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“INGEGNERIA INDUSTRIALE”**

CICLO XXXVIII

**Frameworks and tOols for evaluating LOgistics processes and
enhancing Green, Resilient, Agile and Lean performance
(OLOGRAL)**

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Abstract

The vulnerability of global supply chains (SCs) has become evident in recent years, due to events such as the COVID-19 pandemic, geopolitical tensions, and increasing resource scarcity, which have highlighted the limitations of traditional models based exclusively on efficiency and cost reduction. Modern approaches must take into account a combination of activities and strategies that integrate efficiency, resilience, flexibility, and sustainability. In this context, the lean, agile, resilient, green (LARG), and sustainable (LARGS) paradigms provide a comprehensive framework to support companies and stakeholders. The measurement of key performance indicators (KPIs) is a fundamental management tool that provides essential support for improving the SC. This doctoral thesis aims to develop frameworks and quantitative tools to evaluate logistics processes and improve SC performance according to LARGS paradigms. The research addresses two main questions: (i) how LARGS paradigms can be integrated into a unified decision-making framework and (ii) what interdependencies, barriers and enabling conditions influence their implementation. To answer these questions, the study follows a progressive methodological approach that integrates conceptual development with practical validation, combining multi-criteria decision-making (MCDM) approaches such as analytic hierarchy process (AHP), fuzzy logic, DEMATEL, analytic network process (ANP), and interpretive structural modeling (ISM)-MICMAC. First, the study introduces the LARG framework for mapping and prioritizing KPIs in procurement, production, distribution and reverse logistics. Next, the LARG-AHP model is developed to provide a hierarchical structure and quantitative assessment of supply chain performance. A fuzzy logic-based tool is proposed to manage uncertainty and linguistic judgments, transforming qualitative evaluations into quantitative results and enabling flexible assessment across all SC phases. The research introduces the sustainable dimension, extending the framework to LARGS paradigm, through a hybrid Fuzzy Delphi-DEMATEL-ANP model that captures the interrelationships between criteria and supports sustainable-oriented decisions. This latter dimension is further analyzed in a specific context (i.e., perishable products) using the ISM-MIMAC methodology. The models are validated through several case studies and numerical examples to demonstrate their applicability in real-world contexts.

Keywords: Supply Chain; Logistics; LARGS; Sustainability; Decision-making; Fuzzy Logic; Analytic Hierarchy Process (AHP); Supplier Selection; Key Performance Indicator (KPI).

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Preface

My academic career, which began before I started my doctoral program, has gradually evolved through various experiences in the field of process and supply chain optimization.

My first involvement in research activities dates back to 2021, when I was awarded a research grant at the Department of Engineering and Architecture of the University of Parma for the FIL project entitled “Development of a Machine Learning tool for process optimization in healthcare”. This project represented the first opportunity to explore data-driven process improvement and resulted in both a scientific publication in an international journal and my master's thesis, entitled “Study and development of a simulation model for operating room optimization”. Thanks to this experience, I developed a growing interest in the design and optimization of complex systems and in the potential of quantitative methods to support decision-making in real operational contexts.

Subsequently, I was awarded a research grant as a senior info data scientist at the Department of Law, Political Science, and International Studies at the University of Parma, as part of the national PON project “UNI 4 JUSTICE”. The project aimed to design innovative organizational models for the judicial system. This second experience strengthened my skills in data analysis and process modeling, while also allowing me to learn about the multidisciplinary applications of engineering methods in public sector management.

In November 2022, I began my PhD in Industrial Engineering at the University of Parma, under the supervision of Prof. Eleonora Bottani, presenting a research proposal entitled “Optimization models for logistics processes to improve green, resilient, agile, and lean performance”. The research was conducted at the Department of Engineering and Architecture, now the Department of Engineering for Industrial Systems and Technologies. The project focused on integrating Lean, Agile, Resilient, Green, and Sustainable (LARGS) paradigms into decision support tools for supply chain performance evaluation.

During my PhD journey, I spent a period at the Universitat Politècnica de València (UPV), collaborating with the Centro de Investigación en Gestión e Ingeniería de Producción under the supervision of Prof. Andrés Boza García. The mobility contributed significantly to the finalization of my doctoral research, leading to the development of two scientific contributions that were subsequently integrated in my thesis: (i) a study on strategies for reducing food waste in perishable product supply chains using LARGS-based models, and (ii) an analysis of the obstacles to the simultaneous implementation of LARG paradigms through a two-stage literature review. This experience has also promoted international collaboration and academic exchange, improving the scientific maturity of research results.

This thesis therefore aims to develop quantitative frameworks and tools to evaluate logistics and supply chain performance according to LARGS paradigms. It provides a progressive methodological path, combining conceptual development with practical validation and combining multi-criteria decision-making (MCDM) approaches such as Analytic Hierarchy Process (AHP), fuzzy logic, DEMATEL, Analytic Network Process (ANP), and Interpretive Structural Modeling (ISM)-MICMAC.

The proposed models are intended to support managers in assessing the efficiency, resilience, agility, and sustainability of the supply chain in an integrated manner, bridging the gap between theoretical models and industrial applications.

The following scientific contributions were made during the three years of doctoral study:

1. Bottani, E., Franchi, B., **Monferdini, L.**, Bigliardi, B., Mordonini, M., Pellegrino, M., Lombardo, G., Collini, L., Bellini, V., & Bignami, E. G. (2022). Opportunities for Simulation-Based Optimization in a Hospital Environment: Results and Perspectives From a Review of the Literature. *International Journal of Practical Healthcare Innovation and Management Techniques (IJPHIMT)*, 9(2), 1-21. <http://doi.org/10.4018/IJPHIMT.315771>
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List of acronyms

Acronym	Full Form
AHP	Analytic Hierarchy Process
ANP	Analytic Network Process
CI	Consistency Index
CR	Consistency Ratio
DEMATEL	Decision-Making Trial and Evaluation Laboratory
FDANP	Fuzzy Decision-Making Analytic Network Process
FDM	Fuzzy Delphi Method
GSCM	Green Supply Chain Management
ISM	Interpretive Structural Modeling
MICMAC	Matrice d'Impacts Croisés Multiplication Appliquée à un Classement
MCDM	Multi-Criteria Decision-Making
LARG	Lean, Agile, Resilient, and Green
LARGS	Lean, Agile, Resilient, Green, and Sustainable
KPI	Key Performance Indicator
SC	Supply Chain
SCM	Supply Chain Management
SLR	Systematic Literature Review
SSCM	Sustainable Supply Chain Management
SSIM	Structural Self-Interaction Matrix

1. Introduction

1.1 Background and motivation

A supply chain (SC) is “the network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services delivered to the ultimate consumer” (Christopher, 2011). This organization needs a management in all its phases to distribute the products at the right place and in the right time, ensuring the efficiency of the entire chain (Janvier-James, 2011), including procurement, manufacturing, waste disposal and all the activity associated with transport, storage and information technology (IT) (Gechevski et al., 2016).

The SC, characterized by increasing complexity, volatility and uncertainty, has to face various challenges such as globalization, market demand variability, technological disruptions, price volatility, and unexpected events. This meant that the supply chain had to be not only efficient, but also flexible, resilient, and sustainable.

In recent years, global disruptions (e.g. the COVID-19 pandemic, political instability, ...) have further exposed the fragility of global supply networks. Based on this, digital integration, reconfigurability, and the ability to work continuously in uncertain conditions have become fundamental requirements for supply chains. Technological advances associated with Industry 4.0 and digital decision support systems have also transformed the way supply chains are designed and managed, enabling real-time monitoring and faster responses to market volatility.

Based on the above, traditional supply chain, focused only on lean activity and cost efficiency is no longer sufficient; instead, modern approaches must consider lean, agile, resilient, green (LARG) and sustainable (LARGS) paradigm to balance efficiency with resilience, flexibility and sustainability (Azevedo et al., 2011).

The LARGS paradigm therefore represents an evolution of previous supply chain management models, integrating operational efficiency (lean), responsiveness (agile), adaptability (resilience), environmental management (green) and long-term sustainability encompassing economic, social and environmental dimensions (sustainable). Several studies have examined these paradigms individually or in partial combinations, but analysis that integrate all five perspectives and analyze their interdependencies remain scarce. Addressing these relationships is essential to understanding the criteria and strategies that simultaneously influence cost-effectiveness, adaptability, and sustainable performance.

In this context, Key Performance Indicators (KPIs) measurement serves as a fundamental management instrument, offering essential support for enhancing supply chain and driving operational excellence (Zanjirani et al., 2019). A well-design performance measurement system provides detail information on the current state of the supply chain and, as a result, identifies areas of improvement, thereby aligning operations with strategic objectives (Parker, 2000). Decision makers can thus monitor the status of their supply chains and respond proactively to changes in the market or operating environment. Although these performance measurement tools support the supply chain in its activities and practitioners

in their decision, their implementation, particularly in an integrated manner, remain difficult in practice. Also, for this reason, the investigation in this topic remains necessary.

Recent research has shown that the use of hybrid Multi-Criteria Decision-Making (MCDM) methods, such as Analytic Hierarchy Process (AHP), fuzzy logic, DEMATEL, and Analytic Network Process (ANP), facilitates performance measurement by combining conceptual models with practical applications (Ghazvinian et al., 2024). These tools enable managers to quantitatively assess performance, manage uncertainty, and visualize interdependencies between criteria (Govindan et al., 2015), providing more reliable and data-driven decision support.

Furthermore, the sustainability dimension has gained increasing importance, especially due to the fact that in some sectors (such as perishable products) inefficiencies translate directly into environmental and/or social impact.

1.2 Research objective

The aim of this doctoral thesis is to develop frameworks and tools for evaluating logistics processes and enhancing LARG(S) performance. The main research questions are as follows:

RQ1: How can Lean, Agile, Resilient, Green, and Sustainable (LARGS) paradigms be integrated into a unified decision-making framework, and what are the key criteria that most influence supply chain performance in these perspectives?

RQ2: What are the main interdependencies, barriers, and favorable conditions that influence the implementation of LARGS strategies?

To answer the questions, the thesis follows a progressive methodology that combines qualitative and quantitative approaches. The research (i) translates conceptual insights into practical and replicable applications, (ii) providing an integrated model for evaluating SC performance following the LARG(S) paradigm, (iii) highlighting the relationships between criteria and, therefore, (iv) supporting managers in managing and improving the strategies to be implemented in the stages of the supply chain according to the LARG(S) paradigm.

1.3 Structure of the thesis

This thesis is structured into six chapters, as follows.

Chapter 1 – “Introduction”. It presents the context, motivation, and objectives of the research. It describes the current challenges of supply chain management in an increasingly complex and uncertain context and formulates the two research questions that guide the study.

Chapter 2 – “Literature Review”. It provides an overview of the main frameworks and tools developed for evaluating supply chain performance under the LARG paradigm. It examines the barriers and enablers for LARG implementation. Finally, it defines the gaps in the literature and the novelty of this study.

Chapter 3 – “Methodology”. It describes the methodological progression adopted to answer the research questions, illustrating the integration of the methods: AHP, Fuzzy Logic, Fuzzy Delphi, DEMATEL, ANP, and Interpretive Structural Modeling (ISM)-MICMAC and explaining their individual roles within the LARGS framework.

Chapter 4 – “Results”. It presents the application and results of the proposed models. It illustrates the LARG framework, followed by its operationalization through the AHP model, and extends to the Fuzzy Logic approach for managing uncertainty. The chapter then introduces the Fuzzy DEMATEL-ANP (FDANP) model, which integrates the sustainability dimension and analyzes the interrelationships between the LARGS criteria. Finally, it illustrates the case of a specific context (i.e., perishable products) exploring strategies for reducing food waste along the supply chain using the ISM-MICMAC model.

Chapter 5 – “Discussion”. It interprets the findings and answers the research questions. It provides theoretical, managerial, and practical implications.

Chapter 6 – “Conclusions”. It summarizes the study's main findings and contributions, discusses its limitations and proposes directions for future research.

2. Literature Review

2.1 Framework and tools for evaluating supply chain performance under LARG paradigm

This section examines the state of the art up to 2022 (the year the doctoral program began) to identify the initial gap in research that motivated this work.

An appropriate query was carried out on Scopus database to retrieve documents addressing supply chain performance under the LARG paradigm. The query was structured as follows.

```
TITLE-ABS-KEY ( ( ( "lean" AND "agile" AND "resilient" AND "green" ) OR "LARG" OR "LARGS" ) AND "supply chain" AND ( "performance" OR "efficiency" OR "effectiveness" OR "productivity" OR "competitiveness" OR "improvement" OR "optimization" OR "optimisation" OR "benchmarking" OR "performance evaluation" OR "performance assessment" OR "performance measurement" OR "supply chain excellence" OR "KPI" OR "key performance indicator*" OR "indicator*" OR "metric*" OR "measure*" OR "index" OR "indices" OR "score" OR "scoring" OR "criteria" OR "criterion" OR "parameter*" ) ) AND PUBYEAR > 2010 AND PUBYEAR < 2023 AND ( LIMIT-TO ( LANGUAGE , "English" ) )
```

The initial sample included 45 documents; after eliminating those lacking authors' name and full text, 30 documents were retained for the analysis.

Firstly, bibliometric analyses, using VOSviewer and Bibliometrix package of R software, were carried out to: (i) identify the main themes, (ii) grouping the keywords into different clusters and (iii) explore their evolution over time.

Figure 1 shows the co-occurrence analysis of authors' keywords.

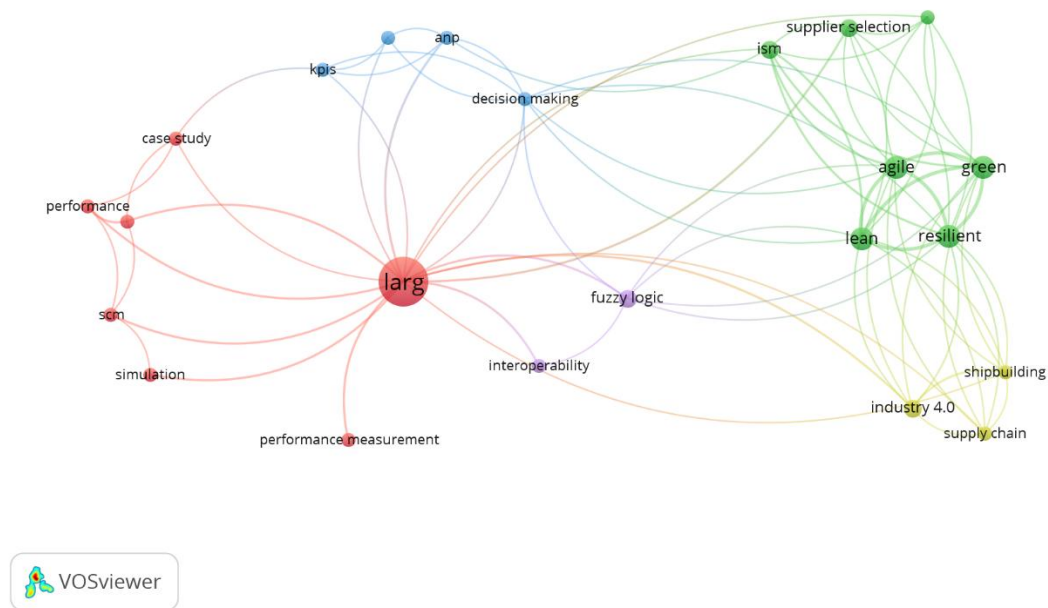


Figure 1. Co-occurrence analysis of authors' keywords (source: VOSviewer).

The analysis identifies six clusters:

- Red cluster includes the keywords green supply chain, agile supply chain, resilient supply chain, lean supply chain, decision making and performance. This group focuses on the operational management of supply chains, highlighting how these practices (lean, agile, resilient) contribute to improving efficiency. Several works emphasize the integration of green practices within these practices to balance the performance accounting operational and environmental responsibility (ESMAEEL et al., 2015; Rachid, 2017; Sen et al., 2018).
- Green cluster connects the words automotive industry, strategic alignment, supplier selection, innovative strategies and fuzzy sets. This group represents the empirical research applied to industrial context, with a particular emphasis on automotive sector, where decision-making tools are used to improve supplier selection process (Azevedo et al., 2016; Espadinha-Cruz et al., 2012).
- Blue cluster encompasses the keywords competition, interoperability, benchmarking, business interoperability and information theory. The integration of information systems and performance benchmarking are seen as enablers of collaboration and competitiveness in the supply chain (Cabral et al., 2011; Divsalar et al., 2022; Espadinha-Cruz et al., 2011, 2012).
- Yellow cluster, including supply chain performance, framework, industry 4.0, food supply chain and performance measurement system, reflects the development of digital transformation for the evaluation of performance (Bottani, Bigliardi, et al., 2023; Bottani et al., 2022; Ramirez-Peña et al., 2019, 2020).

- Purple cluster is represented by the keywords fuzzy logic, fuzzy systems, interoperability and numeric-linguistic interfaces, focusing on studies that introduce advanced tools for decision support (Espadinha-Cruz et al., 2012; Ferreira et al., 2012; Sen et al., 2018; Tavana et al., 2021). These methods are used to model uncertainty, manage the complexity of decision-making processes of supply chain.
- Light-blue cluster includes sustainability, sustainable development, sustainable supply chain, competitive advantage and commerce. This group of keywords reflect the importance of sustainable supply chain models, drivers of long-term competitiveness (Anvari, 2021; Raut et al., 2021; Sadeghi Asl et al., 2023; Sonar et al., 2022).

Figure 2 shows, year by year (from 2011 to 2022), the frequency of occurrence of the keywords included in the sample.

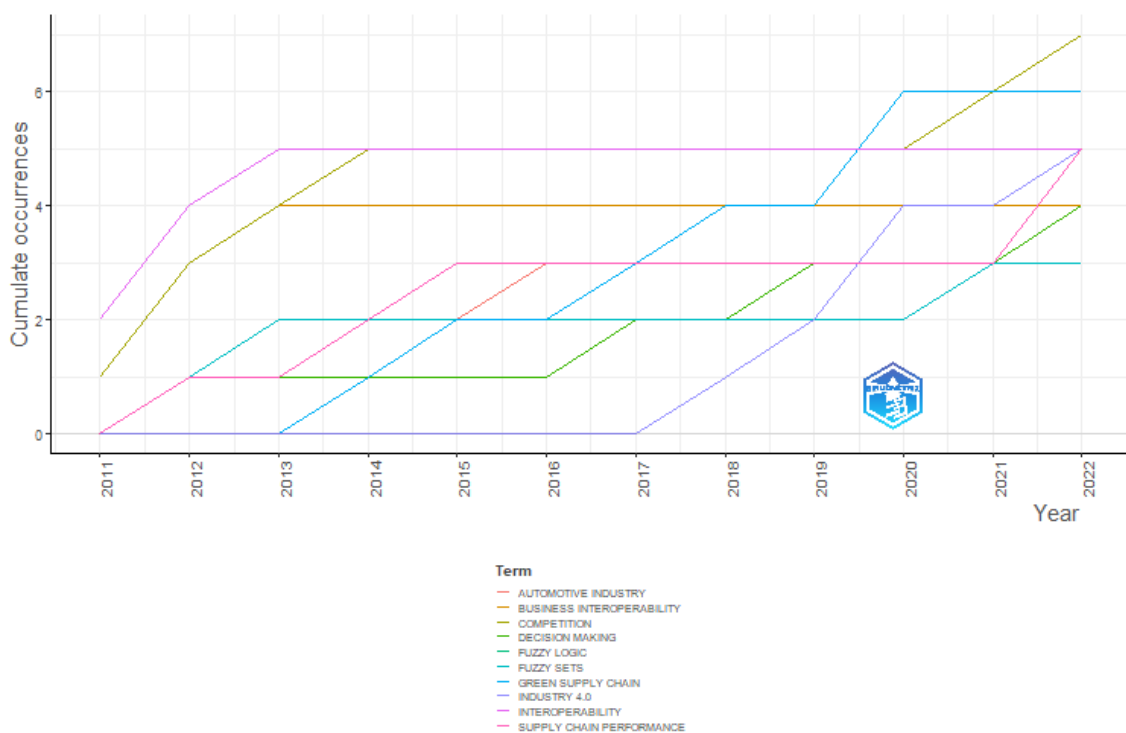


Figure 2. Words frequency over time (source: Bibliometrix).

From 2011 to 2014, interoperability and competition are the most relevant terms, followed by business interoperability and fuzzy sets/logic. This suggests that in the initial phase, the research focused on operative efficiency and information systems integration, with an attention to the interoperability as prerequisite for inter-organizational collaboration. Since 2015, attention has focused on the issue of sustainability: the green supply chain has emerged as a key term. This evolution indicates the introduction of a new focus on this dimension, followed by the need to consider more complex logics (e.g., fuzzy, decision-making tools) that can take into account both activities that increase operational performance (performance, competition) and those oriented toward sustainability and resilience. In parallel, the interest to digitalization and automation, representing by the keywords industry 4.0, automotive industry, fuzzy sets and fuzzy logic increases.

While the Figure 2 focused on the annual frequency of each keywords, Figure 3 provides the temporal overview of the key themes, highlighting when it emerged, reach its maturity and consolidated over time.

