6 %
		Business Continuity Plans (0.5)	2.6 %
	Reliability (0.2)	Presence of Nodes in High Risk Areas (1)	2.6 %
Collaboration (0.21)	Visibility & Collaboration Practices (0.5)	External Stocks and Downstream Demand Visibility (0.5)	2.6 %
		Collaborative Forecasting Level (0.5)	2.6 %
	Communication & ICT Skills (0.5)	SC Information Sharing Quality (0.5)	2.6 %
		Collaborative Communication Level (0.5)	2.6 %
SUSTAINABILITY (0.50)			
Environmental Sourcing (0.1)	Suppliers Env. Certification & Green Procurement (0.66)	Certified Suppliers Share – Environment (0.5)	1.7 %
		Green Procurement Consideration (0.5)	1.7 %
	Env. Supply Visibility (0.33)	Second-tier Environmental Sustainability Assessment (1)	1.7 %
Sustainable Supply Chain and Logistics Practices (0.25)	SC Design & Transportation Mode (0.286)	Modal Transportation (0.5)	1.8 %
		Suppliers Dispersion (0.5)	1.8 %
	Energy Use (0.143)	Renewable Energy Use in Production and Storage facilities (1)	1.8 %
	Waste Recyclability & Reuse, Recycling and Remanufacturing (0.286)	Production Wastes Quality (0.5)	1.8 %
		Recycling, Remanufacturing and Reuse (0.5)	1.8 %
	Waste Production & Water Use (0.286)	Total Waste Production (0.5)	1.8 %
		Total Water Use (0.5)	1.8 %
Environmental Commitment (0.14)	Company's Commitment & Packaging Recyclability (0.5)	Packaging Recyclability (0.6)	2.1 %
		Environmental Roles Diffusion (0.2)	0.7 %
		Environmental Impact Self-Assessment (0.2)	0.7 %
	Env. Certification Use & Environmental Relevance in SCM (0.5)	Environmental Impact in SCM Performance Evaluation (1)	3.5 %
Socially Responsible Sourcing (0.07)	Socially Responsible Procurement & Soc. Supply Visibility (1)	Certified Suppliers Share – Social (0.5)	1.8 %
		Second-tier Social Sustainability Assessment (0.5)	1.8 %
Internal Supply Chain (0.21)	Working Conditions & Employees Satisfaction (0.4)	Employees Satisfaction Measurement (0.5)	2.1 %
		Health and Safety Practices Implementation (0.5)	2.1 %
	Equity, Diversity and Inclusion & Gender Equality (0.4)	Gender Equality Employment (0.5)	2.1 %
		Inclusivity, Equity and Diversity Practices (0.5)	2.1 %
	Social Sust. Relevance in SCM (0.2)	Social Impact in SCM Performance Evaluation (1)	2.1 %
External Stakeholders (0.05)	Community Involvement Initiatives (1)	Community Initiatives (1)	2.5 %
Financial Management (0.18)	Profitability & Growth (0.5)	EBITDA Margin (0.33)	1.5 %
		EBITDA Margin Growth (0.33)	1.5 %
		Revenue Growth (0.33)	1.5 %
	SC Finance (0.25)	NWC/Turnover (1)	2.3 %
	Short & Long Term Solvency (0.25)	Current Ratio (0.5)	1.1 %
		D/E (0.5)	1.1 %

(Red), and strongly correlated with Collaboration (Collab) and Agility (Agility).

Given that supply chain resilience might also contribute to the sustainability of the supply chain, and vice versa (Jabbarzadeh et al., 2018), we explored the correlation between Sustainability and the Resilience pillars, and between the Resilience and the Sustainability pillars. The correlations confirm the interrelationships between Sustainability and Resilience, particularly the strong interrelationship between collaboration and the Sustainability sub-index, as well as between Environmental Sourcing (ESource) and Environmental Commitment (ECom) and the Resilience sub-index. This is also supported by the evidence presented in section 4.1, which shows that collaboration and other elements related to the relationships beyond the boundaries of the focal firm can significantly impact driving sustainability and resilience.

While the literature suggests a common interplay made of synergies and trade-offs between sustainability and resilience (Gouda & Saranga,

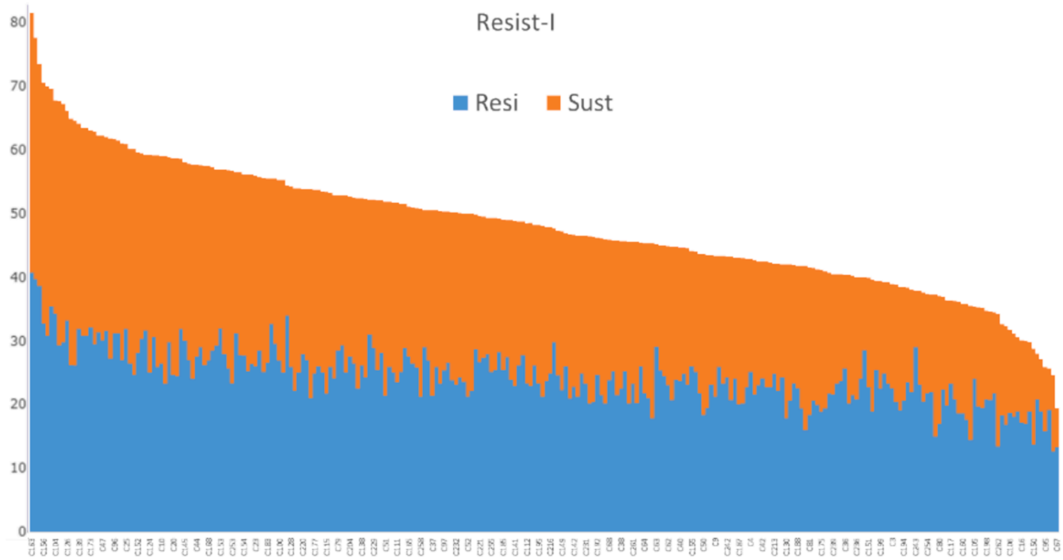

Fig. 1. Supply chain Sustainability and Resilience by firm.

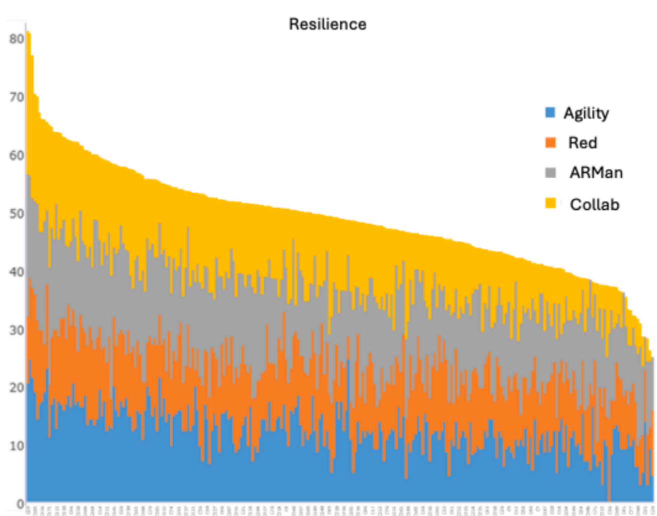

Fig. 2. The four pillars of Supply chain resilience by firm.

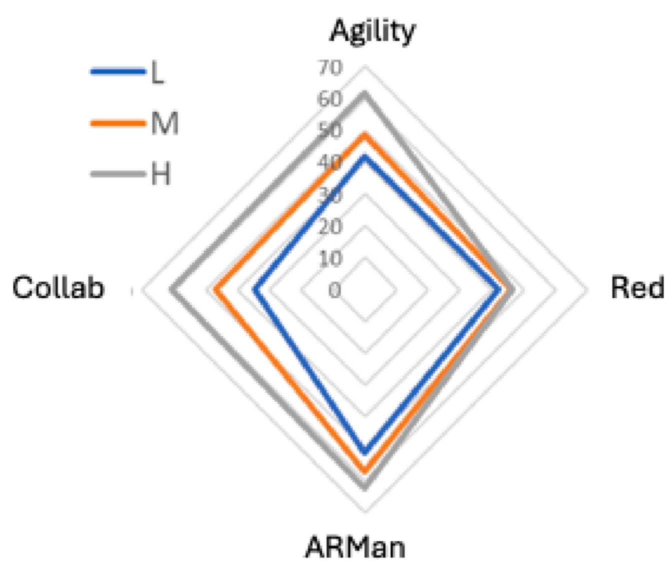

Fig. 3. Low, medium and high performing companies (Supply chain resilience).

2018), it is interesting to note that in our case several pillars related to sustainability have significant and strong correlation with both the sub-indexes of sustainability and resilience. Resilience pillars have significant and strong correlation on the sustainability sub-index only and through collaboration. Collaboration seems to play a more and more essential role in this sense, as the other pillars show weak correlation in the best of cases. ESource and ECom have a positive strong correlation on resilience through collaboration; hence, collaboration seems to be an enabler of Sustainability and Resilience. While the literature has studied the impact of collaboration on sustainability and resilience in a separate way (e.g. Çankaya & Sezen, 2019; Govindan et al., 2015), our study supports a combined effect of collaboration on the two areas.

No significant correlation of financial management with the other pillars can be found, except for ARMan and EStake – in both cases with a weak correlation only. The role of the "must-be" element of financial management seems to emerge again as a foundation for managing risk and presenting oneself to the external stakeholders in a credible way for engaging in sustainability initiatives.

By looking at the bottom left side of Fig. 6, the pillars of resilience seem to be less significantly correlated among each other compared to how they appear to be in relation to the pillars of sustainability (top right of Fig. 6) – in that case it appears that the number of significant correlations (and related strength) is larger. The dimensions of resilience seem more independent of each other, while the dimensions of sustainability are more intertwined and seem to represent a more pervasive holistic system than resilience. Redund (i.e., redundancy) appears to be an independent element as it does not present significant bi-directional correlations with the other pillars. If we add to this the consideration that Fig. 3 shows a low-medium score for this pillar for all companies, it would seem that organizations are moving in the direction indicated by the most recent contributions on resilience, which suggest that firms should get rid of redundancies per se, and develop response diversity (see Walker, 2020). In our case this is represented by those pillars that are related to adaptation and continuity also through an engagement with external partners in the supply chain (i.e., Adaptive Risk Management and Collaboration).

Given that there are no apparent strong negative correlations among pillars and sub-indexes, and that sustainability is more pervasive than resilience, it is likely that no significant trade-offs exist when deciding to invest in building resilient and sustainable supply chains. It is more

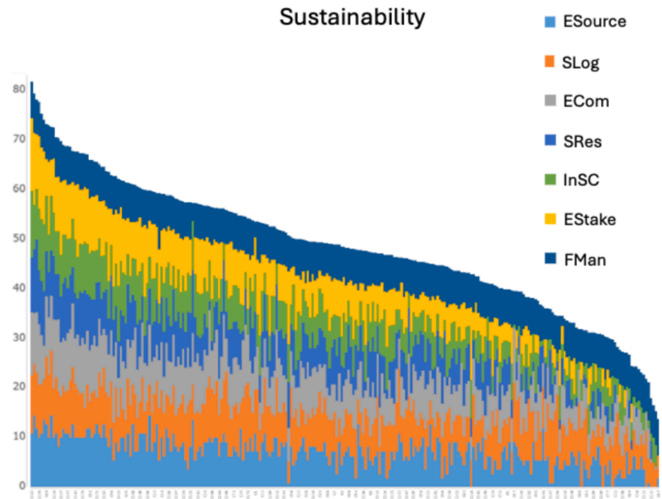

Fig. 4. The seven pillars of Supply chain sustainability by firm.

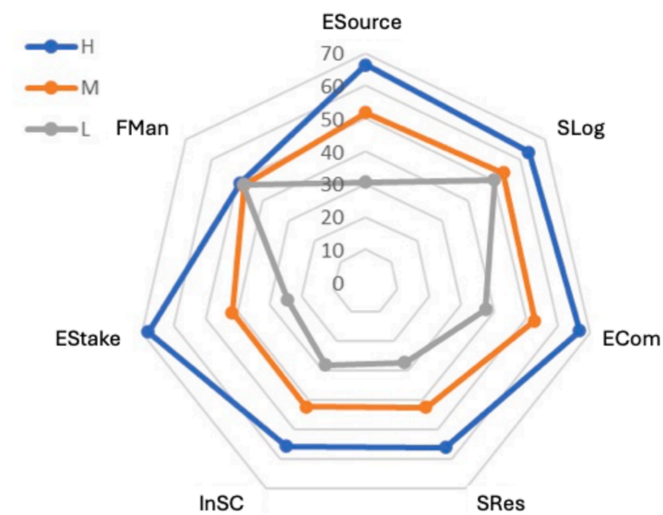

Fig. 5. Low, medium and high performing companies (Supply chain sustainability).

likely that a focus on sustainability might be more pervasive and contribute to the development of resilience of the company's supply chain. By presenting novel evidence on the lack of trade-offs between Sustainability and Resilience, our results align with the literature that affirms that developing sustainability also builds resilience (e.g., Fahimnia et al., 2018; Jabbarzadeh et al., 2018).