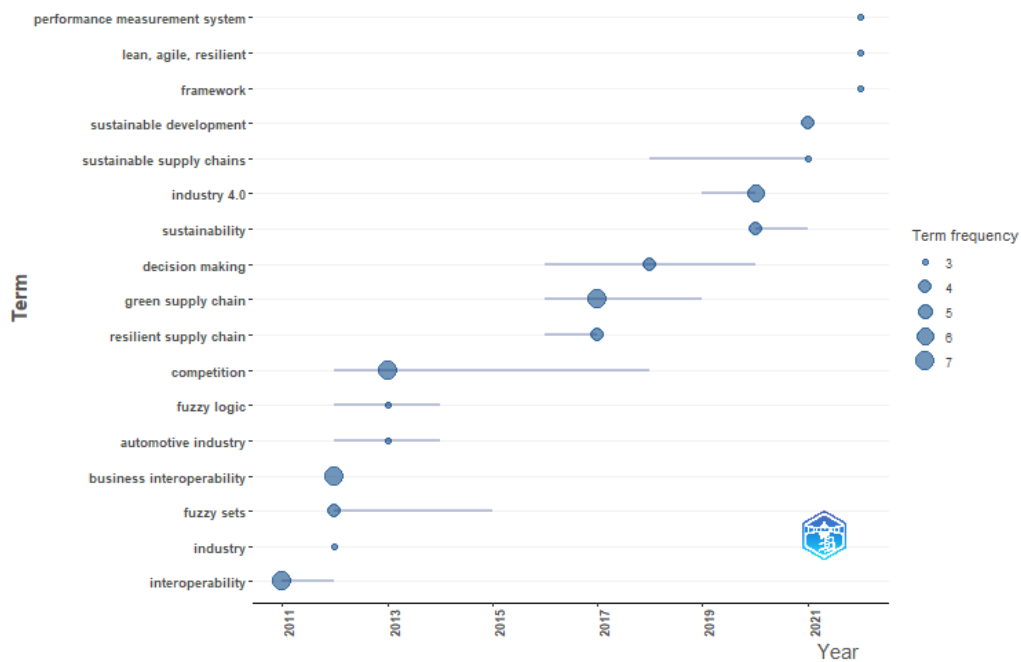


Figure 3. Trend topics (source: Bibliometrix).

The analysis shows that interoperability and business interoperability are among the most frequent and early terms, peaking between 2011 and 2012. Subsequently, from 2013 to 2015, there was an increase in terms such as competition, fuzzy sets, and industry. In particular, the emergence of fuzzy logic and fuzzy sets highlights the growing interest in tools capable of managing uncertainty and complexity. Since 2015, the themes of green supply chains and sustainability have emerged and further consolidated.

In summary, these analyses show three different phases: (i) an initial phase orientated to the efficiency and standardization of processes (competition, interoperability); (ii) an intermediate phase with an interest to the performance and collaboration and (iii) a more recent phase with a strong focus on the sustainability and the introduction of more complex technologies typical of industry 4.0 and, therefore, of complex systems of decision-making.

Beyond the bibliometric analysis, a content analysis was carried out on the 30 papers with the aim to examine (i) which dimensions of the LARG(S) approach were addressed, (ii) the type of performance indicators and KPIs adopted, (iii) the methodology applied, (iv) the industrial sectors investigated and (v) the main insights.

Table 1 shows the outcome of this analysis.

Table 1. Content analysis of 30 papers.

Source	LARG scope	Performance focus / KPIs	Methodology	Sector	Key insights
(Akbarzadeh et al., 2019)	LARG	Practice prioritization and efficiency	Fuzzy DEMATEL + ANP + ISM	Dairy industry	Quantifies interrelations among LARG practices; identifies critical improvement priorities.
(Alqudah et al., 2020)	LARG	Capabilities, sustainability, and performance	Moderated mediation analysis	Cross-sector	Integrates LARG paradigms with SC capabilities and sustainability to explain performance impact.
(Al-Refaie et al., 2020)	LARG	Customer satisfaction, operational costs	ISM + MICMAC validation	Cold supply chain (food/pharma/3PL)	Identifies driving and dependent LARG factors.
(Anvari, 2021)	LARGS	Sustainable performance, competitive advantage	Structural model + GoF analysis	Petrochemical industry	Builds and validates an integrated LARG-Sustainability performance model.
(Azevedo et al., 2016)	LARG	LARG index (aggregated performance)	Delphi weighting + linear aggregation + case study	Automotive industry	Proposes a benchmarking index measuring leanness, agility, resilience, and greenness.
(Bottani et al., 2022)	LARG	Performance metrics for food sector	Literature review + conceptual framework	Food industry	Develops an integrated LARG measurement system tailored to food supply chains.
(Bottani, Bigliardi, et al., 2023)	LARG	Food sector KPIs; performance scoring	Case study + interviews	Food industry	Applies previous LARG framework to a real case, ranking KPI importance and deriving performance scores.
(Cabral et al., 2011)	LARG	Information flow, decision speed, competitiveness	Conceptual information model	Cross-sector	Integrates data flow across paradigms to optimize decision-making and SC performance.
(Cabral et al., 2012)	LARG	KPI selection & prioritization	Analytic Network Process (ANP) + case study	Automotive	Links LARG practices to key KPIs; supports strategic decision-making.
(Catellani & Bottani, 2022)	LARG	Identification of 112 metrics; 15 key KPIs validated	Empirical survey (33 Italian firms)	Cross-sector (Italy)	Maps essential LARG metrics and links company size with KPI use; explores COVID-19 and I4.0 impacts.
(de Sousa et al., 2019)	LARG	Supplier environmental performance	Diagnostic tool based on LARG + ISO 14001	Manufacturing	Develops a tool to measure supplier involvement in environmental management.

(Divsalar et al., 2022)	LARG	SCOR model KPIs (cost, quality, delivery, flexibility)	Hybrid MADM: Fuzzy Delphi + DEMATEL-ANP + EHFL-VIKOR	Medical equipment	Proposes a conceptual decision model integrating SCOR attributes with LARG practices; agility and responsiveness emerge as key drivers.
(ESMAEEL et al., 2015)	LARG	SC performance; technology mediation	Theoretical framework + correlation analysis	Manufacturing	Shows that Advanced Manufacturing Technology strengthens LARG–performance relationship.
(Espadinha-Cruz et al., 2011)	LARG	Business interoperability	Quantitative model	Industrial engineering	Evaluates how interoperability affects performance of LARG SCM.
(Espadinha-Cruz et al., 2012)	LARG	Interoperability as performance factor	Fuzzy evaluation + MCDA	Automotive	Evaluates SC interoperability under LARG; enhances collaboration and performance.
(Ferreira et al., 2012)	LARG	LARG index (efficiency & responsiveness)	Fuzzy logic + linguistic model	Cross-sector	Proposes fuzzy LARG index; handles uncertainty in qualitative performance data.
(Figueira et al., 2012)	LARG	Organizational performance & safety	Conceptual model	Manufacturing	Integrates ergonomics and safety in LARG transformation processes.
(Jamali, Karimi Asl, et al., 2017)	LARG	Competitiveness and performance	SWARA + SWOT + SPACE matrix	Cement industry	Assesses strategic positioning of cement companies under LARG; identifies aggressive strategy fit.
(Jirsák & Holman, 2014)	LARG	Productivity, cost, added value	Conceptual comparison + simulation	Generic SCM	Compares evolution from MassSCM to LARG; emphasizes competitiveness and systemic approach.
(Mohammadzadeh et al., 2020)	LARG	Profit, customer satisfaction, pollution	Multi-objective mathematical model	Manufacturing (industrial case)	Designs a closed-loop network using LARG strategy and uncertain demand.
(Rachid, 2017)	LARG	Performance control and risk mitigation	Risk Management framework + simulation	Logistics education / academic case	Introduces LARG Risk Map to monitor and anticipate performance risks.
(Ramirez-Peña et al., 2019)	LARG	Industry 4.0 readiness; supply chain sustainability index	Quantitative index model	Shipbuilding	Proposes an index combining LARG and I4.0 to assess technological maturity.
(Ramirez-Peña et al., 2020)	LARG	Efficiency, sustainability	Conceptual I4.0 integration model	Shipbuilding industry	Connects Industry 4.0 technologies with LARG paradigms; Lean and Green are dominant.

(Raut et al., 2021)	LARG	Business & sustainability performance	Structural Equation Modelling (SEM)	Manufacturing	Big Data mediates the LARG–performance relationship; quantitative validation on 297 firms.
(Sen et al., 2018)	Green & Resilient	“G-resilient” (ecosilient) index	Fuzzy DOS + ISM	Automotive	Creates a composite performance index integrating green and resilience.
(Sharma et al., 2021)	LARGS	SC performance and sustainability metrics	Systematic Literature Review (160 papers)	Cross-sector	Maps 20 years of LARGS research; identifies trends, tools, and future directions.
(Sonar et al., 2022)	LARGS	Supplier performance, lead time, geographic location	ISM	Multi-sector	Identifies 22 supplier selection criteria under LARGS; highlights lead time and location as most influential.
(Suifan et al., 2019)	LARG	Competitive priorities: quality, flexibility, cost	Entropy weighting + TOPSIS	Pharmaceutical	Empirically analyzes trade-offs among LARG paradigms; quality emerges as main driver.
(Tavana et al., 2021)	LARG	Supplier selection criteria weighting	Fuzzy BWM + Fuzzy CoCoSo + Bonferroni mean	Wood & paper (reverse SC)	Proposes an integrated fuzzy MCDM for LARG-based supplier ranking; validated via industrial case.
(Zanjirani et al., 2019)	LARG	Supplier quality and consistency	HOQ + Taguchi loss + MOPA + TOPSIS	Manufacturing	Integrates LARG into supplier evaluation using multicriteria analysis and sensitivity testing.

Most of the study adopt the full LARG paradigm as an integrated reference model for evaluating supply chain performance. Only some recent works extend it to LARGS, adding sustainability dimension, confirming the growing interest in sustainable practices. The paper by (Sonar et al., 2022) represents one of the first empirical attempts to operationalize the LARGS paradigm. Using an ISM approach, the authors identify 22 criteria for sustainable supplier selection, integrating lean, agile, resilient, green, and sustainability dimensions. The study shows that delivery times and supplier location emerge as the most influential factors, highlighting how sustainability can coexist with efficiency and responsiveness objectives. Similarly, (Sharma et al., 2021) provide a comprehensive systematic review on the integration of sustainability into LARG-based supply chain management. Their analysis highlights a progressive conceptual convergence of these paradigms and identifies sustainability as the most recent and least explored extension. The study highlights the lack of quantitative models and emphasizes the need for decision support frameworks that can link sustainability with traditional performance indicators, thus laying the foundation for further analytical and fuzzy logic-based approaches. Finally, (Anvari, 2021) provides empirical evidence that the integration of LARG and sustainability positively influences both performance and competitive advantage.

The evolution of the methodological approaches for the evaluation of LARG supply chain performance, grouped as listed in Table 2, is detailed in Figure 4.

Table 2. Methods grouped into four categories.

Category	Methods
Conceptual & Model Building	Conceptual model, framework, information model, theoretical model, comparison + simulation
Hybrid Fuzzy & MCDM	Fuzzy logic, ISM, Delphi, ANP, TOPSIS, VIKOR, DEMATEL, CoCoSo, SWARA, BWM
Quantitative Validation / Index Development	Simulation, quantitative model, index model, diagnostic tool, mathematical model
Empirical & Statistical Validation	SEM, GoF, empirical survey, SLR, case study + interviews

The pattern does not suggest a unidirectional evolution of methods, but a process of methodological enrichment and overlap.

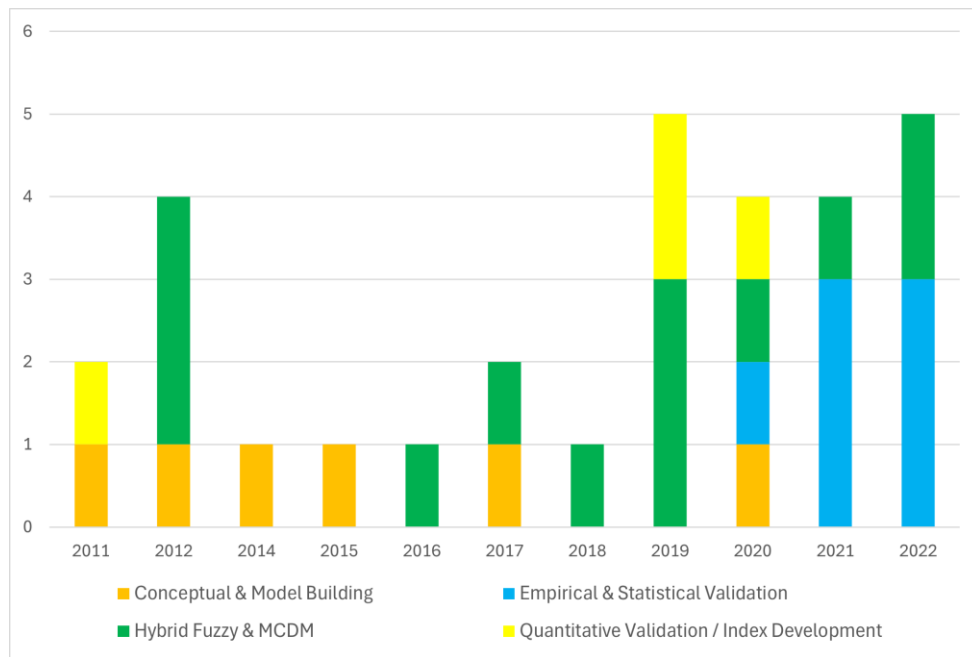


Figure 4. Methodology approach evolution of LARG supply chain research.

In 2011, research was still in its earliest stages: the LARG paradigm had been proposed only a few years earlier. This is demonstrated by the first purely conceptual works published between 2011 and 2015. However, from the early years, scholars did not limit themselves to describing the LARG paradigm, but experimented with various tools through hybrid fuzzy, MCDM, and quantitative validations. In the following years, publications remained stable and limited, with studies such as those by (Rachid, 2017; Sen et al., 2018) applying hybrid fuzzy and ISM. From 2019 onwards, research has grown, and the most advanced methodological techniques have coexisted: hybrid fuzzy/MCDM approach (Akbarzadeh et al., 2019; Zanjirani et al., 2019), quantitative index models (Ramirez-Peña et al., 2019), and empirical/statistical analyses (Raut et al., 2021). The most recent research no longer deals with conceptual studies but is dominated by empirical/statistical validations and complex models such as fuzzy hybrids (Divsalar et al., 2022; Tavana et al., 2021). Over time, this evolution has led not to the replacement of previous approaches, but to their integration: with quantitative and fuzzy models increasingly coupled with empirical validation to provide a more comprehensive understanding of supply chain performance under the LARG paradigm.

Figure 5 shows the correlation between sector and performance, considering the category listed in Table 3 and Table 4.

Table 3. Sectors grouped into 5 categories.

Category	Sectors
Manufacturing	Manufacturing, industrial, generic SCM, cross-sector (if industrial)
Automotive	Automotive industry
Food / Agro	Food industry, cold supply chain
Shipbuilding / Heavy industry	Shipbuilding, shipyards
Cross-sector / Others	Multi-sector, cross-sector, petrochemical, cement, education

Table 4. KPIs grouped into 4 categories.

Category	Performance / KPIs
Operational Performance	Efficiency, productivity, cost, lead time, quality, delivery
Sustainability & Green	Environmental, sustainability
Supplier & Collaboration	Supplier selection, interoperability, collaboration
Strategic & Competitive	Competitive advantage, strategic alignment, resilience, innovation

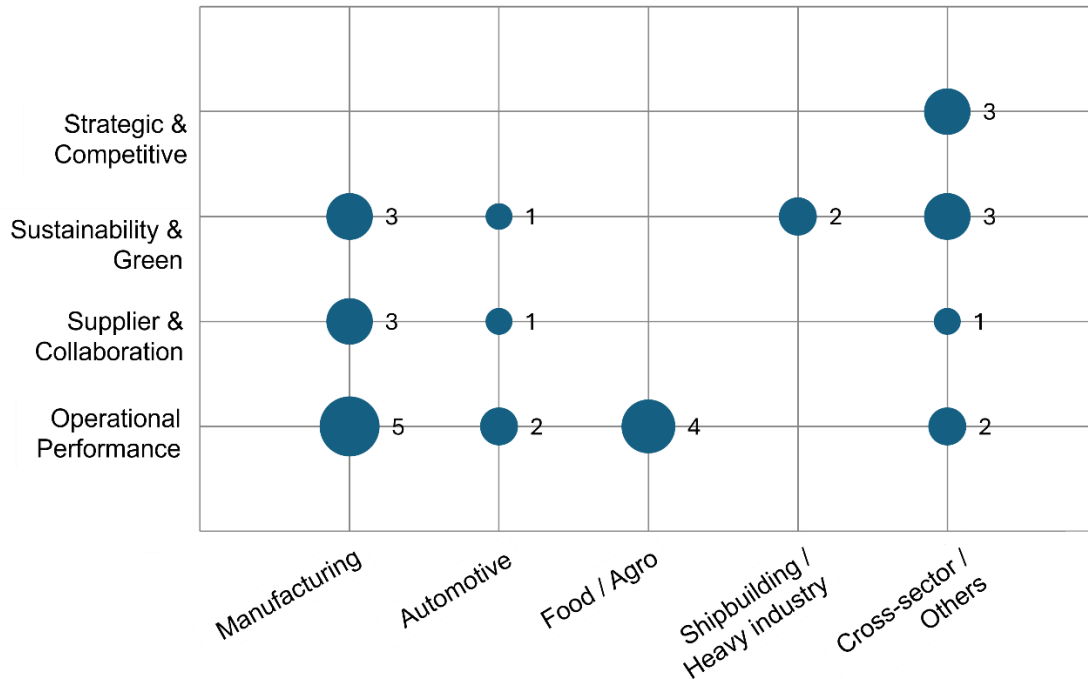


Figure 5. Scatter plot of the 30 reviewed papers showing the relationship between Performance focus / KPIs (y-axis) and Sector (x-axis).

The most studied sector is manufacturing (11 articles out of 30), with a strong focus on operational performance, followed by some research focused on supplier selection and sustainable or ecological KPIs. There is a gap in performance related to strategy and competitiveness. The automotive sector includes four articles that consider: (i) the green dimension, creating a composite performance index that integrates green and resilience, (ii) operational performance, proposing a benchmarking index that measures lean, agile, resilient, and green practices and linking LARG practices to key KPIs using the ANP, and (iii) collaboration, assessing supply chain interoperability. In this sector, the issue of sustainability is unexplored, if we consider the difference between green supply chain management (GSCM) and sustainable supply chain management (SSCM): while GSCM focuses primarily on environmental issues and aspects such as material flows and stakeholder engagement, SSCM extends this scope by explicitly incorporating economic and social dimensions as well, thus offering a more comprehensive framework (Tronnebati & Jawab, 2020). Therefore, GSCM can be considered a subset of SSCM. Furthermore, strategic and competitive issues have been addressed on the one hand by (Sen et al., 2018), but on the other hand, such performance has not been explored in depth. The analysis shows a large gap in the food and agri-food sector: this sector includes research focused on operational performance (such as costs, efficiency, customer satisfaction, etc.) aimed primarily at developing or applying performance measurement frameworks tailored to food

supply chains. However, sustainable approaches are still limited, indicating that the integration of environmental dimensions and ecological performance within food supply chains remains underexplored. The cross-sector category includes contributions that adopt different methodologies to improve: (i) competitiveness, introducing the LARGS risk map to monitor and anticipate performance risks, assessing the strategic positioning of cement companies within LARGS, and integrating data flow between paradigms to optimize decision-making and supply chain performance; (ii) sustainability and environmental performance, containing two papers that addresses the sustainable dimension in the LARGS paradigm; (iii) operational performance, exploring the impacts of COVID-19 and I4.0 on LARG KPIs and proposing a fuzzy LARG index; managing uncertainty in qualitative performance data; (iv) supplier selection processes. From a general point of view, KPIs related to strategy and competitiveness are the least studied, followed by the issue of sustainability.

Figure 6 shows the detail of methodology used to analyze specific KPIs in each industrial sector.

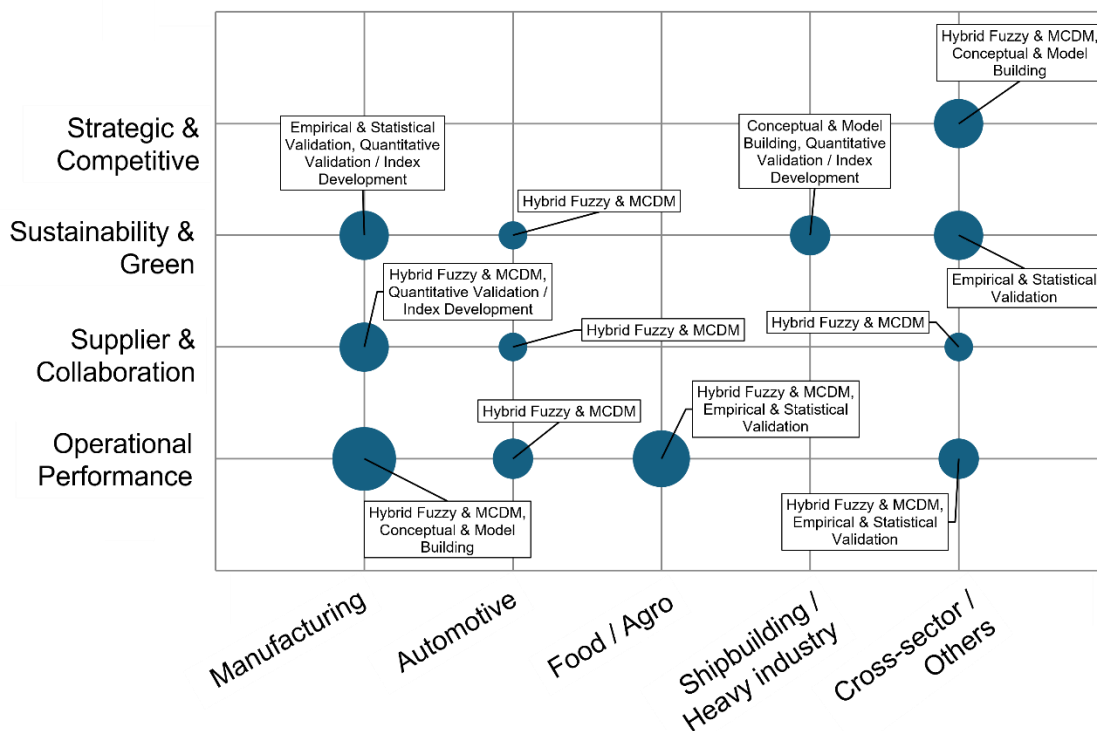


Figure 6. Mapping of methodologies across sector and performance categories.