5. Discussion

By looking at how the surveyed companies position themselves across the survey sample, the index scores differ considerably, and the differences in the scores seem to be driven especially by the Sustainability sub-index, with large differences between high and low performers. The sub-index Resilience, on the other hand, shows more levelled scores across the sample. It seems that −in relative terms- resilience is more developed than sustainability in low performing companies, while high performers present a more balanced score in terms of Sustainability and Resilience. The literature suggests that companies generally feel they undertake actions and initiatives to improve their sustainability levels, while investing less in resilience (Negri et al., 2021). Our data show that companies undertake actions in terms of resilience too, and they even perform better on that side. They seem to take actions towards resilience without completely realizing it (e.g., multiple sourcing), while perceiving they are more focused on developing sustainability. Resilience is something that companies invest in for business survival without even considering it as a choice. This is reflected in the scores achieved by the sample companies across those more developed resilience dimensions, to adapt and evolve with the changing nature of the environment (Wieland and Durach, 2021). These can be seen in the light of business continuity (Namdar et al., 2021) and of the development of a risk management culture oriented towards the use of metrics to monitor key parameters, to anticipate and adjust to changing situations (Tseng et al., 2022). Collaboration and agility are more developed by high performers only. The same applies to sustainability, which shows better scores for high performers. Sustainability emerges as "nice to have", which high performing companies focus on as a complement to resilience (Fahimnia and Jabbarzadeh, 2016). In turbulent and volatile situations, it seems that disruptions might put sustainability objectives on hold (e.g., Mari et al., 2014). When crises occur, supply chain collaboration may sometimes be suspended in favour of internal actions (Sauer et al., 2022). Literature shows that companies able to leverage collaboration to confront crises can transform their supply chain processes and achieve better resilience (Carissimi et al., 2022).

Our evidence confirms that external capabilities (e.g., collaboration) are essential to develop resilience, but also suggests (see Fig. 6) that by developing collaboration it is possible to enhance the sustainability level too (i.e., strong positive correlation on both sub-indexes). Moreover, external capabilities emerge as main drivers of both Sustainability and Resilience in high performing companies, so it is imperative to develop these capabilities to go beyond the focal firm to become a high performer (Graça and Camarinha-Matos, 2017). According to Govindan et al. (2015), collaboration in terms of cooperation with suppliers and customers has a positive effect on resilience. Beske and Seuring (2014) argue that by sharing information and engaging in long-term relationships with other supply chain partners, organizations can enhance their overall level of sustainability and resilience.

The absence of significant strong negative correlations leads us to infer that significant trade-offs between sustainability and resilience do not exist according to our data, supporting the notion that either sustainability or resilience can be developed without a significant negative impact on the other (Fahimnia et al., 2018; Jabbarzadeh et al., 2018). Our evidence suggests which elements to focus on with higher priority towards a concurrent development of Sustainability and Resilience. In fact, environmental sourcing, environmental commitment, and collaboration are those pillars with the strongest correlations on both Sustainability and Resilience (see Fig. 6). Those dimensions have the most significant effect in differentiating between low and high-performing companies (see Figs. 2 and 4). For instance, environmental sourcing implies that companies' supply chains rely on environmentally certified suppliers; they can investigate, understand, and monitor their supply chain's environmental performance while maintaining visibility over the potential environmental impact of their operations. These aspects are crucial for the growing trend towards green transition and the decarbonisation of the EU and globally. Emerging regulations are heavily based on the need to monitor, report, and verify environmental practices and impacts. For example, consider EU regulations such as the CountEmissionsEU (European Parliament, 2024), the Carbon Border Adjustment Mechanisms (DG TAXUD-European Commission, 2024), Emission Trading Systems (ICAP, 2024), and so on. There is a positive correlation of Environmental Sourcing with resilience, which is instantiated through resilience's Collaboration. Given that in this example, the ability to comply with CountEmissionEU and CBAM regulations may require Environmental Sourcing (ESource) related activities to remain competitive in EU and international markets, companies are highly dependent on Collaboration with their supply chains. This is only one illustrative example of the potential interrelationship or interdependency between Environmental Sourcing (Sustainability) and

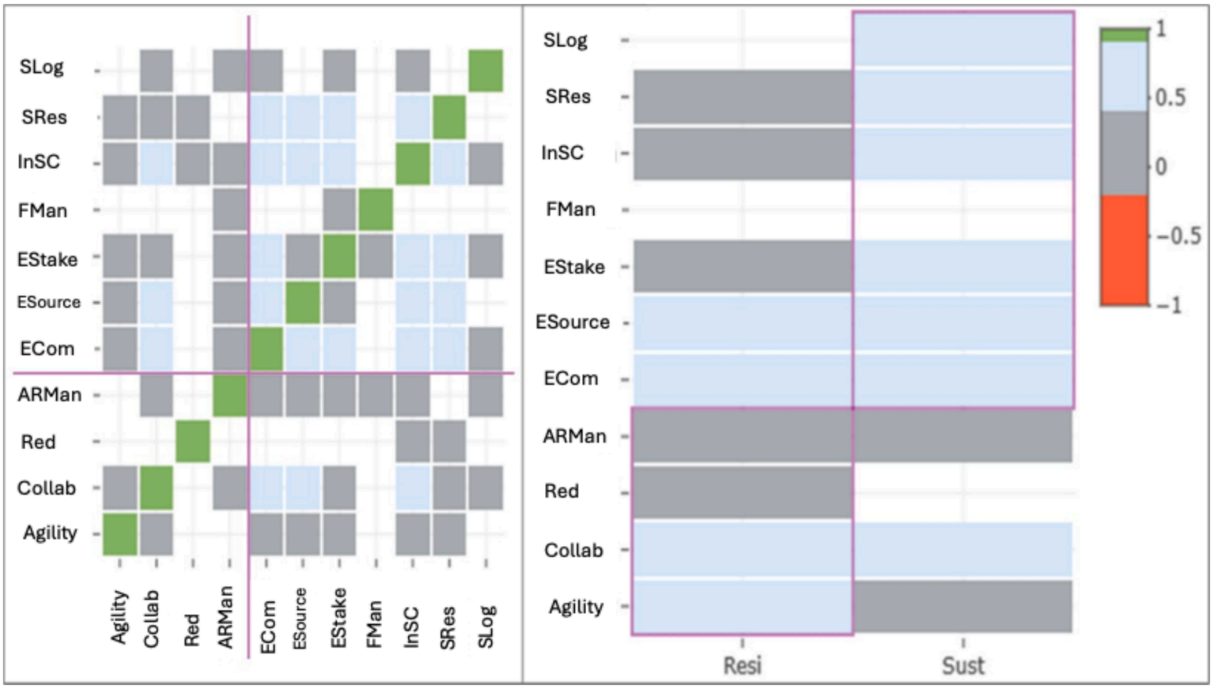

Fig. 6. Pearson correlations between Pillars and Sub-indexes. Strong positive correlations are marked in blue if larger than 0.4, between 0.4 and −0.2 are shaded grey, and if lower than − 0.2 and −1 are shaded red. A white shade indicates the correlation is not statistically significant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Collaboration (Resilience).