The figure reveals that Hybrid Fuzzy & MCDM approaches are predominant in the literature, particularly in the manufacturing and automotive sectors, where uncertainty and multi-criteria evaluation represent key challenges in decision-making. These methods are often used to evaluate operational performance and collaboration with suppliers, confirming the relevance of quantitative and analytical tools for optimizing supply chain efficiency.

Empirical and statistical validations (e.g., case studies, SEM, and surveys) are mainly concentrated in cross-sector studies and in the food/agricultural sector, where the LARG

framework has been applied to real cases to assess mainly sustainability and operational performance. In contrast, conceptual and model-building approaches emerge in initial or exploratory research, particularly in the shipbuilding and heavy industry sectors, where theoretical and digital integration models are proposed (e.g., LARG-Industry 4.0 frameworks).

2.2 Barriers and enablers for LARG implementation

As discussed above, several studies address the LARG paradigm applied to the supply chain, identifying criteria that have a significant impact on activities and developing models or tools to integrate these four dimensions into the company's supply chain. However, several factors hinder the implementation of these tools. On the one hand, the different and often conflicting nature of the LARG dimensions makes the simultaneous integration of these practices complex; on the other hand, resistance to change can hinder the technological growth of companies. This makes the study of LARG practices even more necessary (Monferdini, Boza, et al., 2025; Monferdini & Bottani, 2024a) were conducted to investigate how companies manage change and what are the barriers to implementing lean, agile, resilient, and green dimensions in the supply chain.

A first appropriate query was carried out both on Scopus and Web of Science database: TITLE/ABS/KEY ("change management" AND (optimiz* OR optimis*)). The initial sample included 647 papers from Scopus database and 324 papers from Web of Science. The following inclusion/exclusion criteria were considered:

- Document type: "article" and "review"
- Language: "english"

The final query was as follows: TITLE/ABS/KEY (("change management" AND ("optimiz*" OR "optimis*")) AND (LIMIT-TO (DOCTYPE ,"ar") OR LIMIT-TO (DOCTYPE ,"re")) AND AND (LIMIT-TO (LANGUAGE ,"English"))). The final sample included 291 and 197 from Scopus and Web of science, respectively.

The outcomes were merged and, after eliminating duplicates, the sample was resized to 318 documents. The papers lacking authors' name were excluded, reducing the count to 314.

A manual screening was conducted considering the following inclusion/exclusion criteria:

- Relevance to change management, change processes, leadership in change, organizations undergoing change and change management models focusing on process optimization.
- Exclusion of articles solely concentrating on mathematical models without substantive considerations on change management.
- Inclusion of articles addressing interrelated themes (e.g., resilience, communication, leadership and resistance within the context of change management) in line with the findings reported by (Bottani, Monferdini, et al., 2023).

After the manual screening, a total of 176 documents were retained for the analysis. The data are available among the supplementary materials (Monferdini & Bottani, 2024b).

The documents were classified into seven categories (statistical analysis, modeling and simulation, mathematical models, empirical studies, conceptual research, hybrid methods and review papers). The analysis reveals a clear evolution of research methods over time (Figure 7 and Table 5).

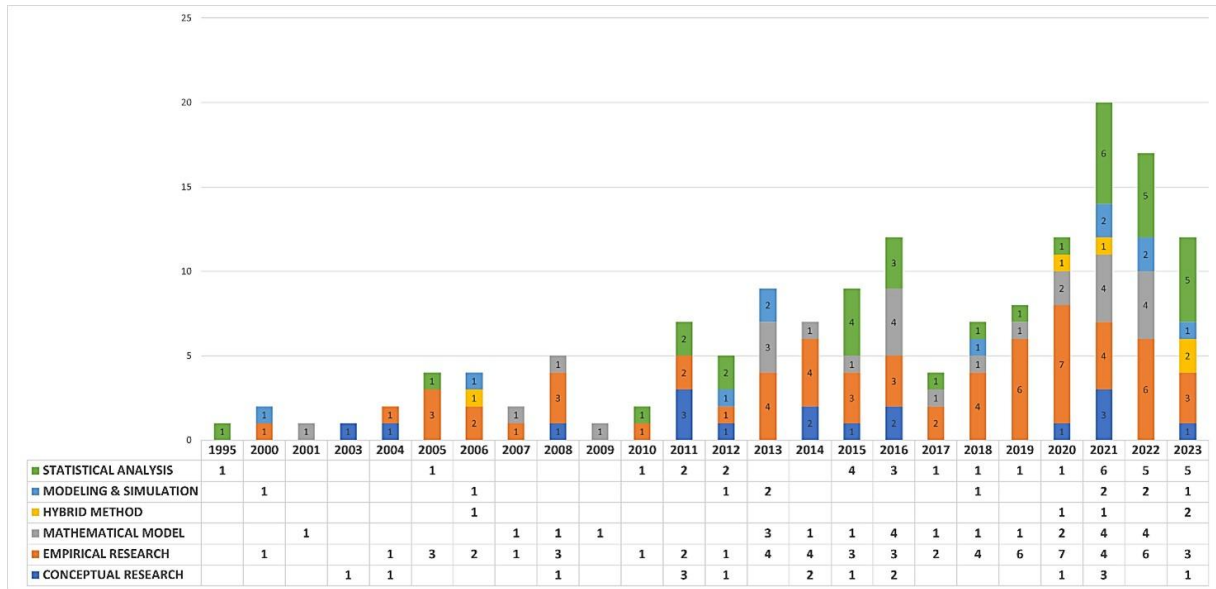


Figure 7. Distribution of papers by research method and publication year (source: (Monferdini & Bottani, 2024a)).

Table 5. Distribution of the groups of papers by method (adapted from: (Monferdini & Bottani, 2024a)).

Methods	N. of papers	%
Empirical Research	61	34.70%
Case Study	21	11.90%
Implementation	18	10.20%
Qualitative	21	11.90%
Quantitative	1	0.60%
Statistical Analysis	34	19.30%
Mathematical Model	26	14.80%
Review	22	12.50%
Conceptual Research	17	9.70%
Conceptual	13	7.40%
Framework	4	2.30%
Modeling & Simulation	11	6.30%
Hybrid Method	5	2.80%
Empirical research (implementation), Statistical Analysis, Mathematical model	1	0.60%
Qualitative and quantitative research	3	1.70%
Statistical analysis, Mathematical model, Case Study	1	0.60%
Total	176	100%

- Empirical studies are the most common approach, showing consistent growth since 2005. This highlights the increasing practical orientation of change management research.
- Statistical analyses represent 19.3% of the sample, with a strong rise after 2021. They are used primarily to investigate behavioral and organizational variables, such as mindfulness, leadership, and resistance to change.
- Modeling and simulation studies account for 6% of publications. Their use reflects the need to test change scenarios and evaluate trade-offs before implementation.
- Mathematical models show fluctuating but increasing interest: until 2001, the use of mathematical models to support change management was limited. However, since 2007, there has been growing interest. In recent years, however, the number of publications using mathematical models has fluctuated without a clear trend. Fuzzy logic is one of the most effective (H. S. Wang & Che, 2007) because change management often involves variables that are challenging to model in mathematical terms. Concepts such as corporate culture, interpersonal dynamics, or resistance to change (Jalagat, 2016) are multifaceted and difficult to depict with mathematical formulas. In this context, fuzzy logic can manage various variables better than other methods.
- Hybrid methods, i.e. combination of quantitative and qualitative tools, have grown significantly after 2020, indicating a shift towards more integrated approaches to addressing complex change dynamics.
- Conceptual research remains limited, confirming that change management is increasingly treated as a practical, applied field than a purely theoretical one.
- Review papers were grouped into a dedicated category to evaluate their content and scope, but they were not considered in subsequent analysis because these papers typically do not consider any specific research method for changing business process nor focus on practical industrial sectors.

The industrial sectors were considered to analyze the different level of maturity within different contexts (Figure 8 and Table 6).

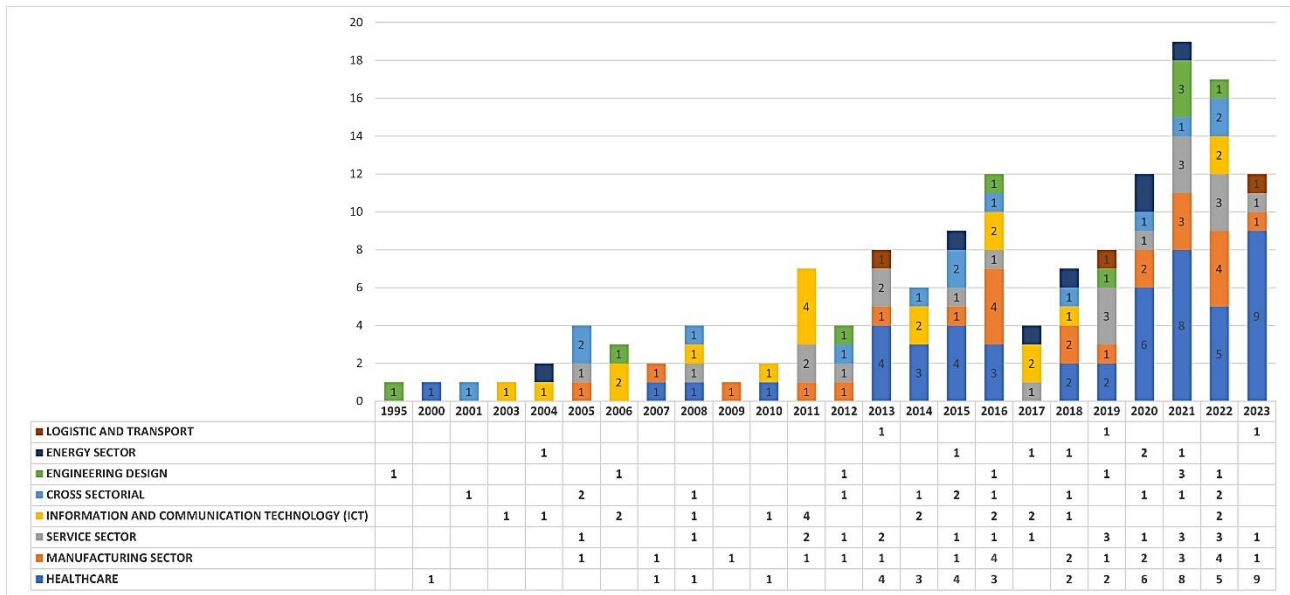


Figure 8. Distribution of papers by industrial sector as a function of the publication year (source:(Monferdini & Bottani, 2024a)).

Table 6. Distribution of papers by industrial sector (adapted from: (Monferdini & Bottani, 2024a)).

Industrial sector	Number of papers	%
Healthcare	50	28%
Manufacturing sector	24	14%
Automotive	2	1%
Aviation	2	1%
Construction	6	3%
General Manufacturing	14	8%
Service sector	21	12%
Public Administration	8	5%
Financial service	1	1%
Human Resource	3	2%
Educational	7	4%
Sport	2	1%
Information and communication technology (ICT)	19	11%
Cross-sectorial	14	8%
Engineering Design	9	5%
Energy sector	7	4%
Oil and gas industry	2	1%
Electricity and Electronic	4	2%
Chemical	1	1%
Logistic and transport	3	2%
N/A	29	16.4%
Total	176	

Healthcare is the most represented sector (34%), particularly in the USA. Studies emphasize transformational leadership, staff training and integrated lean approaches for process improvement.

Manufacturing has seen increasing attention since 2015, focusing on technological change, industry 4.0 adoption and engineering change management.

Service sector, including public administration, shows growing interest after 2011, driven by technological transformation and new business models.

ICT accounts for 13% of the sample, including Enterprise Resource Planning (ERP) adoption, digital transformation and the role of human factors in technology implementation.

Logistics and transport sector includes 3 articles (2% of the sample). The literature highlights the need to deepen knowledge about change management in this sector. The evolution of digitalization in supply chain activities brings with it new risks and requires greater resilience. The studies identified in this sector were mainly empirical, often combined modeling and simulation approaches. Decision-making is supported by these methods, especially when companies are dealing with new technologies adapted to logistics operations.

Energy sector studies highlight change management as a lever for transitioning to renewable sources and sustainable operations.

Cross-sectorial studies explore generic change mechanisms applicable across industries, often using advanced statistical models.

To deeply analyze and understand the barriers of the implementation of LARG paradigms, a second literature review, following a two-stage approach (Figure 9), was carried out.

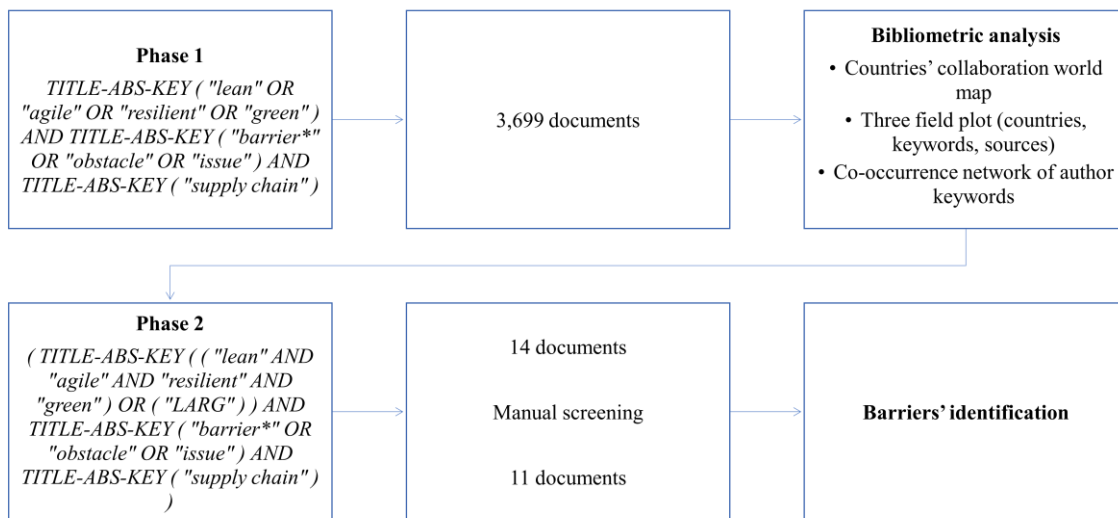


Figure 9. Methodological framework (source: (Monferdini, Boza, & Bottani, 2025)).

To retrieve the initial sample of document, an appropriate query was carried out using the Scopus database: TITLE-ABS-KEY ("lean" or "agile" or "resilient" or "green") AND TITLE-ABS-KEY ("barrier*" OR "obstacle" OR "issue") AND TITLE-ABS-KEY ("supply chain")).

The query returned a total of 3,699 documents, analyzed using Bibliometric R-package.

Figure 10 (a–b) illustrates the geographical distribution of international scientific collaborations. In the first map (Figure 10a), a minimum threshold of 10 joint publications was set, while in the second (Figure 10b), the threshold was raised to 15. The color intensity highlights the number of articles produced by each country, while the connecting lines represent co-authorship relationships: thicker lines indicate stronger collaborative links.

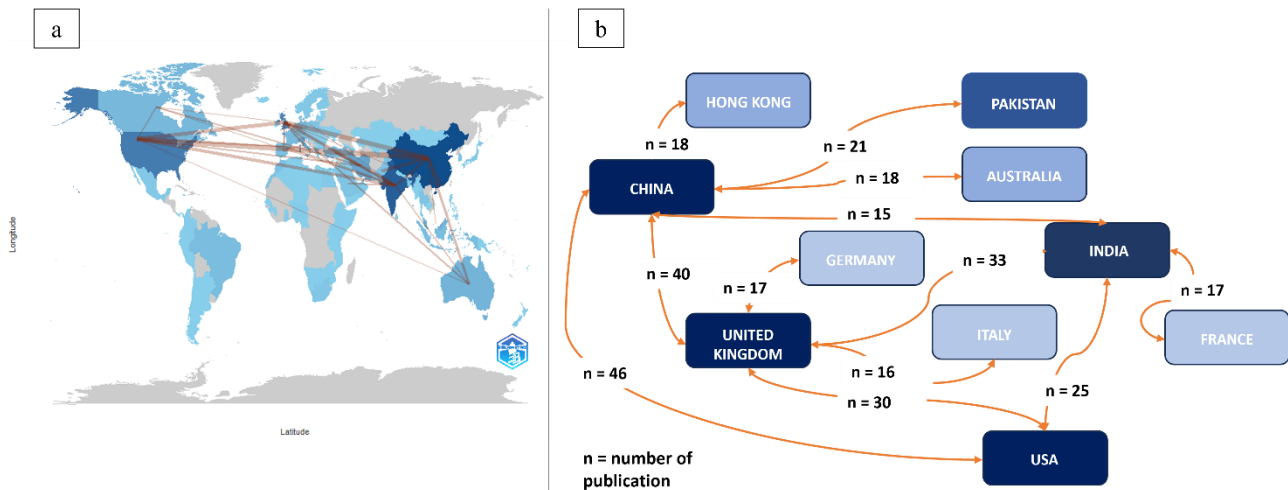


Figure 10. Countries' collaboration world map (a) with minimum documents set to 15 (source: Bibliometrix) and (b) with minimum document set to 10 (source:(Monferdini, Boza, & Bottani, 2025)).

The global map shows a clear concentration of scientific production in North America, Europe, and East Asia, areas that also show the densest collaborative connections. In particular, China leads the ranking with 1,859 publications, followed by India (1,651) and the United States (902). A considerable number of works are the result of international collaborations, highlighting that, despite cultural differences and different approaches to the adoption of LARG practices, a shared vision is emerging at a global level.

China collaborates significantly with the United Kingdom (46 joint articles) and the United States (40). India plays a central role, with significant collaboration flows to the United Kingdom (33), the United States (25), and France (17). The United Kingdom acts as a hub connecting various European countries, including Germany, Italy, Spain, and France. The United States has relationships with both European countries (France and Italy) and Asian countries (Iran and China). Finally, Italy stands out as one of the most active European players, with 16 collaborations with the United Kingdom and 12 with Spain.

A three-field plot (Figure 11) was developed to present the countries (on the left), the keywords (in the middle) and the source (on the right) with the aim to understand which country publish what (i.e., keywords) and where (i.e., source).

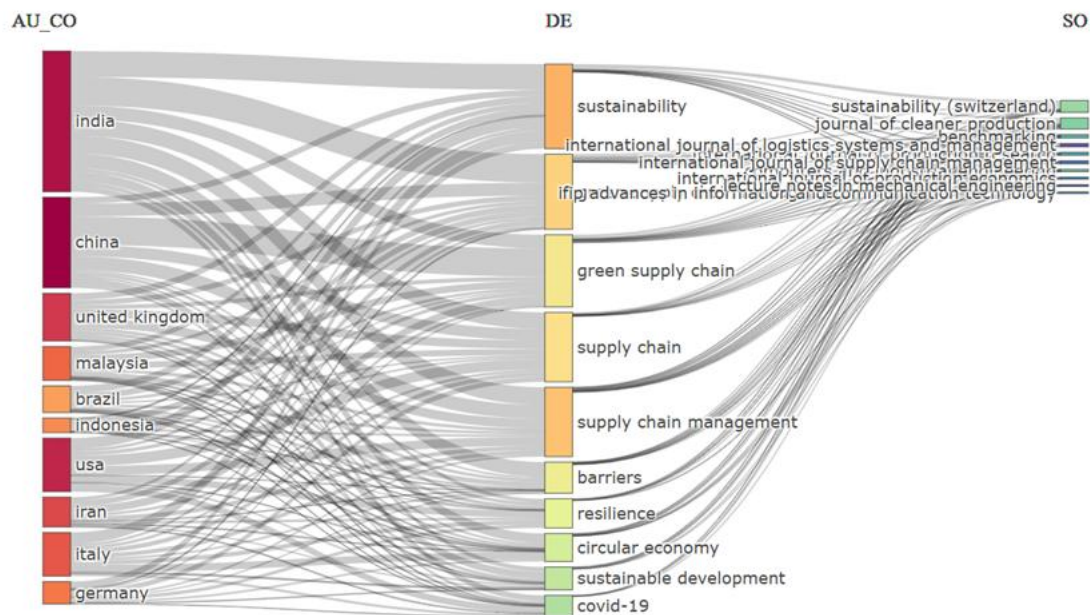


Figure 11. Three Field Plot (developed with: Bibliometrix, source: (Monferdini, Boza, & Bottani, 2025)).