Furthermore, it seems that resilience is driven by a set of pillars that are encapsulated and tend to be quite independent of each other, while sustainability seems to be driven by a set of more intertwined pillars. Thus, it appears that sustainability is a more pervasive concept spanning several dimensions, most of them significant and with strong effects on both Sustainability and Resilience. While it seems that companies are more prone to invest in resilience, it emerges that by developing resilience companies obtain limited benefits (i.e., they predominantly enhance resilience). However, it seems that resilience represents a grounding element for also developing sustainability, as attested by the high performers in our sample who build on resilience and on top of that have sustainability as a differentiating element. An already resilient organization is more likely to "go green" (Fahimnia et al., 2018).

By leveraging sustainability, it seems that companies can achieve better performance in terms of both sustainability and resilience at the same time. Multiple sustainability paths may in fact lead to resilience (Sauer et al 2022). Sustainability can be seen as an enabler of resilience and can reduce risks through better decision-making processes (Jain et al., 2017).

The so-called "sustainability risks" that may result from social or environmental problems in the supply chain, such as non-compliance risk and image risk, are an area of research that is particularly rich (Bag et al., 2019; Gouda and Saranga 2018) and that takes into account the way organizations integrate sustainability into their core values (Wijethilake and Lama, 2019). Traditional approaches to resilience management often do not take social, ecological, and ethical supply chain issues into account. Our empirical evidence supports instead an integrated view of sustainability and resilience through the consideration of pillars such as environmental sourcing, social sourcing and environmental commitment of companies, which are linked to the concept of sustainability risks and show a correlation with resilience (Dobler et al., 2014). In this sense, sustainability can be regarded as an integral part of the social-ecological view of resilience (Wieland and Durach, 2021). The example provided above, related to the positive correlation between environmental sourcing (sustainability) and collaboration (resilience), can be seen as a typical case of sustainability risk, which can be addressed through collaboration as an external capability able to leverage the interplay between sustainability and resilience.

6. Conclusions

In this paper we addressed the joint study of supply chain Sustainability and Resilience, and through an established methodological approach, developed a composite indicator for the joint measurement of sustainability and resilience of supply chains. We provided a view on the key dimensions and aggregation of metrics required to jointly measure Sustainability and Resilience of the supply chain (RQ1) and we explored the interrelationships between Sustainability and Resilience of a supply chain through the conducted empirical survey (RQ2). This work has theoretical and practical implications.

6.1. Theoretical implications

Our study makes a significant contribution to the literature on sustainable and resilient supply chains by extending existing theory in several important ways. First, we address a notable gap in the literature by developing a joint measurement framework for sustainability and resilience, which are typically studied in isolation. Previous research has largely focused on these dimensions separately, and our work offers a novel, integrative approach by defining a set of dimensions that allow for the simultaneous assessment of both. This quantitative contribution advances current theory, which has been predominantly conceptual or qualitative in nature, by providing empirical evidence through the Resist-I framework. This framework adopts a holistic view, capturing the complex interplay between sustainability and resilience in supply chains. Second, our work offers a robust methodological advancement by developing composite indicators that are methodologically rigorous, reliable, and replicable. We provide a transparent description of the underlying framework, the data collection procedures, and the specific steps involved. This transparency is critical in advancing theory, as it sets a new standard for the development of composite measures in the field of sustainable and resilient supply chains—an area where methodologically sound indicators are scarce. Third, we contribute to the theoretical discourse on the relationship between sustainability and resilience. Through quantitative analysis, we demonstrate that these two concepts, often seen as conflicting or involving trade-offs, can coexist and even reinforce one another. Our findings clarify the mixed messages in the current literature, identifying key pillars that facilitate the concurrent enhancement of both sustainability and resilience. Moreover, we show that resilience serves as a foundational element, while sustainability helps distinguish between lower and higher performing firms. Importantly, our results indicate that sustainability exerts a pervasive, synergistic influence on firm performance, not only through direct improvements but also by strengthening resilience. Furthermore, we contribute to the evolving theoretical debate on the nature of supply chain resilience by providing empirical evidence of a shift in focus within organizations. Our findings suggest that firms are moving away from traditional resilience strategies based on redundancy (aligned with the engineering resilience perspective) and toward adaptive measures associated with the socio-ecological perspective. Specifically, our work highlights the growing importance of business continuity planning, collaboration, and external capabilities—measures that align more closely with adaptive resilience thinking. Finally, we also make a contribution in redefining the traditional set of metrics typically used to measure supply chain performance in relation to sustainability and resilience, to isolate high-performers versus low-performers. In fact, we identify a set of dimensions, mainly represented by those external capabilities, that are able to distinguish companies with a high-performing supply chain from low performing situations, taking a wider perspective compared to traditional methodologies, which usually focus on measures such as emissions, financial metrics and time to recover.

6.2. Managerial implications

Through the developed composite indicator, our work provides the industrial community with a performance measurement tool that informs organizations about the dimensions that constitute a sustainable and resilient supply chain, and the weight that the various dimensions have – giving companies a priority list of elements to focus on.

Thanks to its design, which is complete, transparent and replicable, Resist-I is a powerful tool for managers who can deploy it gathering the required information and obtaining an easy to interpret outcome. In fact, the framework of the dimensions and of the items, composing the indicator, represents a guide for managers to identify and select those elements that are necessary and essential to measure the sustainability and resilience performance of their organizations.

By calculating the value(s) of the score thanks to the deployment of Resist-I, organizations can position themselves as a first indication against the scores presented in this work, make a self-assessment of their performance and isolate priority areas (i.e., pillars) that can discriminate between low, medium and high performers and be the driver for improving the sustainability and resilience performance of their supply chains.