Most of the keywords are related to “sustainability”, that is the most prominent keyword, followed by “green supply chain management” and, other keywords related to sustainable practices, such as “circular economy”, “green supply chain” appear. The interest in these topics is also reflected in the sources: the highest number of papers was published by Sustainability (Switzerland) and Journal of Cleaner Production. In addition, some journal (i.e., *international journal of logistics systems and management*, *international journal of supply chain management*, *lectures notes in mechanical engineering*) suggest a connection to operations management and industrial engineering fields, with a strong focus on logistics and supply chain production.

On the one hand, the concept of sustainability and green supply chain is strongly linked to the concept of “barriers” while on the other hand, it is investigated in relation to resilience, especially in response to the COVID-19 pandemic. The topic therefore appears to be at an advanced stage of development in terms of sustainability and resilience but remains unexplored in relation to other dimensions (lean and agile).

Figure 12 support these statements. Sustainability and sustainable development are once again the most prominent topics that connected various themes and concepts.

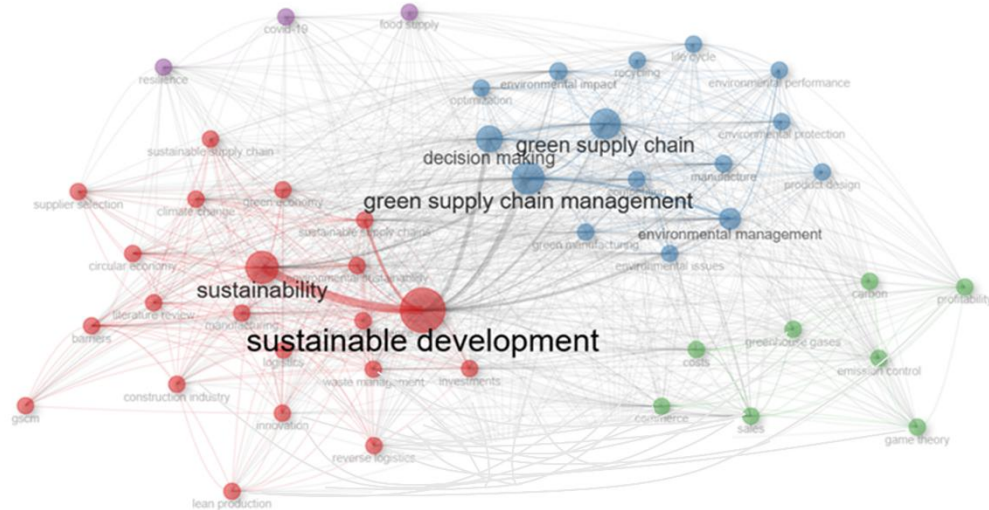


Figure 12. Co-occurrence network analysis (developed with: Bibliometrix, source: (Monferdini, Boza, & Bottani, 2025)).

Red cluster. This cluster includes sustainability topic, covering environmental, economic, and operational dimensions in the context of supply chains. A strong relationship between sustainability and “barriers” is once again highlighted. In addition, the concept of “lean production” appears, linked to the concept of innovation and investment; this underlines a correlation between the technological evolution, the costs and the leanness of the companies.

Blue cluster. This group of keywords focuses on the application of decision-making tools and optimization method that companies can adopt to improve their performance, linked, once again, to green supply chain management and environmental management.

Green cluster. This cluster consider the profitability and costs (i.e., financial implications) and strategic considerations of environmental initiatives.

Purple cluster. This group supports the correlation between resilience and covid-19 pandemic.

To refine the analysis and focus specifically on barriers to the simultaneous integration of the four LARG dimensions, the query was slightly modified (according to Figure 9) as follows:

(TITLE-ABS-KEY ((“lean” AND “agile” AND “resilient” AND “green”) OR (“LARG”)) AND TITLE-ABS-KEY (“barrier*” OR “obstacle” OR “issue”) AND TITLE-ABS-KEY (“supply chain”)).

The sample included 14 documents, of which 11 were selected (Table 7) after manual screening considering the document containing:

- the explicit and simultaneous integration of all four LARG dimensions;
- the discussion of barriers, obstacles or issues related to their integration in supply chain context.

Table 7. Documents analysed for the identification of barriers (adapted from: (Monferdini, Boza, & Bottani, 2025)).

Title	Year	Citation
A moderated mediation model of lean, agile, resilient, and green paradigms in the supply chain	2020	(Alqudah et al., 2020)
An information model in lean, agile, resilient and green supply chains	2011	(Fernandes Cabral et al., 2011)
Integration of human factors principles in LARG organizations - A conceptual model	2012	(Figueira et al., 2012)
Industry 4.0 adoption challenges in lean-agile-resilient-green agri-food supply chain	2024	(Mahajan et al., 2024)
Defining a Cognitive Digital Twin architecture in food supply chains: the early outcomes of DSS4LCO initiative	2024	(Monizza et al., 2024)
Supply chain improvement in LARG (Lean, Agile, Resilient, Green) context: A Risk Management Approach	2017	(Rachid, 2017)
A systematic literature review on supply chain approaches	2023	(Sadeghi Asl et al., 2023)
Lean, agile, resilience and green (LARG) paradigm in supply chain operations: a trial in a seaport system	2020	(Salleh et al., 2020)
A systematic literature review to integrate lean, agile, resilient, green and sustainable paradigms in the supply chain management	2021	(Sharma et al., 2021)
A hybrid decision-making framework for a supplier selection problem based on lean, agile, resilience, and green criteria: a case study of a pharmaceutical industry	2024	(Sheykhizadeh et al., 2024)
An integrated group fuzzy best-worst method and combined compromise solution with Bonferroni functions for supplier selection in reverse supply chains	2021	(Tavana et al., 2021)

The analysis of the 11 documents, brings to a selection of 11 barriers (Table 8).

Table 8. Barriers for the simultaneous integration on LARG dimensions (adapted from: (Monferdini, Boza, & Bottani, 2025)).

Barrier	Source										
	(Alqudah et al., 2020)	(Fernandes Cabral et al., 2011)	(Figueira et al., 2012)	(Mahajan et al., 2024)	(Monizza et al., 2024)	(Rachid, 2017)	(Sadeghi Asl et al., 2023)	(Salleh et al., 2020)	(Sharma et al., 2021)	(Sheykhizadeh et al., 2024)	(Tavana et al., 2021)
Conflicting objectives between paradigms	x	x				x		x	x	x	x
Lack of shared strategic vision	x			x							
Cultural and organizational resistance to change	x	x					x		x		
Organizational silos and poor collaboration	x						x	x			
Limited integration of information systems		x				x	x				
Difficulty in monitoring and performance measurement		x		x			x		x		
Inadequate decision-making tools and methods		x					x				
Technological and infrastructural limitations	x			x	x						
High implementation costs				x	x			x			
Inadequate human capital management			x	x							
Regulatory and market uncertainty	x			x	x						

The description of each factor is provided below:

- Conflicting objectives between paradigms. Different goals and operational logics of LARG paradigm make simultaneous integration (of dimensions, i.e. lean, agile, resilient and green) difficult and may lead to trade-offs or inefficiencies.
- Lack of shared strategic vision. The absence of a shared strategic vision across departments and partners limits the effective coordination and integration of LARG dimensions.
- Cultural and organizational resistance to change. Resistance to change can significantly hinder or delay the implementation of innovative integrated approaches.
- Organizational silos and poor collaboration. Fragmented structures, poor cross-department collaboration, and inadequate supplier alignment hinder the creation of synergies throughout the supply chain.
- Limited integration of information systems. Inadequate data integration, low supply chain visibility, and fragmented IT systems hinder coordinated decision-making.
- Difficulty in monitoring and performance measurement. Discrepancies in performance evaluation parameters between different paradigms make it difficult to standardize evaluations and complicate comparability.
- Inadequate decision-making tools and methods. The lack of advanced multi-criteria decision-making tools limits the ability to effectively manage trade-offs between LARG dimensions.
- Technological and infrastructural limitations. Insufficient or inefficient technologies and infrastructure make it difficult to support integrated supply chain practices.
- High implementation costs. The implementation of LARG practices often requires very expensive technologies.
- Inadequate human capital management. Lack of employee training and attention to human factors obstacle successful implementation of integrated supply chain paradigms.
- Regulatory and market uncertainty. The lack of clarity and rapid evolution of regulations, combined with unstable market conditions, create barriers to the adoption of integrated LARG approaches.

The frequency of occurrence of the barriers across the reviewed studies was considered (Table 9), with the aim to clarify their relative importance.

Table 9. Frequency of occurrence of identified barriers (adapted from: (Monferdini, Boza, & Bottani, 2025)).

Barrier	Frequency	%
Conflicting objectives between paradigms	7	63.6%
Cultural and organizational resistance to change	4	36.4%
Difficulty in monitoring and performance measurement	4	36.4%
Organizational silos and poor collaboration	3	27.3%
Limited integration of information systems	3	27.3%
Technological and infrastructural limitations	3	27.3%
High implementation costs	3	27.3%
Regulatory and market uncertainty	3	27.3%
Lack of shared strategic vision	2	18.2%

Inadequate decision-making tools and methods	2	18.2%
Inadequate human capital management	2	18.2%

“Conflicting objectives between paradigms” is the barrier with the highest number of occurrences ($\cong 64\%$). Other frequently identified obstacles are “cultural and organizational resistance to change” and “difficulty in monitoring and performance measurement” ($\cong 36\%$ each). Secondary issues include “organizational silos and poor collaboration”, “limited integration of information systems”, “technological and infrastructure limitations”, “high costs of implementation”, and “regulatory and market uncertainty” ($\cong 27\%$ each).

Based on the above, while cost and technology-related obstacles are significant, organizational and strategic misalignments emerge as the most widespread difficulties, suggesting that the integration of LARG dimensions is hindered more by managerial and cultural issues than by purely technical constraints (when accompanied by successful performance measurement monitoring).

2.3 Gap and novelty

The literature analyzed in section 2.1 and 2.2 highlights that research is still evolving regarding the evaluation and implementation of the LARG(S) paradigm in supply chain management. Although numerous contributions explore lean, agile, resilient, and green practices, the simultaneous and integrated evaluation of these dimensions, especially when extended to sustainability, remains conceptually recognized but methodologically immature and difficult to implement. Furthermore, empirical applications in specific sectors (such as logistics and food supply chains) are limited, and the link between organizational change management, a key lever for integrating LARG(S) dimensions into the business context, and operational performance has only been partially explored.

Below is a summary of the main gaps identified in the research.

- Limited scope of LARGS. Only a few recent studies integrate the dimension of sustainability into the LARG framework, confirming the growing but still insufficient attention to global sustainable performance models.
- Partial interpretation of sustainability. Most studies equate sustainability with the “green” dimension; however, a comprehensive perspective of sustainable supply chain management, which includes economic and social aspects in addition to environmental ones, is largely lacking.
- Poor methodological support for change management. Quantitative and decision support models that address change processes in supply chains are rare; change management remains mostly analyzed in a qualitative or descriptive manner.
- Need for fuzzy and hybrid models of managerial variables. Concepts such as resistance to change, collaboration, and cultural adaptability are difficult to quantify using traditional mathematical models. Fuzzy logic seems promising, but it has only been partially used in this field.

- Underrepresentation of logistics and transportation sectors. Only a small fraction of studies addresses change management or LARG(S) implementation in logistics operations, despite their centrality to resilience and agility.
- Prevalence of general industry analyses. The literature is heavily biased towards operations management and manufacturing, while sector-specific investigations (e.g., food, logistics, machinery) remain limited.
- Unbalanced focus among LARG dimensions. Sustainability (i.e., green dimension) and resilience are relatively mature topics, while lean and agile aspects are less explored in integrated frameworks.
- Insufficient decision support models. Most studies use descriptive or empirical approaches; there is a lack of advanced multi-criteria and fuzzy hybrid tools capable of managing trade-offs between LARG dimensions.
- Inconsistent performance measurement systems. Divergent definitions of KPIs and heterogeneous evaluation criteria hinder comparability and standardization across studies.
- Organizational and cultural misalignments. Beyond technological barriers, managerial resistance and the absence of a shared strategic vision are the most common obstacles to effective LARG integration.

In response to these gaps, this thesis develops and validates a methodological framework that integrates qualitative and quantitative tools to support decision-making within the LARG(S) paradigm.

The novelty lies in:

- Development of a multi-level decision support system, combining AHP, fuzzy logic, and hybrid fuzzy Delphi-DEMATEL-ANP approaches to evaluate supply chain performance and supplier selection under uncertainty.
- Explicit incorporation of sustainability into the traditional LARG framework, extending it to LARGS.
- Mapping of KPIs across all stages of the supply chain (procurement, production, distribution, and reverse logistics).
- Application of fuzzy logic to complex decision-making contexts, enabling the quantitative treatment of subjective and uncertain judgements (e.g., expert opinions, KPI evaluation, and interdependence between LARG(S) dimensions).
- Validation through multiple case studies and numerical examples, focusing on the logistics and food machinery sectors, two underrepresented but strategically relevant contexts.
- Implementation of a computational tool in Python to map the interdependencies between LARG(S) criteria.

3. Methodology

The methodology adopted in this thesis combines qualitative and quantitative approaches, with the aim to analyze the logistics performance and support the improvement of supply chain activities according to lean, agile, resilient, green and sustainable perspectives.

3.1 Decision-making support tools

The first methodological step consists of identifying, developing, and adapting decision-making tools to evaluate supply chain performance according to LARG(S) perspectives.

Framework

A LARG-framework for evaluating supply chain performance was developed, considering LARG paradigm and typical supply chain processes: (i) supply, (ii) production, (iii) distribution/sale and (iv) reverse logistics. To this aim, KPIs were identified in literature, classified according to four LARG dimensions (i.e., lean, agile, resilient and green) and mapped on the four operational areas of the supply chain. The list of KPI and their applications will be presented in the results section.

AHP

The analytic hierarchy process was employed as a multi-criteria decision-making method to assign weights at the KPIs. The procedure adopted in this thesis followed the classical AHP steps (Saaty, 1977):

- i. Hierarchy construction according to (Gavade, 2014) including criteria (lean, agile, resilient and green), sub-criteria (i.e. the KPIs) and the possible x alternatives (Figure 13)

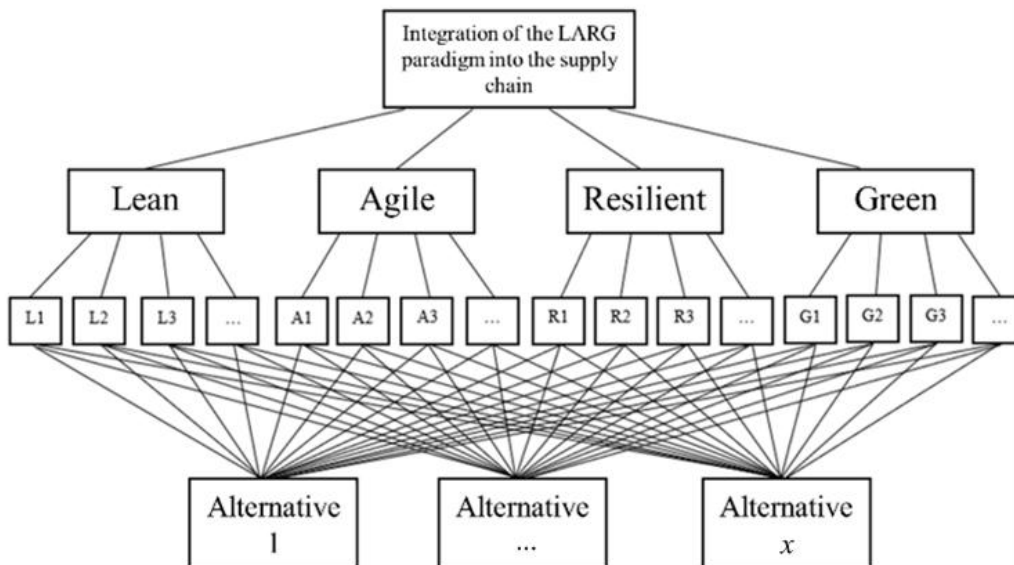


Figure 13. Hierarchical structure of the AHP model for integration of the LARG paradigm (source:(Bottani, Monferdini, et al., 2025)).

- ii. Pairwise comparison matrices construction (Saaty, 2002). These are square matrices with size $[n \times n]$, where n represents based on the application level either the number of criteria, the number of sub-criteria or the number of alternatives. For a given row i and column j , the entry a_{ij} represents the relative importance of the criterion/sub-criterion/alternative in row i compared to that in column j .
- iii. Weight derivation. Eigenvalue methods were applied to compute the relative weights of each dimension and KPI. The consistency index (Eq. 1) and consistency ratio (CR) was calculated to verify the logical coherence of judgments, in line with the AHP methodology (Saaty, 1988).

Eq. 1

$$CI = \frac{\lambda_{max} - n}{n - 1}$$

Where n represents the number of sub-criteria and thus corresponds to the size of the matrix and λ_{max} is the principal eigenvalue. By applying the same procedure to the next level of the hierarchy, pairwise comparison matrices can be built for the alternatives vs. each identified sub-criterion.

Fuzzy Logic

The fuzzy logic was applied to support decision-making under uncertainty and subjective judgments. The main steps involved are shown in Figure 14.

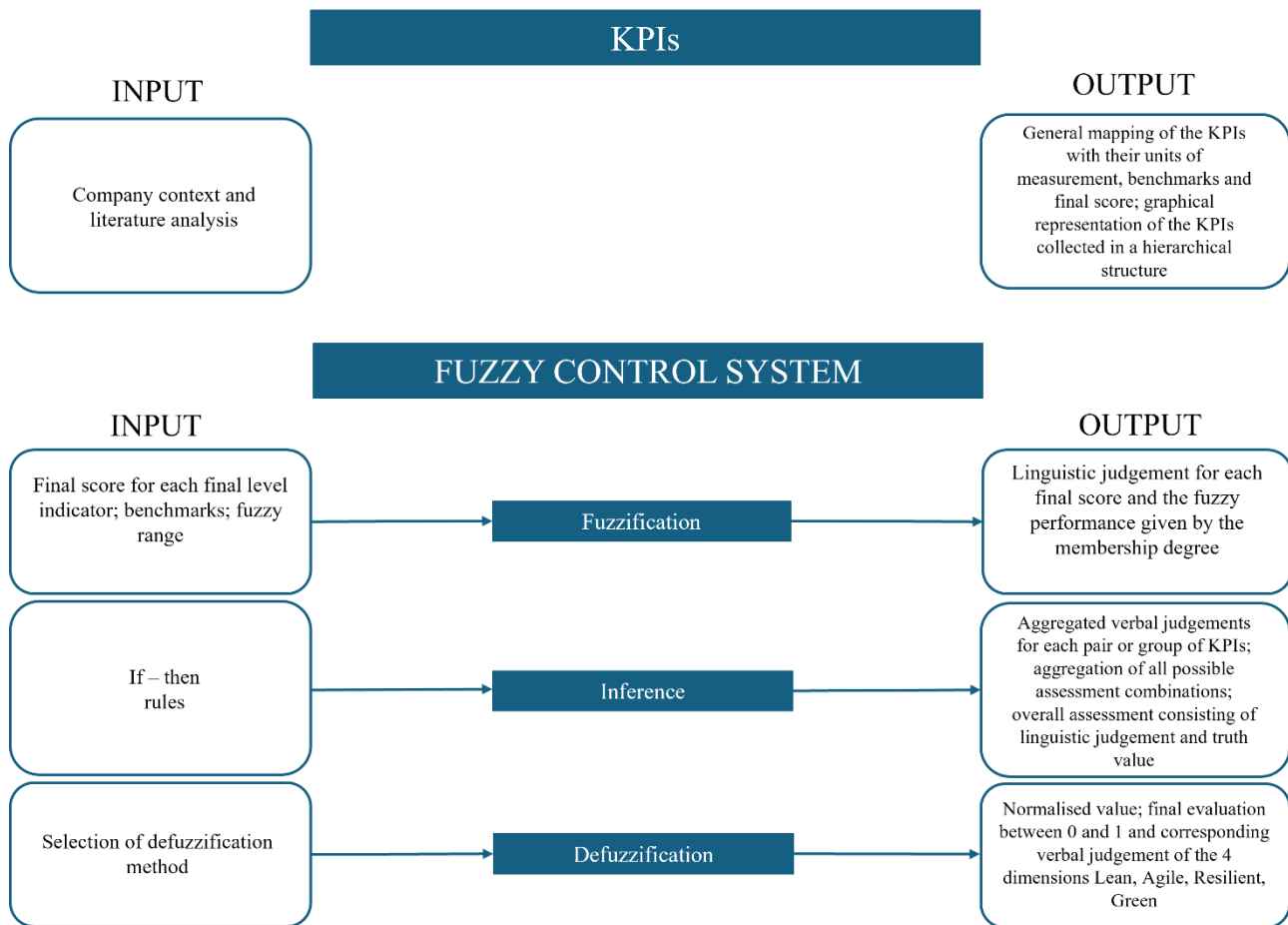


Figure 14. Methodological framework (source: (Monferdini, Casella, et al., 2025)).

The first step in developing the fuzzy logic-based framework was the identification and definition of relevant KPIs. The first output was the general mapping of the KPIs along with their units of measurement and benchmark values. In addition, the final score for each KPI is calculated in accordance with Eq. 2.

Eq. 2

$$Final\ score = \begin{cases} \frac{company\ value}{benchmark} * 100, & if\ benchmark \neq 0 \\ company\ value, & if\ benchmark = 0 \end{cases}$$

The second output of the first step was a graphical representation of the KPIs within a hierarchical structure, reflecting the relationships between individual indicators and their respective categories (procurement, production, distribution and reverse logistics) and subcategories.

The second step included the developing of fuzzy control system and followed the classical fuzzy structure:

- i. Fuzzification. The linguistic terms (e.g., Very Low, Low, High and Very High) were used to get a linguistic evaluation of the final score calculated for each KPIs (Chen & Ku, 2008) . The trapezoidal functions were adopted to model the fuzzy numbers (Eq. 3), according to various studies (Kaur & Kumar, 2011).

Eq. 3

$$\mu(x) = \begin{cases} 0, & x < a \\ \frac{x-a}{b-a}, & a \leq x \leq b \\ 1, & b \leq x \leq c \\ \frac{x-d}{c-d}, & c \leq x \leq d \\ 0, & x > d \end{cases}$$

Where:

- x represents the numerical value of the variable (i.e., the final score against the selected KPI);
- $\mu(x)$ is the corresponding membership degree;
- a, b, c are the parameters that define the shape of the trapezoidal fuzzy number, based on decision-makers' judgment or benchmark tables.

The outputs of the fuzzification were: (i) the linguistic judgment for each final score and (ii) the fuzzy performance given by the membership degree.

ii. Inference.

To evaluate and combine fuzzy sets of two or more indicators, the inference process uses if-then rules. The indicators were aggregated in pairs to simplify the hierarchical structure, but the method can be extended to multiple indicators when necessary.

The linguistic input values are derived from expert consultation, therefore, the if-then rules used in the inference process are derived from the semantic aggregation matrix based on linguistic combinations of input variables (Table 10).

Table 10. Fuzzy inference rule matrix used to determine the output linguistic values.

	Very low	Low	Average	High	Very high
Very low	Very low	Very low	Low	Low	Average
Low	Very low	Low	Low	Average	High
Average	Low	Low	Average	High	High
High	Low	Average	High	High	Very high
Very high	Average	High	High	Very high	Very high

Each combination of input values (row and column) of the two indicators produces an aggregated fuzzy value (intersection of each row and column), which corresponds to the aggregated output value.

The truth value of each indicator (Eq. 4) corresponds to the final output of the inference.

Eq. 4

$$\text{Truth value} = \prod_{j=1}^i \mu_j(x_j)$$

Where,

- i : total number of KPIs considered
- $\mu_j(x_j)$: membership degree of the j-th KPI

iii. Defuzzification

Defuzzification was applied to convert qualitative results into quantitative output. The fuzzy output, known as a fuzzy set, was transformed into a crisp set to obtain numerical equivalents of linguistic expressions that contain the final evaluation of the system.

The following key steps were applied:

- Selecting the defuzzification method

Several defuzzification methods exist un the literature. Among them, the fuzzy mean (FM) method (Eq. 5) is one of the most applied due to its simplicity and effectiveness (Van Leekwijck & Kerre, 1999).

Eq. 5

$$FM = \frac{\sum_{k=1}^n a_k X_k}{\sum_{k=1}^n a_k}$$

Where:

- n is the number of fuzzy conclusions;
- a_k is the truth value (i.e., degree of membership) of the k-th conclusion obtained from the inference phase;
- X_k is the numeric value associated with the k-th conclusion. For trapezoidal fuzzy numbers, this is typically the average of the two values where the membership function reaches its maximum. Table 11 shows the fuzzy interval used to determine the X_k value.

Table 11. Fuzzy ranges.

Linguistic judgment	a	b	c	d
Very low	0.00	0.00	0.10	0.20
Low	0.10	0.20	0.30	0.40
Average	0.30	0.40	0.50	0.60
High	0.50	0.60	0.70	0.80
Very high	0.70	0.80	1.00	1.00

- Normalizing the final score

The following normalization formula (Eq. 6) was used to express the output within a standardized range (typically between 0 and 1).

Eq. 6

$$\text{Normalized value} = \frac{(x - \text{min})}{(\text{max} - \text{min})}$$

Where:

- x is the crisp index before normalization;
- min and max are the minimum and maximum values in the possible range of variation, which correspond to the extreme cases where the company achieves the lowest or highest scores across all indicators.

Hybrid fuzzy Delphi-DEMATEL-ANP

In addition to the fuzzy logic framework previously described, a hybrid fuzzy approach was implemented to address the specific problem of supplier selection. At this level of analysis, in addition to the four dimensions (lean, agile, resilient, and green), the sustainability (S) dimension was added. This extension was motivated by the relevance of suppliers in shaping overall supply chain performance under the LARGS paradigm, as well as the importance of sustainability in this activity. In particular, the methodology combined the Fuzzy Delphi Method (FDM), to screen and validate the most important evaluation criteria based on expert judgments, with the Fuzzy DEMATEL-ANP (FDANP) method, to analyze the cause-effect relationship among criteria and determine their final weights. This approach allowed to both reduce the subjectivity in the definition of relevant factors and to capture interdependencies across LARG(S) dimensions, providing a robust decision-making tool for supplier selection within sustainable supply chains.

Both FDM and FDANP are well-known in studies on supplier selection (Abdollahi et al., 2015; Rahardjo et al., 2023; Sahu et al., 2023) .

The methodology followed consisted in three key phases (Figure 15).

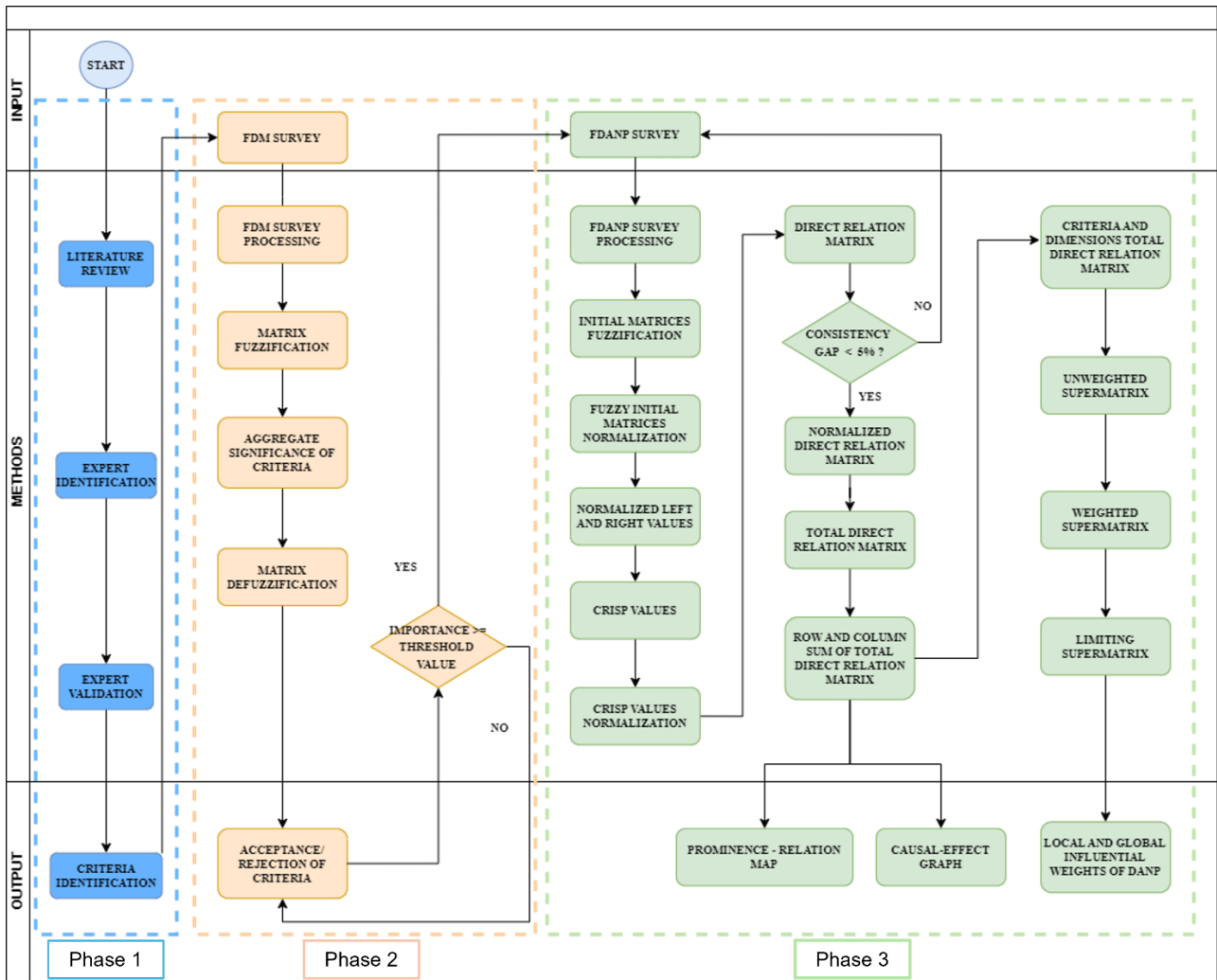


Figure 15. Process diagram of the methodology (source: (Bottani, Nardo, et al., 2025)).

phase 1: identification of evaluation criteria

Through a review of the literature, a list of evaluation criteria for the selection of suppliers in the LARGS context was created. In addition, to verify the clarity of the criteria, their frequency of use among researchers was evaluated.

Phase 2: selection of evaluation criteria – FDM survey

The FDM was applied to a questionnaire administered to a group of experts operating in different industrial contexts to gather their opinions on the importance of the criteria identified in order to assess their relevance.

The FDM questionnaire was created *via* Google Forms and consists of a series of questions to obtain information regarding the importance of the LARGS evaluation criteria identified, as well as information regarding the experts' profile (i.e., industrial sector, year of experience, educational level, role).

The experts were identified among professionals, academics and consultants with specific expertise in supply chain and supplier selection. The information regarding experts will be presented in the result section.

Each expert i ($i=1,\dots,p$) was requested to assess the relevance of every criterion k by choosing among predefined linguistic options. For instance, expert I was asked question like “How do you rate the importance of criterion k in the supplier selection process?”. Responses were provided on a five-point scale, ranging from 1 (“very unimportant”) to 5 (“very important”). Since linguistic or subjective assessments often involve vagueness and uncertainty, fuzzy set theory has been widely adopted as an appropriate tool (Beikkhakhian et al., 2015), as stated before. In particular, fuzzy logic has proven to be effective in addressing supplier selection problems (Matawale et al., 2016; ŞAHİN et al., 2023) and in related research problems (Bhunias et al., 2024; Mondal & Roy, 2024a, 2024b). Accordingly, the judgments provided by the experts, $\tilde{x}_k^i = (x_{1k}^i, x_{2k}^i, x_{3k}^i)$, were represented through triangular fuzzy numbers, as summarized in Table 12.

Table 12. Fuzzy linguistic scale.

Fuzzy linguistic scale	Triangular fuzzy number
$\tilde{5}$	(0.75,1.00,1.00)
$\tilde{4}$	(0.50,0.75,1.00)
$\tilde{3}$	(0.25,0.50,0.75)
$\tilde{2}$	(0,0.25,0.50)
$\tilde{1}$	(0,0,0.25)

By aggregating the judgements of the experts, the overall importance of criterion k was computed as shown in Eq. 7

Eq. 7

$$\tilde{x}_k = (x_{1k}, x_{2k}, x_{3k}), \text{ with } \begin{cases} x_{1k} = \min_i(x_{1k}^i) \\ x_{2k} = \frac{1}{p} \sum_{i=1}^p x_{2k}^i \\ x_{3k} = \max_i(x_{3k}^i) \end{cases}$$

The defuzzification phase included the calculation of the crispy value S_k (Eq. 8)

Eq. 8

$$S_k = \frac{x_{1k} + x_{2k} + x_{3k}}{3}$$

A threshold value ρ was set to identify the most evaluation criteria. The rationale behind the selection of the relevant criteria is that a criterion could be retained if $S_k \geq \rho$.

Phase 3: Analysis of the relationships between criteria and priority calculation - FDANP survey

A second questionnaire (FDANP) was administered to the experts who, after the FDM survey, expressed their willingness to continue participating in the research with the aim of assessing the influence/impact of each LARGS perspective on the others and of each criterion on the other criteria within the same perspective. The objective is to explore the

relationships and graphically represent the direct/indirect influence on a random diagram. The experts were initially asked some preliminary questions about their profile, followed by questions such as “How do you rate the influence of the “Lean” strategy on the “Agile” strategy?” or “How do you rate the influence of the “Price” criterion on the “Guarantees and Claims Policies” criterion?”.

According to (Fontela & Gabus, 1976) the full process for the implementation of FDANP method was applied as follows.

M dimensions $D = \{D_1, D_2, \dots, D_M\}$ representing the PARGS perspectives, along with n evaluation criteria $C = \{C_1, C_2, \dots, C_n\}$ and p experts $E = \{E_1, E_2, \dots, E_p\}$ were considered for the construction of the experts' initial matrices. Each expert i ($i = 1, \dots, p$) was asked to assess how strongly each criterion C_k affects each criterion C_j ($j, k = 1, \dots, n$) using five-point linguistic scale (previously presented in Table 12), ranging from 1 = “no influence” to 5 = “very influence”, but with slightly adjusted interpretations. The conversion of these linguistic ratings into triangular fuzzy numbers (TFNs) follows the same procedure described in Table 12. The evaluation provided by each expert generate a non-negative $n \times n$ influence matrix $X_i = (x_{ikj})$ for the criteria, where each element x_{ikj} represents the influence score assigned by expert i . The diagonal entries of these matrices are zero. A similar process was applied to assess the influence between dimensions, where the impact of dimension m_1 on dimensions $m_1 = (m_1, m_2 = 1, \dots, M)$ is evaluated. This leads to the construction of another non-negative $M \times M$ influence matrix representing relationships among the dimensions. “Converting fuzzy data into crisp scores” (CFCS) was chosen as the defuzzification method because it provides a better final crisp value than other methods (Opricovic & Tzeng, 2011).

Denoting with $\tilde{x}_{kj}^i = (x_{1kj}^i, x_{2kj}^i, x_{3kj}^i)$ the degree of influence that criterion k exerts on criterion j as expressed by expert i , the CFSC method starts with a normalization of the fuzzy values, which is obtained by applying Eq. 9:

Eq. 9

$$\begin{cases} zx_{1kj}^i = (x_{1kj}^i - \min x_{1kj}^i) / \Delta_{min}^{max} \\ zx_{2kj}^i = (x_{2kj}^i - \min x_{2kj}^i) / \Delta_{min}^{max} \\ zx_{3kj}^i = (x_{3kj}^i - \min x_{3kj}^i) / \Delta_{min}^{max} \end{cases}$$

with $\Delta_{min}^{max} = \max x_{3kj}^i - \min x_{1kj}^i$.

The left zl and right zr normalized values are then computed:

Eq. 10

$$\begin{cases} zls_{kj}^i = zx_{2kj}^i / (1 + zx_{2kj}^i - zx_{1kj}^i) \\ zrs_{kj}^i = zx_{3kj}^i / (1 + zx_{3kj}^i - zx_{2kj}^i) \end{cases}$$

Eq. 11 is thus used for deriving the single crisp values:

Eq. 11

$$z_{kj}^i = \frac{[zls_{kj}^i(1 - zls_{kj}^i) + (zrs_{kj}^i)^2]}{(1 - zls_{kj}^i + zrs_{kj}^i)}$$

Results of the computation must be normalized as follows:

Eq. 12

$$h_{kj}^i = \min x_{1kj}^i + z_{kj}^i \Delta_{min}^{max}$$

Finally, crisp values are aggregated into matrix A , by adding up the outcomes obtained from all experts, using the following formula:

Eq. 13

$$A = \frac{1}{p} (H_{kj}^1 + H_{kj}^2 + \dots + H_{kj}^i)$$

Matrix A consists in the aggregated crisp values of all experts and is called the direct relationship matrix.

The confidence level $(1 - \alpha)$ represents the level of agreement among the experts and reflects how consistent their evaluations are. A significant level α below 5% (that is, $((1 - \alpha) \geq 95\%)$) indicates that the results can be considered reliable. Following the method proposed by (Liou et al., 2014), the value of α can be determined using the following expression:

Eq. 14

$$\alpha = \frac{1}{n(n-1)} \cdot \sum_{i=1}^p \sum_{k=1}^n \sum_{j=1}^n \frac{|a_{kj}^p - a_{kj}^{p-1}|}{a_{kj}^p} \cdot 100\%$$

Where:

- n is the total number of criteria
- p is the number of experts, and
- $a_{kj}^{(p)}$ represents the average influence score assigned by expert p for the impact of criterion k on criterion j .

A lower α value indicates that the differences between experts' assessments are smaller, which in turn implies a higher degree of consensus and greater reliability of the obtained data results.

In addition, the normalized direct relation matrix $NA = (a_{kj})_{n \times n}$, with $0 \leq a_{kj} \leq 1$ and main diagonal elements equal to zero, was obtain following Eq. 15- Eq. 16. All values were converted to a range between 0 and 1, following the common normalization used during the

DEMATEL process (Fontela & Gabus, 1976; Tzeng & Huang, 2011), ensuring that all values of a matrix are expressed on a common scale (Saaty, 2004).

Eq. 15

$$NA = s \cdot A$$

Eq. 16

$$s = \min \left(\frac{1}{\max_k \sum_{j=1}^n |a_{kj}|}, \frac{1}{\max_j \sum_{k=1}^n |a_{kj}|} \right)$$

The total relationship matrix $T = (t_{kj})_{n \times n}$, computed using Eq. 17, considers the direct and indirect influence among the criteria.

Eq. 17

$$\begin{aligned} T &= NA + NA^2 + NA^3 + \dots + NA^\gamma = NA(I + NA + NA^2 + \dots + NA^{\gamma-1})[(I - NA)(I - NA)^{-1}] \\ &= NA(I - NA^\gamma)(I - NA)^{-1} \end{aligned}$$

Where I is the identity matrix. The indirect influences are reduced to zero by raising NA to increasingly higher powers. This is because, in general, the T matrix considers a continuous decrease in the indirect influences of the criteria along the powers in the NA matrix. Therefore, the following applies: when $\gamma \rightarrow \infty$, $NA^\gamma = (0)_{n \times n}$ and T is as follows.

Eq. 18

$$T = NA(I - NA)^{-1}$$

The sum of rows R and the sum of columns C of matrix T are two vectors that can be expressed by Eq. 19 - Eq. 20.

Eq. 19

$$R = (r_k)_{n \times 1} = (r_k)'_{1 \times n} = \left(\sum_{j=1}^n t_{kj} \right)'_{1 \times n}$$

Eq. 20

$$C = (c_j)_{1 \times n} = \left(\sum_{k=1}^n t_{kj} \right)_{1 \times n}$$

Here, r_k represents the sum of the k -th row of matrix T , and it shows the total direct and indirect effects that criterion k has on all the other criteria.

Similarly, c_j is the sum of the j -th column of matrix T , which indicates the total direct and indirect effects that criterion j receives from all the other criteria.

The value $r_k + c_j$ (when $k = j$) is called "prominence", and it reflects the overall influence a factor has and receives, showing its relative importance in the system.

On the other hand, the value $r_k - c_j$ (also with $k = j$) is referred to as “relation”. This measures the net influence that factor k contributes to the problem:

If $r_k - c_j > 0$, criterion k is considered a “net cause”, meaning it mainly influences other criteria.

If $r_k - c_j < 0$, criterion k is a “net receiver”, meaning it is mostly influenced by the other criteria.

The threshold value β was calculated to evaluate the significance of the relationship between factors and criteria, according to Eq. 21.

Eq. 21

$$\beta = \frac{\sum_{k=1}^n \sum_{j=1}^n t_{kj}}{nxn}$$

Where nxn is the total number of elements of the matrix T .

The criteria considered significant were included in the Influential Network Relation Matrix (INRM).

The total relationship matrix of the criteria (T_c) is composed of several sub-matrices, where each element $(t_c)_{mxm}$ represents the relationships among the criteria within a specific dimension m . These sub-matrices can be normalized using the same procedure applied to matrix A , but restricted to their own entries. This produces the normalized total criteria relationship matrix $T'_c = (t'_c)_{mxm}$.

The unweighted supermatrix (W_u) is generated by transposing the normalized matrix T'_c , i.e. $W^u = (T'_c)^T$.

If a sub-matrix contains only zero (i.e., it is null), this indicates that the criteria belonging to dimension D_{m1} do not influence the criteria associated with dimension D_{m2} .

Similarly to the criteria matrix, a total dimension relationship matrix (T_D) can be created to represent the influence relationships among dimensions. This matrix can also be normalized using the same approach as before, resulting in the normalized dimension relationship matrix T'_D .

The weighted supermatrix (W) is then computed by applying Eq. 22.

Eq. 22

$$W = T'_D W^u$$

This step combines both the dimension level and criteria-level information to reflect the relative weights in the system.

The weighted supermatrix W is repeatedly multiplied by itself and raised to a sufficiently large power until it reaches a steady state. At this point, the matrix stabilizes and its columns converge to constant values, forming what is known as the limiting supermatrix W^* (Eq. 23).