Another managerial contribution is that our work provides companies with clarity about the interrelationships between sustainability and resilience. Our evidence suggests that trade-offs are potentially absent and that synergies can exist between supply chain Sustainability and Resilience. It informs organizations that resilience is a grounding element to improve sustainability and that sustainability can be built in their supply chain without being at the expense of resilience. Our work helps companies in identifying those factors to be leveraged that can have beneficial effects on both Sustainability and Resilience. Among these factors, companies can leverage collaboration and the capacity to work with supply chain partners and stakeholders, exploiting external capabilities for being more resilient and sustainable at the same time.

6.3. Limitations and directions for future research

Our work is not exempt from limitations, however. First, it has been developed on an established methodology that proves to be reliable but that is not the only one available for building composite indicators. A limitation of the composite indicators is their lack of capability to apply interaction terms analysis, as is done in econometrics. Thus, the composite indicator framework uses correlation and sensitivity analyses to assess interactions, interrelationships, and interdependencies. Correlation analysis identifies the extent to which two dimensions can be associated with or influence each other. In contrast, sensitivity analysis helps determine the impact of one dimension's absence on another's behaviour.

In addition, the sample of companies surveyed in this study is reflective of the Italian industrial population, but it cannot be considered as totally generalizable. In fact, we see our endeavour as a first explorative attempt to analyse the investigated phenomena; hence, more stratified observations may be required in the future, also to create reliable and constantly updated benchmarks – useful to organizations to position themselves in different business contexts and make a self-assessment of their performance. Also, the application of the developed composite indicator to different geographical areas might be of interest, due to different business populations and contingent factors. In this sense, extending the study to various countries and focusing on the implications of the features of the sample business demography on the scores of the indicator could be one interesting future extension of this work, along with the comparison of the outcomes of the adopted method for developing the indicator with outcomes deriving from alternative methods, such as the Data Envelopment Analysis. Nevertheless, and conscious of these limitations, we take the opportunity to point out that the Italian manufacturing sector has multiple elements that are similar to other manufacturing sectors in European countries and the world. For instance, apart from China, the US, Japan, and Germany, there are 11 countries with contributions between 1.1 % and 3.1 % of the global manufacturing value added (Fornasiero and Tolio, 2024). Data shows that Italy contributes 2.2 % of the worldwide manufacturing value-added; in the mid-range. Additionally, as shown in Appendix I, the top industry represented in our sample is 'Machinery and Equipment', which in Italy, on average, generates 5.6 million Euro in turnover and 22 employees yearly. This is also similar to the contributions of other countries, such as the UK, Spain, and other EU countries (Fornasiero and Tolio, 2024). Thus, given the economic structure of the manufacturing industry in terms of value-added, turnover, and employment generation, Italy's manufacturing industry is not atypical, and it can be argued to be representative of other manufacturing sectors in Europe and the world.

Further areas for developing the present work could be represented by extending the application of Resist-I to specific business contexts through case studies or action research projects, for understanding how the index could be practically implemented for positioning an organization and developing a roadmap for improving its sustainability and resilience performance, and derive insights that can inform theory and practice. Given that the focus would shift to the organization, it would be interesting to combine the organizational resilience dimension considering the human factor in the management of sustainability and resilience.

7. Research involving human participants and/or animals

All procedures performed in this study were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

CRediT authorship contribution statement

Yari Borbon Galvez: Writing – review & editing, Writing – original

draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Maria Del Sorbo:** Writing – review & editing, Writing – original draft, Visualization, Software, Methodology, Formal analysis, Data curation. **Claudia Colicchia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandro Creazza:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Project administration, Investigation, Conceptualization.

Informed consent

Informed consent was obtained from all individual participants included in this study.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The views expressed here are of the authors only and do not necessarily reflect those of the respective institutions, such as the European Commission.

Appendix 1. . Sampling bias assessment

Bajgar et al., (2020) showed that Orbis data has representative and coverage issues. Orbis tends to be biased towards larger, older, and more productive firms, and it does not emulate the industrial structure of the Italian economy. These limitations may not be incommensurate, as the authors believe that a more balanced sample by firm size will allow for better comparisons between firm sizes and industries, even though the indicator is not expected to be representative of the average Italian firm.

Fig. A1, shows the under and overrepresented industries by Orbis sample universe, and by the Resist-I respondents. It shows substantial differences in four industries comparing Italy's industrial structure and the Orbis sample universe. Division 47- Retail trade is the most underrepresented in the Orbis sample with 4.4 %, compared to Italy's share representing 41.6 % of the total of the sectors included in our study. Division 28- Manufacture of machinery and equipment n.e.c. is the most overrepresented by the Orbis sample universe with 12.1 % of the firms, compared to its industry contribution of just 1.5 %. Division 25- Manufacturing of fabricated metal products, exc. machinery and equipment, is overrepresented with 10.7 %, whilst its industry contribution is 4.6 %. Finally, division 45- Wholesale, retail, and repair of motor vehicles and motorcycles is underrepresented with 5 %, compared to its contribution of 8.5 %. It is worth noting that the degree of over and underrepresentation for the rest of the divisions are not substantial in terms of their shares when comparing the Italian industry structure and the Orbis sample universe. More importantly, the differences in shares of each division comparing the sample universe and the respondents, are also minimal. Thus, apart from the four divisions described above, the rest of the shares vary to a small degree.

The substantial underrepresentation of retail trade activities can be explained by the fact that 97 % of the firms are micro size, and it is difficult to keep track of their changing contact information. Firms with missing contact information were selected out of the Orbis sample universe (see Table 3).