Eq. 23

$$W^* = \lim_{g \rightarrow \infty} (W)^g$$

In this equation, G indicates the power to which the matrix is elevated. When convergence is achieved, the elements in each row of the limiting supermatrix are identical, and each row represents the global weight of the corresponding criterion. These values are also referred to as the influential weights in the DANP method.

To determine the local weights for each dimension, the global weights of all criteria belonging to that dimension were summed. Finally, by dividing the global weight of an individual criterion by the local weight of its dimension, the local weight of that specific criterion was obtained.

Software implementation

To automate the process described above, a computational procedure was developed in Python in order to (i) map the criteria/dimensions based on their prominence and relation, (ii) represent the cause-effect graphs related to the various criteria/dimensions and (iii) calculate the local and global weights of criteria/dimensions.

This implementation provides not only a flexible tool but also reduce the processing times and minimize the risk of errors.

ISM-MICMAC

To complement the quantitative decision-support tools, previously described, and to provide a concrete and operational overview of sustainability measures, the thesis incorporates a qualitative structural analysis based on ISM and MICMAC. Reducing food waste is a concrete manifestation of the green and sustainable perspectives in LARGS.

The ISM phase aims to: (i) identify the key operational strategies that reduce food waste in perishable supply chains, (ii) analyze how these factors are interconnected (e.g., which strategies drive others), and (iii) create a model showing the hierarchical structure of these relationships. MICMAC approach classifies factors based on their power to influence, called “driving power” (i.e., how much they can influence other factors) and their “dependence power” (i.e., how much they are influenced by other factors).

To achieve the results the following steps were adopted.

- i. Identification of strategies

Thirteen key strategies were derived from the literature. The key strategies will be presented in the results section.

- ii. expert survey

A survey was administrated to academic experts to (i) assess the effectiveness of each strategy in reducing waste, and (ii) explore the interrelationships between factors. The survey was divided into 2 sections: “the effectiveness of strategies in reducing food waste” (from 1 = “very low” to 5 = “very high”) and “relationship between strategies”. Section 2 consists of 13 questions, each relating to one of the 13 factors. In each question, participants were asked to indicate which strategies are influenced by strategy i, where strategy i represents the focus of the question. For example, if strategy i is “inventory management optimization”, the question will be: “Select the strategies that are influenced by inventory management optimization”.

iii. Interpretive structural modeling

To implement the ISM approach the section 2 of the survey was used. The following key steps were applied.

- Development of structural-self interaction matrix (SSIM)
For each pair of strategies (i,j), was indicated the directed relationship using standard ISM symbols (V,A,X,O) as follows.
V – Strategy i influences Strategy j
A – Strategy j influences Strategy i
X – Strategies i and j influence each other
O – No direct relationship between Strategies i and j
- Conversion of SSIM into a reachability matrix
The SSIM was converted into a reachability matrix by replacing the symbols (V,A,O,X) into 1 and 0, according to ISM conversion rules (Table 13).

Table 13. ISM conversion table.

SSIM	(i,j)	(j,i)
V	1	0
A	0	1
X	1	1
O	0	0

Given the large sample of respondents (145), binary conversion used a threshold: if at least 50% of respondents indicates a dependency, the relation was coded as present (1), otherwise absent (0).

Transitivity was considered (Sushil, 2012) to ensure logical consistency (if strategy a influences strategy b, and strategy b influences strategy c, then strategy a influences strategy c) (S. Warshall, 1962).

- Hierarchical structure
To develop the final hierarchical structure, where each strategy is positioned in different levels based on their dependence on other strategies (i.e., the most influential strategies appear at the bottom of the structure), the reachability and

antecedent set was determined. The reachability set indicates the strategy itself and all other strategies it can influence, while the antecedent set indicates the strategy itself and all strategies that can influence it. The intersection of these sets was calculated, and the strategies having reachability set equal to antecedent set were positioned at the top level of the hierarchical structure. Once the top level was created, the strategies positioned in this level were removed and the same procedure was developed iteratively for the subsequent levels.

iv. MICMAC

Considering SSIM, the MICMAC matrix was developed. Based on driving power and dependence power of each strategy, the output was the classification of the factors into four categories:

- Driver (high impact, low dependence)
- Dependent (low impact, high dependence)
- Linkage (high impact, high dependence)
- Autonomous (low impact, low dependence)

3.2 Case study e numerical examples

To validate the proposed decision-support tools, several case study and/or numerical examples were carried out.

First, the AHP-based framework was tested on a supplier selection problem in automotive sector. Starting from the methodology described above, some relevant factors (of the LARG perspectives) were extrapolated for this specific problem.

Second, the applicability and effectiveness of the proposed fuzzy-based framework was demonstrated, presenting a case study. The tool was applied to a real company scenario to evaluate supply chain performance under LARG perspective.

Finally, the Hybrid fuzzy Delphi-DEMATEL-ANP model was validated through a numerical example focused on supplier selection in the food machinery sector. The numerical example refers to an Italian company founded in 1881, which operates in over 50 countries worldwide as one of the leading manufacturers of innovative equipment and process technologies for the food industry.

4. Results

This section presents the main results of the research activities carried out during the doctoral program.

The analyses and experimental applications are structured according to the methodological development described in Chapter 3, progressively evolving from the conceptual definition of the LARG framework to its operational implementation and extension to sustainability.

Each sub-section corresponds to a specific research result, also associated with scientific articles published during the doctoral period.

The first part (Section 4.1) focuses on the development of the LARG framework, in which supply chain processes were mapped through the four traditional paradigms: Lean, Agile, Resilient, and Green. This phase was the conceptual basis for the construction of a framework of KPIs covering procurement, production, distribution, and reverse logistics (Bottani et al., 2024).

Section 4.2 illustrates the application of the Analytic Hierarchy Process (AHP) to the developed framework, demonstrating its ability to hierarchically evaluate and prioritize the LARG dimensions through a case study in the automotive supply chain (Bottani, Monferdini, et al., 2025).

Section 4.3 presents the fuzzy logic-based decision support tool designed to overcome the limitations of deterministic approaches. The fuzzy system allows for the management of uncertainty and subjective assessments, providing a linguistic interpretation of performance levels in the LARG dimensions and validating its practical applicability in a real industrial case (Monferdini, Casella, et al., 2025).

Based on these results, Section 4.4 introduces the transition from LARG to LARGS, incorporating the sustainability dimension into the model. A hybrid Fuzzy Delphi-DEMATEL-ANP method was implemented to analyze the interdependencies between the criteria and determine their global and local weights (Bottani, Nardo, et al., 2025).

Finally, section 4.5 extends the analysis to a qualitative and industry-specific context. Through ISM and MICMAC analysis, the study identifies the hierarchical relationships between operational strategies for food waste reduction in perishable supply chain, highlighting the fundamental role of initiatives in improving supply chain sustainability (Monferdini, Boza, Alemany, et al., 2025).

4.1 Development of the LARG Framework

21 studies were analyzed to list a set of KPIs related to the four LARG perspectives and develop the initial framework (Bottani et al., 2024).

Table 14 proposes a summary of those studies.

Table 14. List of LARG-related studies.

Perspectives analysed	Source
-----------------------	--------

Lean, Agile, Resilient, Green	(Carvalho et al., 2010) (Carvalho & Cruz-Machado, 2011) (Carvalho, Duarte, et al., 2011) (Azevedo et al., 2011) (Espadinha-Cruz et al., 2012) (Azfar et al., 2014) (Azevedo et al., 2016) (Jamali, Asl, et al., 2017) (Zanjirani et al., 2019) (Al-Refaie et al., 2020) (Divsalar et al., 2022) (Salleh et al., 2020) (Amjad et al., 2021) (Anvari, 2021) (Sahu et al., 2023)
Lean	(So, 2010)
Lean, Green	(Carvalho, Azevedo, et al., 2011) (Azevedo et al., 2012)
Resilient, Green	(Azevedo et al., 2013) (Sen et al., 2018)
Lean, Resilient, Green	(Govindan et al., 2015)

Most of the studies focus on the whole set of LARG dimension, while some other studies have evaluated some perspectives only (e.g., resilient and green, lean and green). Only one study refers to one dimension (i.e., lean).

From the analysis of each article, 71 KPIs were extracted. Table 15 shows the KPIs divided by dimension (lean, agile, resilient, and green), with the relative frequency of occurrence indicating the popularity of each index.

Table 15. List of KPIs from the LARG-related studies and frequency.

Dimension	Key Performance Indicator (KPI)	Weight / Score
Lean	% material loss due to operations	12
	Stock level	12
	Cycle time	11
	Total ordering time	10
	FTL or LTT deliveries	10
	Design hours	9
	Inventory costs	8
	Capacity utilisation	8
	Operational production time	8
	Overall Equipment Effectiveness (OEE)	8
	% marketing cost	8
	Effectiveness by sector	7
	% integrated and motivated employees	7
	% development cost	7
	% hours of training per year	6
	Customer satisfaction	5
	Impact of changeovers on total production hours	5
	Productivity by sector	4
	% profit on sales	4
	% average monthly sales	3
Accuracy of forecasting	2	
Agile	Customer service	14
	Accuracy of delivery / % of delivery errors	12
	Coordination among supply chain members	11
	Timeliness of delivery	10
	Delivery flexibility	9

	Proximity to suppliers and customers	9
	% bottlenecks	7
	Supplier involvement in product development	7
	Timeliness	6
	Frequency of delivery (actual vs. scheduled)	5
	Defect rate	5
	Inventory velocity	4
	Number of nodes in the supply chain	4
	% overtime hours	2
	Inventory turnover rate	2
	PCR testing costs	2
Resilient	Availability of alternative supplies	11
	Stock coverage	10
	Stock service ratio	10
	Mean time between failures	8
	Distribution channel (single / omni / multi)	8
	Maintenance ticket management	8
	Forecast adjustment time	7
	% demand satisfaction	7
	Standardization of components	6
	Product customization	6
	Average downtime	5
	Net promoter score	5
	% lost sales	5
	Mean time to preventive maintenance	4
	Punctuality of payments	4
	% rate of rework or changes	4
	Mean time to repair	3
	Inventory adjustment	3
	Average customer seniority	3
	Range breadth	1
Green	CO ₂ emissions	17
	Energy consumed from fossil and renewable resources	16
	% raw material cost	16
	Electricity consumption	16
	Waste ratio	13
	% waste cost	12
	% smart working	12
	Water consumption per unit produced	9
	% compliant products	8
	Sanitation costs	5
Human equity	2	

Across lean dimension, % material loss due to operation and stock level are the KPIs with the highest occurrence (12), followed by some indicators related to time and deliveries efficiency (i.e., cycle time; total ordering time and FTL/LTT deliveries). The most recurrent indicators encompassed in the agile dimension are related to delivery efficiency and responsiveness: customer service, accuracy of delivery / % of delivery errors, coordination among supply chain members, timeliness of delivery, delivery flexibility, proximity to suppliers and customers. Metrics such as availability of alternative supplies, stock coverage, stock service ratio represents the key KPIs across resilient dimension; followed by mean time between failures. distribution channel (single / omni / multi), maintenance ticket management. Finally, with regard to green dimension, CO₂ emissions, energy consumed from fossil and renewable resources, % raw material cost and electricity consumption are the most studied indicators in the literature reviewed, with 16/17 occurrences.

The indices have been organized into a framework considering typical supply chain processes: (i) procurement; (ii) production; (iii) distribution; and (iv) reverse logistics. Each process was then associated with a set of KPIs (Figure 16 - Figure 19). The rhombuses represent some supporting technologies, while the rectangles indicate best practices for each process.

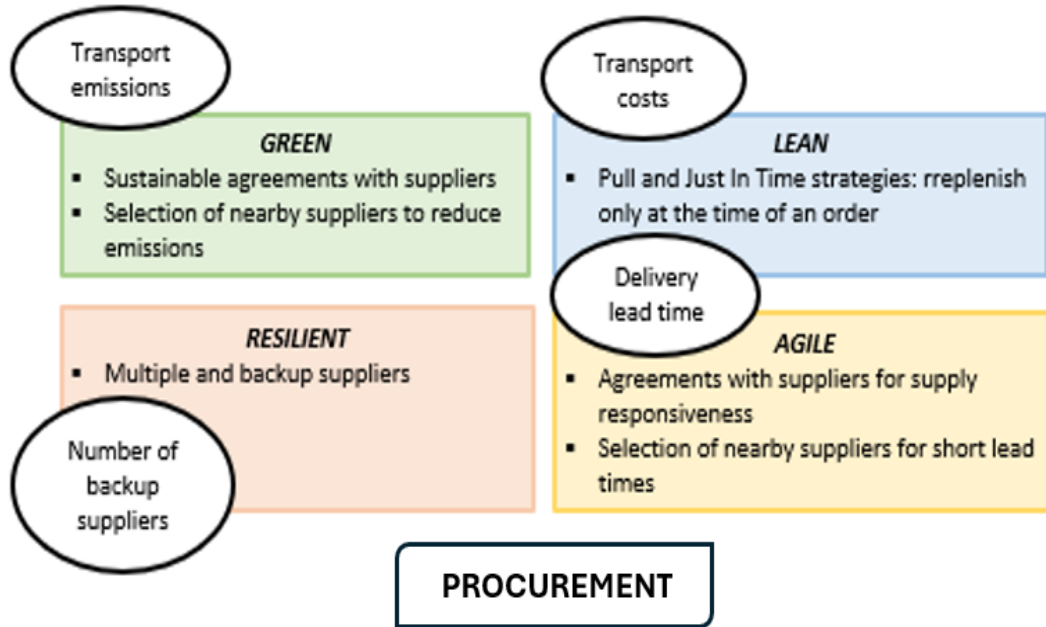


Figure 16. Production phase within the LARG framework

The procurement dimension of the framework highlights how the integration of LARG dimensions can improve supplier management and the overall efficiency of supply processes. Under the lean dimension, procurement is guided by just in time and pull strategies, aimed at minimizing inventory levels and reducing waste associated with overstocking. The main KPIs (e.g., transport costs and delivery lead time) are used to assess economic efficiency and the timeliness of deliveries. The agile dimension emphasizes flexibility and responsiveness to fluctuations in demand. Key practices include establishing adaptive agreements with suppliers and selecting geographically close partners to ensure rapid delivery and minimize disruptions. These practices directly support the KPI delivery lead time, reducing the time between order placement and fulfillment. From a resilience perspective, procurement strategies focus on risk management and mitigation through the creation of multiple and backup suppliers. Finally, the green dimension promotes sustainable procurement through the selection of local or low environmental impact suppliers, reducing transport-related emissions.

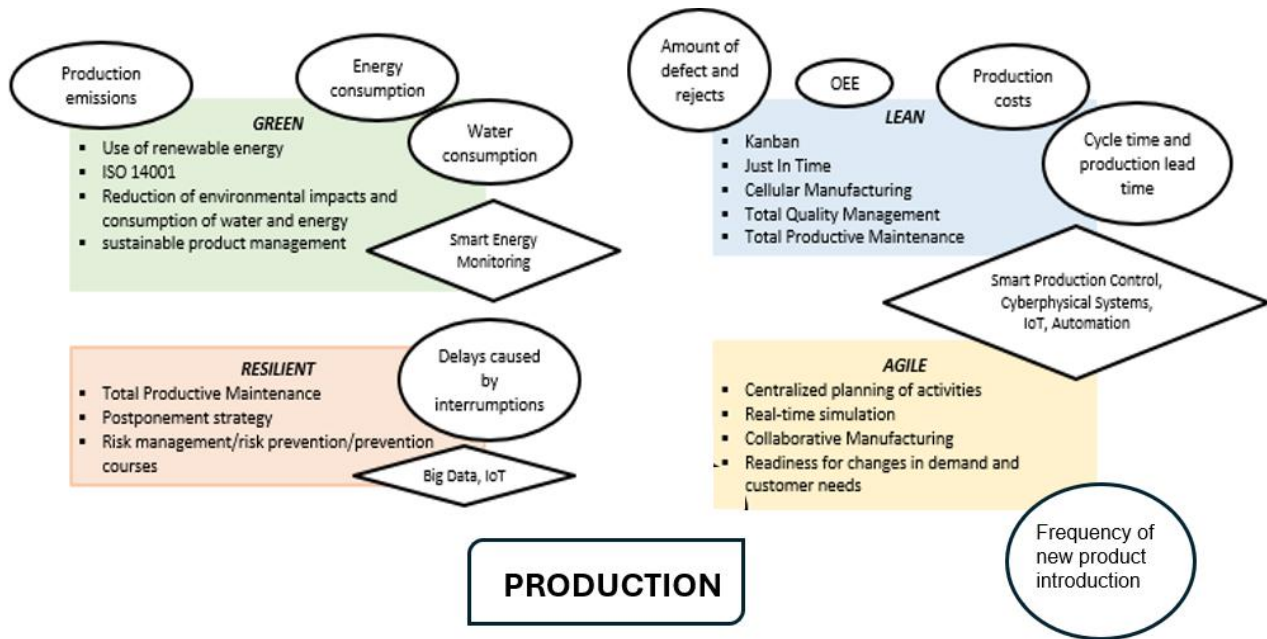


Figure 17. Production phase within the LARG framework.

The production phase represents the operational core of the supply chain, where efficiency, flexibility, resilience and sustainable converge through the LARG dimensions. Within the lean dimension, production focuses on standardizing processes and eliminating waste through practices such as Kanban, Just in Time, cellular manufacturing, total quality management, and total productive maintenance. Associated KPIs (e.g., OEE, production costs, cycle time, and the amount of defects and scrap) measure operational efficiency, cost control, and product quality. The implementation of intelligent production control systems and cyber-physical systems (CPS) enables real-time monitoring and optimization of production processes. The agile perspective complements this approach by emphasizing the importance of adaptability and responsiveness. Practices such as centralized activity planning, real-time simulation, and collaborative production enable dynamic adaptation to fluctuations in demand. The frequency of KPIs related to the introduction of new products reflects the system's capacity for innovation and flexibility in product development, key elements of an agile production environment. In the Resilience dimension, the focus shifts to continuity and recovery from disruptions. Various practices (e.g., total productive maintenance, risk deferral and prevention strategies) strengthen the system's ability to minimize delays caused by disruptions. In this context, certain technologies such as Big Data and the Internet of Things (IoT) are essential and increase the robustness of the production system. Finally, the green perspective integrates sustainability into production processes through the use of renewable energy, ISO 14001 certification, and sustainable product management. Key KPIs (i.e., production emissions, energy consumption, and water consumption) quantify environmental performance, while smart energy monitoring technologies enable continuous control and optimization of resource utilization.

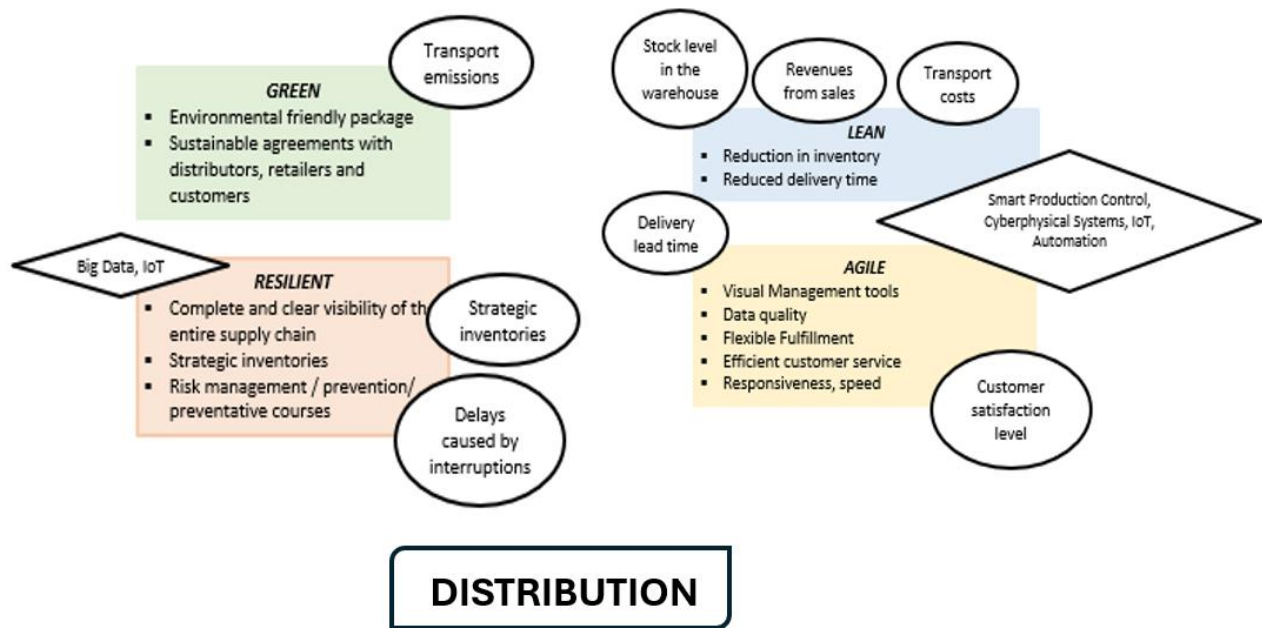


Figure 18. Distribution phase within the LARG framework.