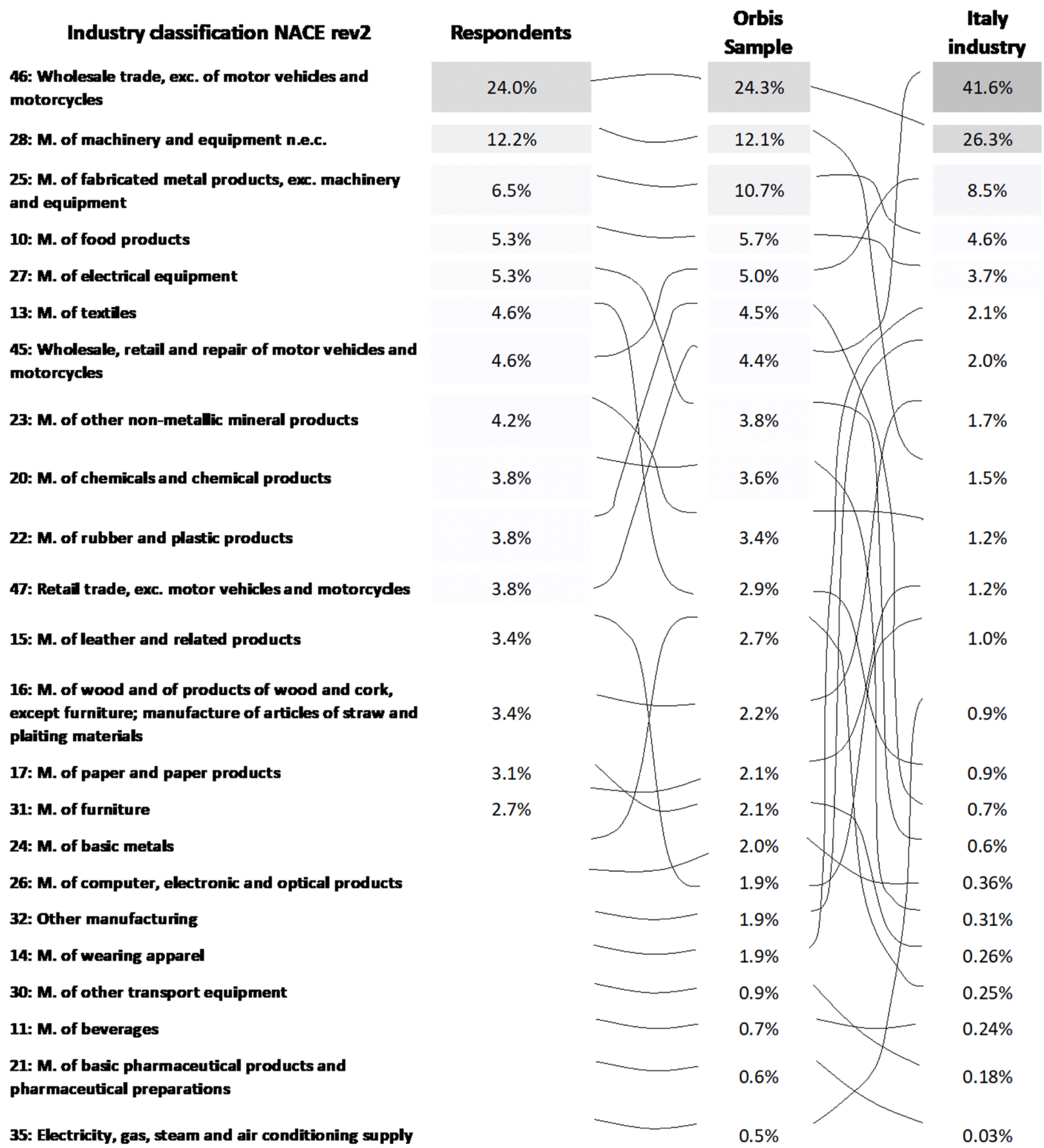

Fig. A1. share of Industry classification of respondents, Orbis survey sample universe, and of Italian Industry

* Division data with less than 5 respondents are masked for anonymity.
Source: Own elaboration based on Eurostat's Structural Business Statistics, Orbis, and Resist-I survey results.

Table A1
Composition of survey respondents and the Italian industry by firm size.

	Large	Medium	Small	Micro	NA	Total
Italy's industry structure	0.1 %	0.8 %	6.5 %	92.5 %	–	100 %
Survey respondents	5 %	23.3 %	56.1 %	14.1 %	1.5 %	100 %

Source: Own elaboration based on Eurostat's and Resist-I survey responses.

Several solutions can address these biases, as described by Bajgar et al., (2020). Weights can be corrected upwards for the underrepresented activities or the selection constrained (handpicking) to reproduce the industry structure of the country, selection stratified by value-added or turnover, etc. (Bajgar et al.; 2020) For the present indicator, in agreement with the AB, none of the said procedures were considered, due to the explorative nature of the investigation. Moreover, whilst the weighting correction method was used in the sensitivity analysis for validation of the results, correcting or handpicking under or overrepresented activities is not part of the composite indicators building methodology. Thus, this can be proposed for future research.

Appendix 2. . Sensitivity and uncertainty analysis (step 8 Robustness and Sensitivity)

This section evaluates the potential effects on the composite indicator of using alternative weighting, normalization, imputation, and distribution methods, aiming at identifying the assumptions that are more important for the overall composite. With regard to the distributions (i.e., the plausible alternatives), there are various decisions that may affect how the variables are distributed, such as:

Imputation using indicator mean, or no imputation
Normalization using either min–max, rank, or distance to maximum
Perturb pillar and sub index weights by +/-25 %

The sensitivity analysis runs 1000 replications, modifying the methods at aggregation levels 2 and 3 (pillars and sub-indexes). The weights are modified by a factor of 0.25 (+/-25 % of nominal weight values). Figure A-I1 plots the firms ordered by their nominal ranks with the median rank across all the replications of the uncertainty analysis, as well as the 5th and 95th percentile rank values. Ranking is the focus of the uncertainty analysis because it is the only comparable metric across different composite indicator methodologies.