The distribution phase addresses the management of outbound logistics processes, where the integration of the lean, agile, resilient and green dimensions enhances the efficiency, responsiveness and sustainability of delivery and customer service activities. From a lean perspective, distribution aims to minimize waste and inefficiencies along the supply chain through inventory reduction and shorter delivery times. The KPIs included in this dimension (i.e., inventory levels, sales revenue, transportation costs, and delivery times) measure the overall efficiency of distribution processes. Technologies such as intelligent production control and CPS can be used to support real-time monitoring and logistics optimization, enabling more accurate synchronization between production and delivery. Agility focuses on flexibility and responsiveness in order to adapt to customer needs. Monitoring data quality, for example, ensures that logistics operations can quickly adapt to fluctuations in order volumes or disruptions. Good management of agile practices, which improve service quality and responsiveness, increases customer satisfaction. From a resilient perspective, the focus shifts to ensuring the continuity and stability of logistics operations. Delays create inefficiencies, often caused by disruptions. To avoid this, companies must consider using strategic inventories, risk management practices, and complete supply chain visibility. Here too, technologies such as Big Data and IoT help improve risk management, increasing overall service reliability. Finally, the green dimension contributes to environmental sustainability in distribution through the use of eco-friendly packaging and collaboration with sustainable distributors, retailers, and customers. The transport emissions indicator is key in this perspective, as it links distribution efficiency to environmental performance.

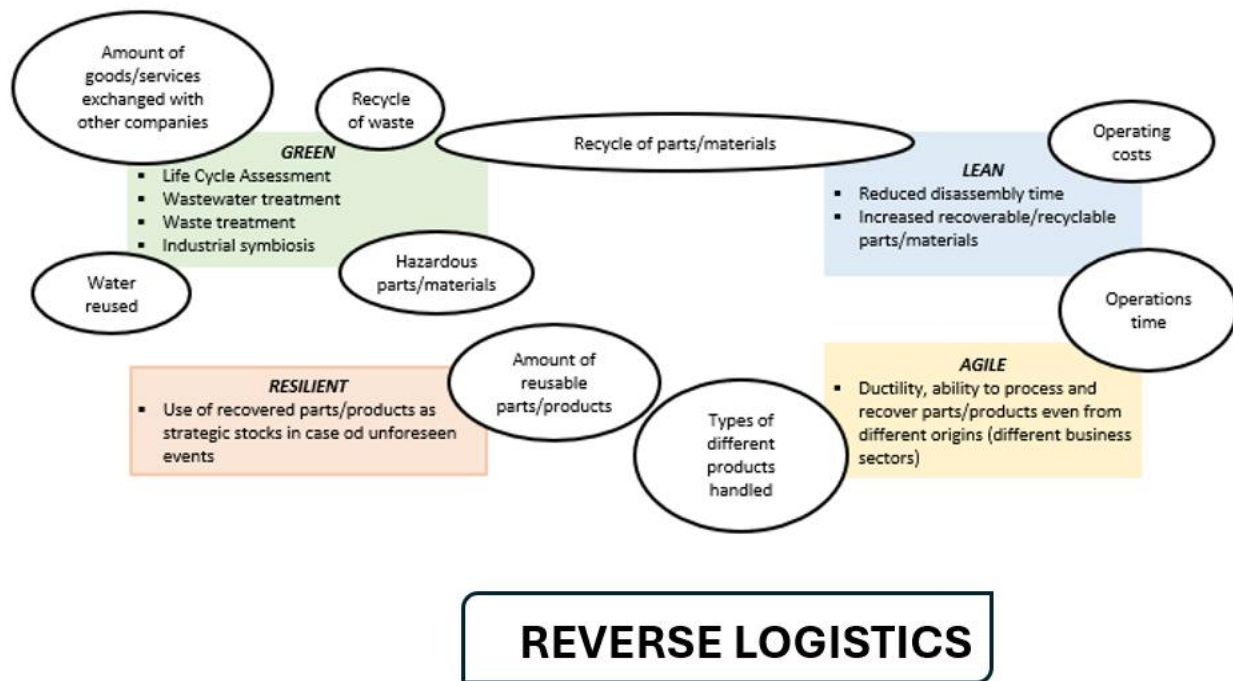


Figure 19. Reverse logistics phase within the LARG framework.

Reverse logistics phase closes the supply chain loop by focusing on the recovery, recycling and reintegration of products and materials into the production system. Within the lean dimension, reverse logistics aims to minimize inefficiencies and operational costs related to material recovery. Practices such as reduced disassembly time and increased recoverable or recyclable parts and materials focus on waste reduction and value retention. Key KPIs (i.e., operating costs, operating times, and recycling of parts/materials) reflect the focus on minimal resource consumption and maximum cost efficiency. Agility improves the flexibility of reverse logistics operations by promoting adaptability and the ability to process and recover parts/products from different sectors. This adaptability is essential when returned products vary greatly in type, condition, and origin. KPIs related to the different products handled and the quantity of reusable parts/products indicate the responsiveness of the system and its ability to adapt. From a resilience perspective, the focus is on maintaining business continuity in uncertain conditions. The use of recovered parts/products enables companies to mitigate disruptions and ensure supply during unforeseen events. The green dimension integrates circular and environmental economy principles into reverse logistics. Practices such as life cycle assessment (LCA), wastewater and waste treatment, and industrial symbiosis aim to reduce environmental impact and maximize material recovery. Related KPIs (e.g., waste recycling, water reuse, hazardous parts/materials, and quantity of goods/services exchanged with other companies) measure the effectiveness of sustainable practices.

Figure 20 shows the overall structure of the LARG framework, illustrating the interconnections between processes and the integration of the four paradigms along the supply chain.

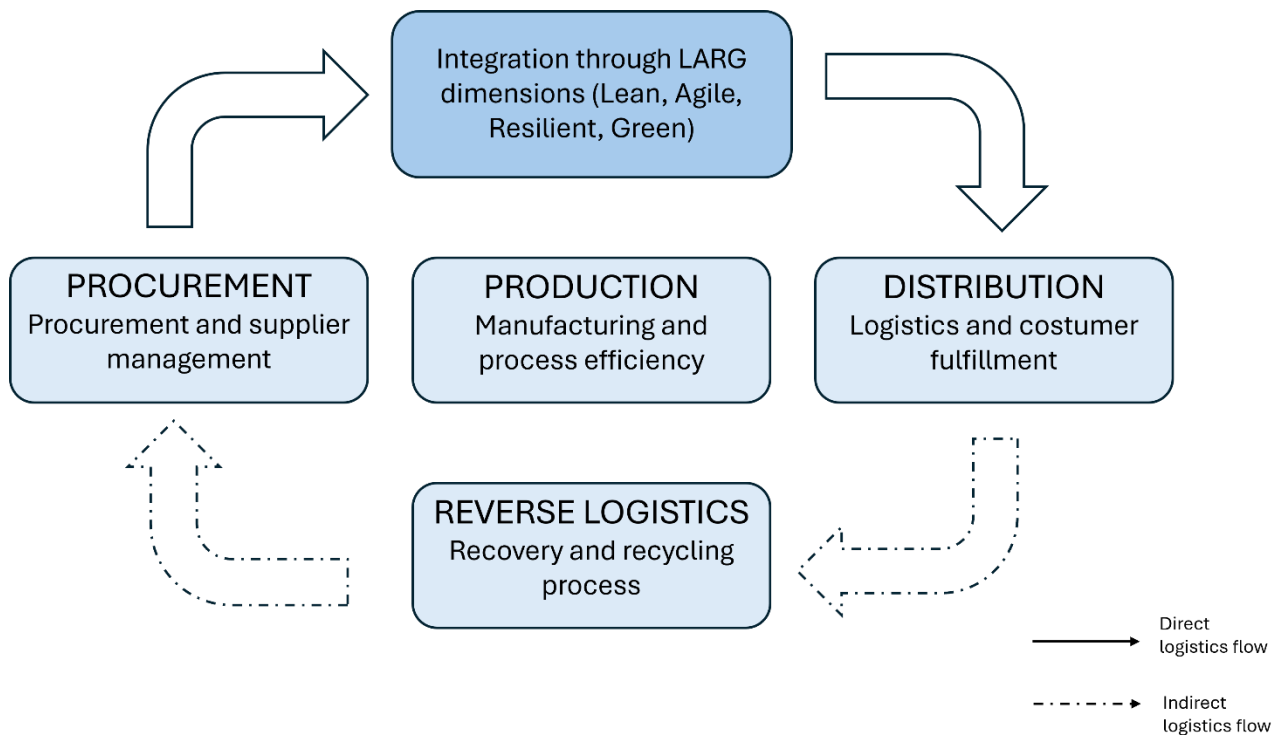


Figure 20. Scheme of the LARG framework

4.2 LARG – AHP model and case study application

Building on the framework developed in section 4.1, the Analytic Hierarchy Process was applied to quantify the relative importance of the four LARG perspectives and their associated performance indicators (Bottani, Monferdini, et al., 2025). The KPIs identified in the literature (Table 15, section 4.1) were reorganized into a hierarchical structure suitable for AHP analysis.

Each KPI was coded (e.g., L1-L22, A1-A16, R1-R22, G1-G11) and grouped under its corresponding LARG dimension. This codification, summarized in Table 16, allowed for the construction of pairwise comparison matrices and the computational of local and global weights.

Table 16. Operational representation of KPIs as AHP sub-criteria.

Lean		
KPIs	Sub-criteria	Frequency
% average monthly sales	L1	3
Customer satisfaction	L2	5
% material loss due to operations (transfer to other containers)	L3	12
Effectiveness	L4	7
Productivity	L5	4
Accuracy of forecasting	L6	2
% integrated and motivated employee	L7	7
% hours of training per year	L8	6
Inventory costs	L9	8
Perception of employees through internal research	L10	12
Stock level	L11	12
Capacity utilisation	L12	8
Operational production time	L13	8
Impact of changeovers of total production hours	L14	5

Overall Equipment Effectiveness	L15	8
Design hours	L16	9
Cycle time	L17	11
% development cost	L18	7
Total ordering time	L19	10
% marketing cost	L20	8
Full Truckload (FTL) or Less Than Truckloads (LTL) deliveries	L21	10
% profit on sales	L22	4
Agile		
KPIs	Sub-criteria	Frequency
% overtime hours	A1	2
Customer service	A2	14
Accuracy of delivery or % of delivery errors	A3	12
Inventory turnover rate	A4	2
PCR testing costs	A5	2
Proximity to suppliers and customers	A6	9
Timeliness of delivery	A7	10
Inventory velocity	A8	4
Frequency of delivery (N° actual deliveries/N° scheduled deliveries)	A9	5
Number of nodes in the SC	A10	4
Coordination among supply chain members	A11	11
Delivery flexibility	A12	9
Defect rate	A13	5
% bottlenecks	A14	7
Supplier involvement in product development	A15	7
Timeliness	A16	6
Resilient		
KPIs	Sub-criteria	Frequency
Mean time between failures	R1	8
Stock coverage	R2	10
Mean time to repair	R3	3
Mean time to preventive maintenance	R4	4
Average downtime time	R5	5
Inventory adjustment	R6	3
Forecast adjustment time	R7	7
Range breadth	R8	1
Distribution channel single/omni/multi channel	R9	8
Punctuality of payments	R10	4
% rate of rework or changes	R11	4
Standardization of components	R12	6
Product customization	R13	6
Average customer seniority	R14	3
Net promoter score	R15	5
Maintenance ticket management	R16	8
% breakdown of buyer lead time and vendor lead time	R17	4
Stock service ratio	R18	10
Availability of alternative supplies	R19	11
% demand satisfaction	R20	7
% lost sale	R21	5
Customer retention rate (CRR)	R22	4
Green		
KPIs	Sub-criteria	Frequency
Water consumption per unit produced	G1	9
Human equity	G2	2
Energy consumed from fossil and renewable resources	G3	16
Sanitation costs	G4	5
Waste ratio	G5	13
% waste cost	G6	12
% raw material cost	G7	16
% smart working	G8	12
% compliant products	G9	8

Electricity consumption	G10	16
CO ₂ emission	G11	17

While Table 15 in the previous section listed KPIs according to their frequency of occurrence in the literature, Table 16 provides their operational representation as AHP sub-criteria, maintaining conceptual coherence with the original framework. While agile and green dimension maintain almost identical indicators, a new KPI (i.e., perception of employees through internal research) was introduced across lean dimension and assigned a high frequency (12). This addition reflects the growing recognition in recent literature that lean performance is not solely determined by process efficiency but also by human and cultural factors. In addition to the previous KPI “% of motivated and integrated employees”, this indicator highlights the employees’ qualitative perception of process effectiveness, communication and engagement within lean initiatives. Two additional indicators were included in the resilient dimension of the AHP model compared with the initial framework (i.e., “% breakdown of buyer lead time and vendor lead time” and “the customer retention rate (CRR)”). The first indicator provides a time-based view of resilience, decomposing total total lead time into internal (buyer) and external (vendor) components. This allows the most vulnerable stages of the supply process to be identified and reflects companies’ ability to prevent disruptions rather than simply recover from them. The second indicator, CRR, emphasizes a supply chain’s ability to maintain customer relationships and trust despite operational disruptions.

To build the pairwise comparison matrices, the difference between the frequencies of two KPIs ($f_i - f_j$) was used to assign the relative importance value (a_{ij}) according to an adapted Saaty’s fundamental scale (Saaty, 2002), as shown in Table 17.

Table 17. Summary of relative importance between KPIs and their corresponding values based on frequencies’ difference.

$f_i - f_j$	Relative importance of i compared to j	a_{ij}
0,1-1	Same importance	1
2	Slightly more important	2
3	Moderately more important	3
4	Moderately plus more important	4
5	Strongly more important	5
6	Strongly plus more important	6
7	Much more important	7
8	Much plus more important	8
≥9	Extremely more important	9
-2	Slightly less important	1/2
-3	Moderately less important	1/3
-4	Moderately plus less important	1/4
-5	Strongly less important	1/5
-6	Strongly plus less important	1/6
-7	Much less important	1/7
-8	Much plus less important	1/8
≤-9	Extremely less important	1/9

Figure 21 - Figure 24 show the pairwise comparison matrix for the sub-criteria for each dimension.

	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20	L21	L22
L1	1	1/2	1/9	1/4	1	1	1/4	1/3	1/5	1/9	1/9	1/5	1/5	1/2	1/5	1/6	1/8	1/4	1/7	1/5	1/7	1
L2	2	1	1/7	1/2	1	3	1/2	1	1/3	1/7	1/7	1/3	1/3	1	1/3	1/4	1/6	1/2	1/5	1/3	1/5	1
L3	9	7	1	5	8	9	5	6	4	1	1	4	4	7	4	3	1	5	2	4	2	8
L4	4	2	1/5	1	3	5	1	1	1	1/5	1/5	1	1	2	1	1/2	1/4	1	1/3	1	1/3	3
L5	1	1	1/8	1/3	1	2	1/3	1/2	1/4	1/8	1/8	1/4	1/4	1	1/4	1/5	1/7	1/3	1/6	1/4	1/6	1
L6	1	1/3	1/9	1/5	1/2	1	1/5	1/4	1/6	1/9	1/9	1/6	1/6	1/3	1/6	1/7	1/9	1/5	1/8	1/6	1/8	1/2
L7	4	2	1/5	1	3	5	1	1	1	1/5	1/5	1	1	3	1	1/2	1/4	1	1/3	1	1/3	3
L8	3	1	1/6	1	2	4	1	1	1/2	1/6	1/6	1/2	1/2	1	1/2	1/3	1/5	1	1/4	1/2	1/4	2
L9	5	3	1/4	1	4	6	1	2	1	1/4	1/4	1	1	3	1	1	1/3	1	1/2	1	1/2	4
L10	9	7	1	5	8	9	5	6	4	1	1	4	4	7	4	3	1	5	2	4	2	8
L11	9	7	1	5	8	9	5	6	4	1	1	4	4	7	4	3	1	5	2	4	2	8
L12	5	3	1/4	1	4	6	1	2	1	1/4	1/4	1	1	3	1	1	1/3	1	1/2	1	1/2	4
L13	5	3	1/4	1	4	6	1	2	1	1/4	1/4	1	1	3	1	1	1/3	1	1/2	1	1/2	4
L14	2	1	1/7	1/2	1	3	1/3	1	1/3	1/7	1/7	1/3	1/3	1	1/3	1/4	1/6	1/2	1/5	1/3	1/5	1
L15	5	3	1/4	1	4	6	1	2	1	1/4	1/4	1	1	3	1	1	1/3	1	1/2	1	1/2	4
L16	6	4	1/3	2	5	7	2	3	1	1/3	1/3	1	1	4	1	1	1/2	2	1	1	1	5
L17	8	6	1	4	7	9	4	5	3	1	1	3	3	6	3	2	1	4	1	3	1	7
L18	4	2	1/5	1	3	5	1	1	1	1/5	1/5	1	1	2	1	1/2	1/4	1	1/3	1	1/3	3
L19	7	5	1/2	3	6	8	3	4	2	1/2	1/2	2	2	5	2	1	1	3	1	2	1	6
L20	5	3	1/4	1	4	6	1	2	1	1/4	1/4	1	1	3	1	1	1/3	1	1/2	1	1/2	4
L21	7	5	1/2	3	6	8	3	4	2	1/2	1/2	2	2	5	2	1	1	3	1	2	1	6
L22	1	1	1/8	1/3	1	2	1/3	1/2	1/4	1/8	1/8	1/4	1/4	1	1/4	1/5	1/7	1/3	1/6	1/4	1/6	1

Figure 21. Pairwise comparison matrix (lean dimension).

	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16
A1	1	1/9	1/9	1	1	1/7	1/8	1/2	1/3	1/2	1/9	1/7	1/3	1/5	1/5	1/4
A2	9	1	2	9	9	5	4	9	9	9	3	5	9	7	7	8
A3	9	1/2	1	9	9	3	2	8	7	8	1	3	7	5	5	6
A4	1	1/9	1/9	1	1	1/7	1/8	1/2	1/3	1/2	1/9	1/7	1/3	1/5	1/5	1/4
A5	1	1/9	1/9	1	1	1/7	1/8	1/2	1/3	1/2	1/9	1/7	1/3	1/5	1/5	1/4
A6	7	1/5	1/3	7	7	1	1	5	4	5	1/2	1	4	2	2	3
A7	8	1/4	1/2	8	8	1	1	6	5	6	1	1	5	3	3	4
A8	2	1/9	1/8	2	2	1/5	1/6	1	1	1	1/7	1/5	1	1/3	1/3	1/2
A9	3	1/9	1/7	3	3	1/4	1/5	1	1	1	1/6	1/4	1	1/2	1/2	1
A10	2	1/9	1/8	2	2	1/5	1/6	1	1	1	1/7	1/5	1	1/3	1/3	1/2
A11	9	1/3	1	9	9	2	1	7	6	7	1	2	6	4	4	5
A12	7	1/5	1/3	7	7	1	1	5	4	5	1/2	1	4	2	2	3
A13	3	1/9	1/7	3	3	1/4	1/5	1	1	1	1/6	1/4	1	1/2	1/2	1
A14	5	1/7	1/5	5	5	1/2	1/3	3	2	3	1/4	1/2	2	1	1	1
A15	5	1/7	1/5	5	5	1/2	1/3	3	2	3	1/4	1/2	2	1	1	1
A16	4	1/8	1/6	4	4	1/3	1/4	2	1	2	1/5	1/3	1	1	1	1

Figure 22. Pairwise comparison matrix (agile dimension).

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22
R1	1	1/2	5	4	3	5	1	7	1	4	4	2	2	5	3	1	4	1/2	1/3	1	3	4
R2	2	1	7	6	5	7	3	9	2	6	6	4	4	7	5	2	6	1	1	3	5	6
R3	1/5	1/7	1	1	1/2	1	1/4	2	1/5	1	1	1/3	1/3	1	1/2	1/5	1	1/7	1/8	1/4	1/2	1
R4	1/4	1/6	1	1	1	1	1/3	3	1/4	1	1	1/2	1/2	1	1	1/4	1	1/6	1/7	1/3	1	1
R5	1/3	1/5	2	1	1	2	1/2	4	1/3	1	1	1	1	2	1	1/3	1	1/5	1/6	1/2	1	1
R6	1/5	1/7	1	1	1/2	1	1/4	2	1/5	1	1	1/3	1/3	1	1/2	1/5	1	1/7	1/8	1/4	1/2	1
R7	1	1/3	4	3	2	4	1	6	1	3	3	1	1	4	2	1	3	1/3	1/4	1	1/2	1/3
R8	1/7	1/9	1/2	1/3	1/4	1/2	1/6	1	1/7	1/3	1/3	1/5	1/5	1/2	1/4	1/7	1/3	1/9	1/9	1/6	1/4	1/3
R9	1	1/2	5	4	3	5	1	7	1	4	4	2	2	5	3	1	4	1/2	1/3	1	1/2	4
R10	1/4	1/6	1	1	1	1	1/3	3	1/4	1	1	1/2	1/2	1	1	1/4	1	1/6	1/7	1/3	1	1
R11	1/4	1/6	1	1	1	1	1/3	3	1/4	1	1	1/2	1/2	1	1	1/4	1	1/6	1/7	1/3	1	1
R12	1/2	1/4	3	2	1	3	1	5	1/2	2	2	1	1	3	1	1/2	2	1/4	1/5	1	1	2
R13	1/2	1/4	3	2	1	3	1	5	1/2	2	2	1	1	3	1	1/2	2	1/4	1/5	1	1	2
R14	1/5	1/7	1	1	1/2	1	1/4	2	1/5	1	1	1/3	1/3	1	1/2	1/5	1	1/7	1/8	1/4	1/2	1
R15	1/3	1/5	2	1	1	2	1/2	4	1/3	1	1	1	1	2	1	1/3	1	1/5	1/6	1/2	1	1
R16	1	1/2	5	4	3	5	1	7	1	4	4	2	2	5	3	1	4	1/2	1/3	1	1/2	1/4
R17	1/4	1/6	1	1	1	1	1/3	3	1/4	1	1	1/2	1/2	1	1	1/4	1	1/6	1/7	1/3	1	1
R18	2	1	7	6	5	7	3	9	2	6	6	4	4	7	5	2	6	1	1	3	5	6
R19	3	1	8	7	6	8	4	9	3	7	7	5	5	8	6	3	7	1	1	4	6	7
R20	1	1/3	4	3	2	4	1	6	1	3	3	1	1	4	2	1	3	1/3	1/4	1	2	3
R21	1/3	1/5	2	1	1	2	2	4	2	1	1	1	1	2	1	2	1	1/5	1/6	1/2	1	1
R22	1/4	1/6	1	1	1	1	3	3	1/4	1	1	1/2	1/2	1	1	4	1	1/6	1/7	1/3	1	1

Figure 23. Pairwise comparison matrix (resilient dimension) source:.