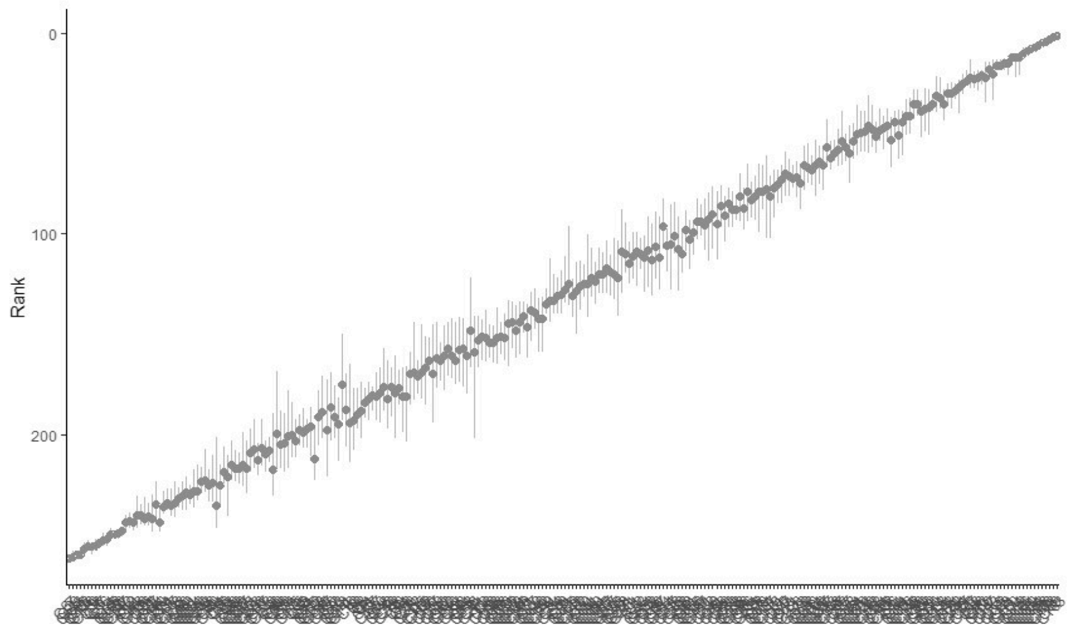

Fig. A2. Sensitivity plot: anonymized firms by their nominal ranks

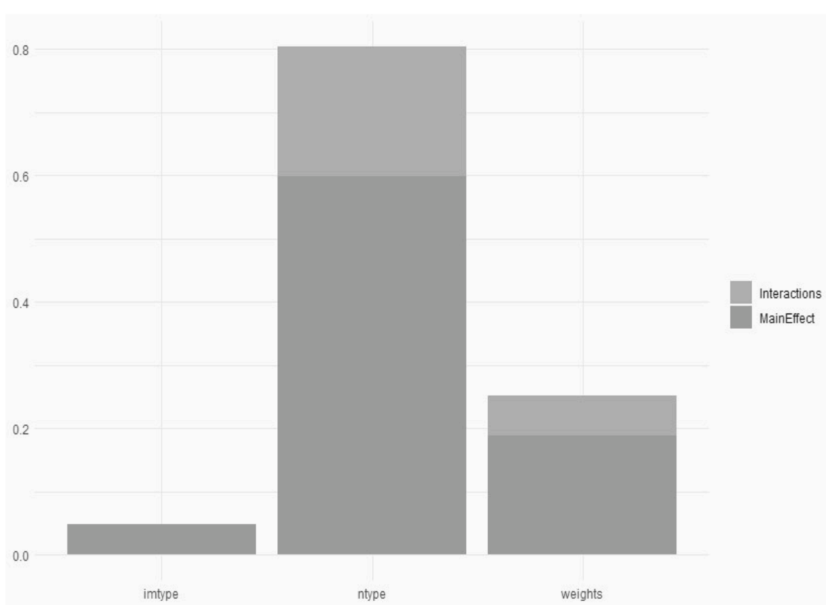

Fig. A3. Interaction and Main effect Uncertainties: imputation, normalization, and weights.

Fig. A3 shows uncertainties induced by the imputation (imtype), normalization (ntype), and weighting methods. The y-axis is the sensitivity index, and the total height of each bar is the total effect index STi, i.e., the uncertainty caused by the variable on its own (MainEffect) as well as the uncertainty resulting from multiple methods acting simultaneously (interactions).

The normalization method is the most important source of uncertainty, followed by the weights, and last by the imputation type. Whereas the imputation method does not seem to interact with the other inputs. Figure A-III shows the proportion of each uncertainty. More than half of the uncertainty is caused by the normalization method choice alone, while a bit less than a quarter is caused by the weights, and the rest by interactions and imputation methods. It is likely that a source of uncertainty in the normalization method is the alternative use of rank normalization, which alters radically the distribution of each indicator.

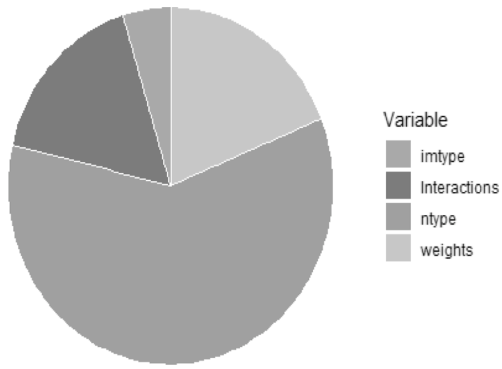

Fig. A4. Contribution of each method to the uncertainty of the composite indicator

Figure A-IV shows the effect of removing pillars from the framework. Removing either the "Agility" or "SLog" pillar has more than twelve times the impact on the overall rankings than removing the pillar "EStake".

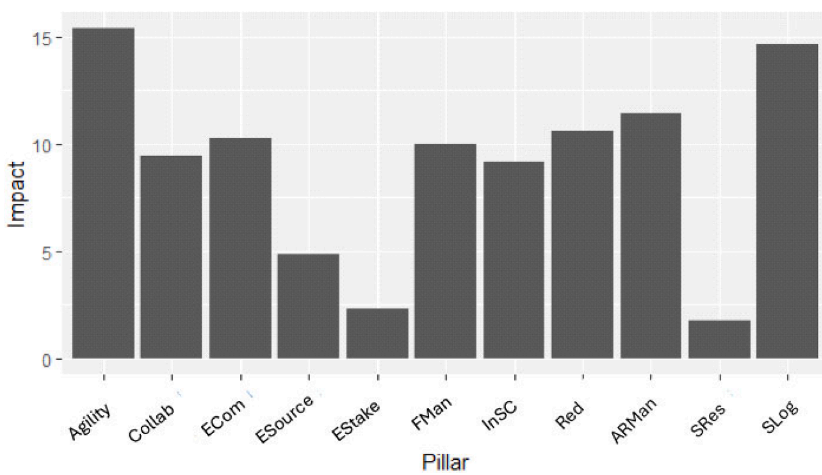

Fig. A5. Contribution of each method to the uncertainty of the composite indicator

The uncertainty and sensitivity analyses show that the Resilience and Sustainability Index, Resist-I is built upon a robust methodological approach, the first shows that the ranks do not change significantly. The sensitivity shows that the normalization method is the main source of uncertainty, because choosing different methods, i.e., rank normalization, may result in radically altering the distribution of each indicator, and hence in the overall rankings in the indicator, whereas our choice of normalization is the min–max method.

Finally, the analysis shows high relevance of the Agility and SLog pillars for the Resist-I Index. Should they be excluded from the framework, we would have radically different results, whilst removing social sourcing (SRes) or EStake from the framework would not alter substantially the overall results of the indicator.

Appendix 3. . Survey questionnaire

Agility: evaluates the supply chain capability to respond to a disruption quickly, smoothly and with a limited economic impact.

Question ID	Indicator ID	Question	Answers (1 = Very Low, 2 = Low, 3 = Average, 4 = High, 5 = Very High)
		In case of *disruption* (an unexpected negative shock with a very strong impact), what is the capability (in a short time and at a low cost) of the:	1 2 3 4 5
1.1	1	Company to switch to alternative logistics and transportation providers?	

(*continued on next page*)

(*continued*)

Question ID	Indicator ID	Question	Answers (1 = Very Low, 2 = Low, 3 = Average, 4 = High, 5 = Very High)
		In case of *disruption* (an unexpected negative shock with a very strong impact), what is the capability (in a short time and at a low cost) of the:	1 2 3 4 5
1.2	2	Company to modify its transportation modes and transportation channels?	
1.3	5	Production lines [or organizational unit] to be converted to produce a different product model?	
1.4	4	Production lines [or organizational unit] to vary the production volumes?	
1.5	7	Company to change its most critical suppliers?	
1.6	9	Company's employees to fill different roles?	
1.7	11	Company to change the supply batch sizes from its suppliers?	
1.8	12	Company to change the delivery batch sizes toward its customers?	

Redundancy: refers to resources held by a company more than its own needs; these resources are relevant in supply chain resilience since they can help absorb the impact of a disruption in the supply chain.

Question ID	Indicator ID	Question	Answers				
1.9	13	How many days of components and finished products does the company hold in stock?	<5	5–10	11–14	15–30	30+
1.10	16	What is the company's average saturation level of the production [or storage]?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
1.11	25	Where are your production plants [or distribution centres] located?	There is only 1 plant	Same region	Same country	In Europe	At least one outside Europe
		Percentage of products/services purchased from more than one supplier regarding:	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
1.12	20	Raw Materials					
1.13	21	Finished or semi-finished products					
1.14	22	How many external (outsourced) transportation/logistics service providers do you use?	0	1	2–3	4–5	5+
1.15	23	How many external (outsourced) storage logistics service providers do you use?	0	1	2–3	4–5	5+

Supply chain risk management: evaluates the degree of development of risk assessment and risk management skills in the company and the ability to keep the business running in the case of a disruption with the least possible impact.

Question ID	Indicator ID	Question	Answers (1 = Very Low, 2 = Low, 3 = Average, 4 = High, 5 = Very High)
		Can you say to what extent your:	1 2 3 4 5
1.16	29	Company implements digital security practices for the protection and backup of its data?	
1.17	30	Company uses risk management indicators and metrics for their business functions?	
1.18	32	Company trades (through suppliers, production plants or customers) with high-risk countries (economic, sociological, political and financial)? (e.g., *Geographical areas at risk: Africa, Latin America and Asia –Excluding China and Japan)*	
1.19	37	Company implements formalized and structured business continuity plans?*(Business continuity is the ability of an organization to continue to deliver products or services at acceptable predefined levels following an incident)*	
1.20	35	Suppliers' short and long-term financial situation is solvent?	

Collaboration: evaluates to what extent the company makes use of collaborative practices and partnerships to identify and mitigate disruptions in the supply chain.

Question ID	Indicator ID	Question	Answers(1 = Very Low, 2 = Low, 3 = Average, 4 = High, 5 = Very High)
		Can you say to what extent your company:	1 2 3 4 5
1.21	38	Has visibility on the stock levels of customers and suppliers?	
1.22	40	Involves customers in demand forecasting and planning process?	
1.23	41	Has immediate and accurate information on disruptions and incidents throughout the supply chain? (e.g.*, production interruptions, cyber-attacks, delivery delays)*	
1.24	43	Shares information and collaborates with customers and suppliers to optimize production and distribution processes?	

Environmental Sourcing.

Question ID	Indicator ID	Question	Answers				
2.1	44	What percentage of the company's suppliers have an environmental certification?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
2.2	46	In evaluating potential suppliers, what relevance do environmental sustainability performances have?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
2.3	48	To what extent does the company have visibility on the environmental sustainability of raw materials' [or products'] original source?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high

Sourcing and Transportation

Question ID	Indicator ID	Question	Answers				
2.4	54	What percentage of your suppliers are located in:	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
		The same region Different region but same country Different country but inside the EU Outside EU					
2.5	53	What percentage of the goods (inbound raw materials and outbound finished products) are transported by: Sea Transportation Air Transportation Rail Transportation Road Transportation	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %

Production and Storage.

Question ID	Indicator ID	Question	Answers				
2.6	59	What is the share of renewable energy use in the production and storage facilities?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
2.7	67	How intensive is your production [or storage] processes' use of water?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
2.8	66	What is the ratio of volume of waste materials to volume of finished products?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
2.9	63	What percentage of wastes could (ideally) be reused, recycled, or remanufactured?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
2.10	64	What percentage of wastes is (currently) reused, recycled, or remanufactured?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %

Sale and Governance.

Question ID	Indicator ID	Question	Answers				
2.11	68	To what extent is the packaging used for the final products recycled, or coming from recycled materials?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
2.12	73	How often does the company measure the consumption of the main natural resources, or carry out a life cycle analysis? (e.g., *CO_2 emissions, water consumption, land consumption)*	Never	Rarely	Every 3/5 years	Every 2 years	At least once a year
2.13	70	What is the importance of environmental performance in assessing the overall performance of the company and the supply chain?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
2.14	72	How widespread are roles within the company that have clear responsibilities and priorities in the field of environmental sustainability?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
2.15	71	Does the company hold an environmental management certification?	No	Yes			

Social Sustainability: Social sourcing, Internal supply chain and External stakeholders.

Question ID	Indicator ID	Question	Answers				
3.1	76	What percentage of the company's suppliers have a social responsibility certification?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %
3.2	78	To what extent does the company have visibility on the social sustainability of raw materials' [or products'] original source?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
		How often does the company:					
3.3	82	Measure the satisfaction level of its employees?	Never	Every 2 to 5 years	Yearly	Biannually	Monthly
3.4	83	Implement programs and practices with the aim of ensuring the health and safety of all its employees?	Never	Every 2 to 5 years	Yearly	Biannually	Monthly
3.5	88	Implement programs and practices linked to the themes of inclusivity, equality and diversity?	Never	Every 2 to 5 years	Yearly	Biannually	Monthly
3.6	92	Commit to providing and organizing programs or activities to improve the conditions of local communities?	Never	Every 2 to 5 years	Yearly	Biannually	Monthly
3.7	93	What is the importance of social responsibility performance in assessing the overall performance of the company and the supply chain?	1 = Very low	2 = Low	3 = Average	4 = High	5 = Very high
3.8	91	Does the company hold a social sustainability management certification?	No	Yes			
3.9	86	What is the percentage of your female employees?	0–20 %	20–40 %	40–60 %	60–80 %	80–100 %

Data availability

The data supporting this study's findings are available from the corresponding author upon reasonable request.

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