	G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11
G1	1	7	1/7	4	1/4	1/3	1/7	1/3	1	1/7	1/8
G2	1/7	1	1/9	1/3	1/9	1/9	1/9	1/9	1/6	1/9	1/9
G3	7	9	1	9	3	4	1	4	8	1	1
G4	1/4	3	1/9	1	1/8	1/7	1/9	1/7	1/3	1/9	1/9
G5	4	9	1/3	8	1	1	1/3	1	5	1/3	1/4
G6	3	9	1/4	7	1	1	1/4	1	4	1/4	1/5
G7	7	9	1	9	3	4	1	4	8	1	1
G8	3	9	1/4	7	1	1	1/4	1	4	1/4	1/5
G9	1	6	1/8	3	1/5	1/4	1/8	1/4	1	1/8	1/9
G10	7	9	1	9	3	4	1	4	8	1	1
G11	8	9	1	9	4	5	1	5	9	1	1

Figure 24. Pairwise comparison matrix (green dimension).

The consistency of each comparison matrix was verified through the Consistency Index and Consistency Ratio, which remained within acceptable thresholds ($CR \leq 0.1$).

To test the applicability of the proposed model, the LARG-AHP was applied to a supplier selection problem in the automotive industry, adapting the general structure to the context described by (Ghazvinian et al., 2024). From the 71 KPIs, a subset relevant to supplier

evaluation was extracted, covering key aspects such as cost, flexibility, risk management, and environmental performance (Table 18).

Table 18. Sub-criteria for the evaluation of supplier from a LARG perspective.

Sub-criteria from (Ghazvinian et al., 2024)	KPIs
Price	% profit on sales (L1)
	Design hours (L2)
Lead time	Cycle time (L3)
	FTL o LTL deliveries (L4)
Defect reduction	Effectiveness by sector (L5)
	Operational production time (L6)
JIT practices	% marketing cost (L7)
	Stock level (L8)
Collaboration with supply chain	% material loss due to operations (L9)
Innovation capability	Number of nodes in the SC (A1)
	Customer service (A2)
Response speed	Accuracy of delivery or % of delivery errors (A3)
	Proximity to supplier and customers (A4)
	Timeliness of deliveries (A5)
Dynamic alliance	Supplier involvement in product development (A6)
	Coordination among supply chain members (A7)
Flexibility	Delivery flexibility (A8)
Capacity for dealing with unexpected disruption	Stock Service Ratio (R1)
	Availability of alternative supplies (R2)
Strategy capacity and inventory buffer	Mean time between failures (R3)
	Stock coverage (R4)
SC risk management culture	Forecast adjustment time (R5)
Capacity for mass customization	Product customization (R6)
Green innovation	Water consumption per unit produced (G1)
Green product	Waste Ratio (G2)
	% raw material cost (G3)
Environment management system	Sanitation costs (G4)
	Electricity consumption (G5)
Renewable energy/initiative	CO2 emission (G6)
	Energy consumed from fossil and renewable resources (G7)
Waste recycling	% smart working (G8)
Environmental competency	Human equity (G9)

The resulting hierarchical structure of the model is shown in Figure 25, where the four LARG dimensions form the main evaluation criteria, and the KPIs act as measurable sub-criteria.

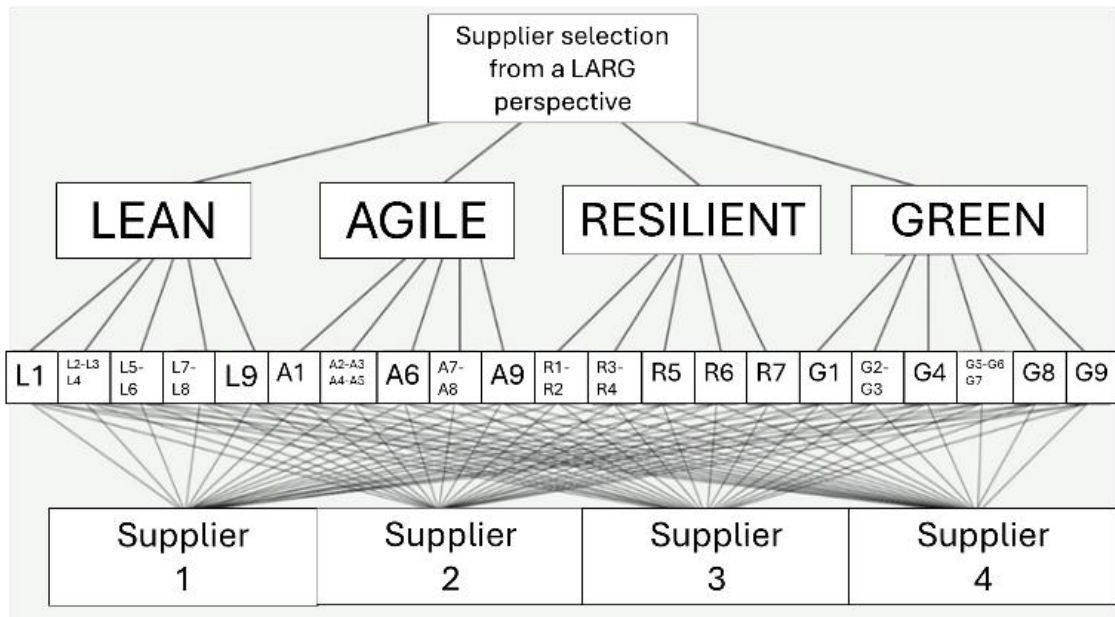


Figure 25. Hierarchical structure of the supplier selection model (source:(Bottani, Monferdini, et al., 2025)).

The pairwise comparison matrices were then adapted for this specific case (Figure 26 - Figure 29).

	L1	L2	L3	L4	L5	L6	L7	L8	L9
L1	1	1/5	1/7	1/6	1	1/4	1/4	1/8	1/8
L2	5	1	1/2	1	2	1	1	1/3	1/3
L3	7	2	1	1	4	3	3	1	1
L4	6	1	1	1	3	2	2	1/2	1/2
L5	1	1/2	1/4	1/3	1	1	1	1/5	1/5
L6	4	1	1/3	1/2	1	1	1	1/4	1/4
L7	4	1	1/3	1/2	1	1	1	1/4	1/4
L8	8	3	1	2	5	4	4	1	1
L9	8	3	1	2	5	4	4	1	1

Figure 26. Pairwise comparison matrices of lean sub-criteria for supplier selection.

	A1	A2	A3	A4	A5	A6	A7	A8
A1	1	1/9	1/8	1/5	1/6	1/3	1/7	1/5
A2	9	1	2	5	4	7	3	5
A3	8	1/2	1	3	2	5	1	3
A4	5	1/5	1/3	1	1	2	1/2	1
A5	6	1/4	1/2	1	1	3	1	1
A6	3	1/7	1/5	1/2	1/3	1	1/4	1/2
A7	7	1/3	1	2	1	4	1	2
A8	5	1/5	1/3	1	1	2	1/2	1

Figure 27. Pairwise comparison matrices of agile sub-criteria for supplier selection.

	R1	R2	R3	R4	R5	R6
R1	1	1	2	1	3	4
R2	1	1	3	1	4	5
R3	1/2	1/3	1	1/2	1	2
R4	1	1	2	1	3	4
R5	1/3	1/4	1	1/3	1	1
R6	1/4	1/5	1/2	1/4	1	1

Figure 28. Pairwise comparison matrices of resilient sub-criteria for supplier selection.

	G1	G2	G3	G4	G5	G6	G7	G8	G9
G1	1	1/4	1/7	4	1/7	1/8	1/7	1/3	7
G2	4	1	1/3	8	1/3	1/4	1/3	1	9
G3	7	3	1	9	1	1	1	4	9
G4	1/4	1/8	1/9	1	1/9	1/9	1/9	1/7	3
G5	7	3	1	9	1	1	1	4	9
G6	8	4	1	9	1	1	1	5	9
G7	7	3	1	9	1	1	1	4	9
G8	3	1	1/4	7	1/4	1/5	1/4	1	9
G9	1/7	1/9	1/9	1/3	1/9	1/9	1/9	1/9	1

Figure 29. Pairwise comparison matrices of green sub-criteria for supplier selection.

For suppliers (S1-S4) were evaluated by four decision-makers with over ten years of experience in supply chain management, procurement and logistics. Each DM provided linguistic judgments (e.g., very low, medium, high, very high) that were converted into numerical values on a 1-10 scale.

Table 19. Judgments expressed by the decision-makers for lean sub-criteria (Ghazvinian et al., 2024).

KPI	Supplier	DM1	DM2	DM3	DM4
Price	S1	10	7	6	7
	S2	7	7	8	6
	S3	8	7	6	6
	S4	8	9	10	8
Lead time	S1	5	6	4	5
	S2	3	5	5	6
	S3	6	7	5	7
	S4	8	8	7	6
Defect reduction	S1	4	3	7	4
	S2	3	2	3	3
	S3	5	5	4	5
	S4	3	1	2	3
JIT practices	S1	9	9	7	9
	S2	10	9	10	7
	S3	7	5	6	7
	S4	5	6	7	5
Collaboration with SC	S1	10	8	9	10
	S2	7	7	8	6
	S3	6	6	8	8
	S4	9	7	9	8
Innovation ability	S1	5	7	7	6
	S2	8	9	7	9
	S3	3	4	3	5
	S4	4	3	5	1
Response speed	S1	8	8	7	7
	S2	5	6	7	5
	S3	7	8	7	7
	S4	7	7	8	7

Dynamic alliance	S1	5	6	3	2
	S2	8	7	8	6
	S3	5	8	8	6
	S4	9	7	9	8
Capacity for new product lines	S1	8	7	6	6
	S2	10	9	7	8
	S3	6	4	4	4
	S4	5	6	5	1
Flexibility	S1	7	4	5	4
	S2	2	2	4	3
	S3	4	5	4	5
	S4	5	4	2	4
Capacity for dealing with unexpected disruption	S1	10	9	7	7
	S2	4	4	3	3
	S3	7	6	5	7
	S4	7	10	8	8
Flexible transportation	S1	5	4	5	3
	S2	8	7	7	8
	S3	3	2	4	3
	S4	5	5	6	6
Strategic capacity and inventory buffer	S1	5	5	6	6
	S2	7	8	8	6
	S3	3	2	4	5
	S4	7	7	9	8
SC risk management culture	S1	7	8	7	6
	S2	5	4	7	6
	S3	3	4	5	4
	S4	7	9	7	7
Capacity for mass customization	S1	3	3	4	6
	S2	2	2	4	3
	S3	4	4	4	5
	S4	7	4	5	5
Green innovation	S1	6	5	5	4
	S2	3	5	5	3
	S3	6	4	4	7
	S4	8	10	7	6
Green product	S1	8	7	7	7
	S2	6	7	6	5
	S3	4	4	3	4
	S4	7	8	8	6
Environment management system	S1	7	8	6	7
	S2	4	6	6	5
	S3	6	4	5	5
	S4	9	7	7	6
Renewable energy/initiatives	S1	8	7	7	8
	S2	8	6	6	7
	S3	5	4	3	4
	S4	9	10	10	9
Waste recycling	S1	3	2	3	4
	S2	4	5	5	4
	S3	6	6	5	7
	S4	6	7	6	6
Environmental competency	S1	7	8	6	6
	S2	7	4	6	5
	S3	3	4	3	5
	S4	8	8	7	8

Pairwise comparison matrices were then constructed for each KPI, and local and global priorities were computed using the eigenvalue method.

The ranking of suppliers obtained for each perspective is summarized in Table 20.

Table 20. Ranking of suppliers by the four criteria.

Perspective	S1	S2	S3	S4
Lean	0.279	0.226	0.194	0.301
Agile	0.3248	0.1136	0.2846	0.2770
Resilient	0.2954	0.1466	0.1058	0.4521
Green	0.2555	0.1424	0.0767	0.5254

The results indicate the following rankings for each criterion:

- Lean: Supplier 4 ranks first, followed by S1, S2, and S3.
- Agile: Supplier 1 ranks first, followed by S3, S4, and S2.
- Resilient: Supplier 4 leads, followed by S1, S2, and S3.
- Green: Supplier 4 ranks highest, followed by S1, S2, and S3.

Integrating the scores across the four criteria (weighted equally at 25%), the overall performance ranking identifies supplier 4 as the best alternative, followed by S1, S3 and S2 (Table 21).

Table 21. Final suppliers ranking for LARG paradigm.

Supplier	S1	S2	S3	S4
Sum	0,2885	0,1573	0,1654	0,3889

Compared to traditional AHP models that depend exclusively on expert opinion, the proposed methodology enhances objectivity and transferability, weighting KPIs based on their citation frequency in literature.

However, the study identifies some limitations:

- As KPIs (and therefore criteria and sub-criteria) increase, pairwise comparison matrices become more complex.
- Some qualitative factors (such as sustainability) remain difficult to quantify through the assignment of quantitative evaluation scores.

These considerations motivate the methodological transition, developed in section 4.3, toward fuzzy logic-based decision support, which enables managing uncertainty and linguistic evaluations more effectively.

4.3 Development of a Fuzzy Logic-Based Tool for Evaluating LARG supply chains

Building on the results of the previous sections, the proposed fuzzy system was structured to evaluate the performance of supply chain processes across the four key areas: procurement, production, distribution and reverse logistics. The fuzzy-based system was applied to a real-context to evaluate its performance under the four LARG perspectives (Monferdini, Casella, et al., 2025). For each dimension (lean, agile, resilient and green), company's value, unit of measurement, benchmark and final score of KPIs were listed and calculated Table 22.

Table 22. Company's value, unit of measurement, benchmark and final score for KPIs.

	KPI Indicator	Company's Value	Unit of Measure	Benchmark Type	Benchmark Value	Final Score
	Quantity of non-compliant supplies	3	%	Lower is better	—	3%
	Inventory level (raw materials)	30,000.00	units	Best competitor	50,000.00	60%
	Inventory cost	300,000.00	euro	Lower is better	—	#####
	Productivity	200	pcs/hour	Best competitor	250	80%
	Production capacity utilization	87	%	Higher is better	—	87%
	Overall equipment effectiveness (OEE)	80	%	Higher is better	—	80%
	Set-up change impact on total production hours	15	%	Lower is better	—	15%
	Operating production time	2.5	hours	Lower is better	—	2.5
	Cycle time	4	hours	Best competitor	3	133.33%
	Design time	5	months	Best competitor	3.5	142.86%
	Development costs	250,000.00	euro	Lower is better	—	#####
	Inventory level (consumables and semi-finished goods)	20,000.00	units	Best competitor	25,000.00	80%
	Rework and defect cost	15,000.00	euro	Lower is better	—	15,000.00
Lean	Material loss due to operations (e.g., transfer to other containers)	1	%	Lower is better	—	1%
	Full truckload (FTL) deliveries vs. less-than-truckload (LTT)	85	%	Higher is better	—	85%
	Total order fulfillment time	4	days	Lower is better	—	4
	Marketing cost	50,000.00	euro	Lower is better	—	50,000.00
	Average monthly sales	250	absolute number	Higher is better	—	250
	Sales effectiveness	92	%	Higher is better	—	92%
	Profit margin on sales	25	%	Higher is better	—	25%
	Inventory level (finished products)	15,000.00	units	Best competitor	15,000.00	100%
	Customer satisfaction	86	%	Higher is better	—	86%
	Annual training hours per employee	40	hours	Average training hours in Italy	40	100%
	Employee perception of work environment	87	%	Higher is better	—	87%
	Proximity to suppliers	30	Km	Best competitor	15	200%
	Number of nodes in the supply chain	15	absolute number	Best competitor	20	75%
Agile	Supplier flexibility	75	%	Higher is better	—	75%
	Supplier response time (supplier lead time)	2	Hours	Lower is better	—	2
	Supplier involvement in product development	40	%	Best competitor	45	88.89%
	Production mix flexibility	77	%	Best competitor	85	90.59%
	Total production time	4	Hours	Best competitor	2.5	160%

	Overtime hours	2	Hours	Best competitor	1	200%
	Quantity of defective products	2	%	Lower is better	—	2%
	Number of bottlenecks	1	absolute number	Lower is better	—	1
	Delivery error rate	5	%	Lower is better	—	5%
	Delivery frequency (No. of actual deliveries / No. of scheduled deliveries)	95	%	Best competitor	97	97.94%
	Delivery punctuality	90	%	Higher is better	—	90%
	Delivery flexibility	80	%	Higher is better	—	80%
	Timeliness	87	%	Higher is better	—	87%
	Speed of inventory turnover to sales	23	Days	Best competitor	10	230%
	Inventory turnover ratio	4	absolute number	Best competitor	6	66.67%
	Problem resolution time after service request	1.5	Days	Lower is better	—	1.5
	Customer service rating	8.5	absolute number	Best competitor	9	94.44%
	Flexibility defined as the ability to process and recover parts/products from various sources (Return flexibility)	75	%	Best competitor	82	91.46%
	Response time to return request	3	Hours	Lower is better	—	3
	Supplier lead time	15	Days	Best competitor	10	150%
	Supplier flexibility	83	%	Higher is better	—	83%
	Availability of alternative supplies	85	%	Higher is better	—	85%
	Inventory adjustment time	13	Days	Best competitor	8	162.50%
	Average time for preventive maintenance	4	Hours	Lower is better	—	4
	Mean time between failures (MTBF)	2	Months	Lower is better	—	2
	Mean time to repair (MTTR)	2.5	Hours	Lower is better	—	2.5
Resilient	Average downtime	2.7	Hours	Lower is better	—	2.7
	Percentage of reworked or modified products	2	%	Lower is better	—	2%
	Component standardization percentage	70	%	Best competitor	55	127.27%
	Product customization	30	%	Best competitor	45	66.67%
	Product range breadth	100	absolute number	Best competitor	150	66.67%
	Distribution channel resilience	93	%	Higher is better	—	93%
	Demand satisfaction	97	%	Higher is better	—	97%
	Cost of raw materials	65,000	Euro	Lower is better	—	65,000
Green	Use of renewable materials	70	%	Higher is better	—	70.00%
	Suppliers with environmental certifications	40	%	Best competitor	42	95.24%
	Water consumption	95,000	Cubic meters per year	Lower is better	—	95,000

Energy consumed produced from fossil and renewable resources	25	%	(Directive (EU), 2018)	32	78.13%
Energy consumption	17,000	MW per year	Lower is better	–	17,000
Human capital	150	Absolute number	Best competitor	170	88.24%
Waste index	5	%	Lower is better	–	5.00%
Compliant products	95	%	Higher is better	–	95.00%
Number of smart tasks	80	%	Higher is better	–	80.00%
Sanitation costs	22,000	Euro	Lower is better	–	22,000
CO2 emission	25,000	Kg CO ₂	Lower is better	–	25,000
Fuel consumption	520,000	Liters per year	Lower is better	–	520,000
Route efficiency	90	%	Higher is better	–	90%
Vehicle load rate	75	%	Higher is better	–	75%
Cost of waste	27,000	Euro	Lower is better	–	27,000
Recycled packaging quantity	70	%	(DIRECTIVE 94/62/EC, 1994)	65	107.69%

Table 23 show a possible aggregation of the KPIs listed in for the LARG perspective.

Table 23. Aggregation of KPIs.

	Level	KPI ₁	KPI ₂	Final Indicator
Lean	1	Design time	Development costs	Design and Development
	2	Set-up change impact on total production hours	Operating production time	Operational Timing
	2	Cycle time	Design and Development	Design Timing
	2	Average monthly sales	Sales effectiveness	Sales
	2	Profit margin on sales	Inventory level (finished products)	Finished Product
	3	Production capacity utilization	Overall equipment effectiveness (OEE)	Production Line Efficiency
	3	Operational Timing	Design Timing	Production Time
	3	Rework and defect cost	Inventory level (consumables and semi-finished goods)	Work-In-Progress Product
	3	Sales	Finished Product	Sales Quality
	3	Material loss due to operations (e.g., transfer to other containers)	Full truckload (FTL) deliveries vs. less-than-truckload (LTT)	Shipping Efficiency
	4	Inventory cost	Inventory level (raw materials)	Inventory
	4	Production Line Efficiency	Productivity	Production Line Utilization
	4	Production Time	Work-In-Progress Product	Production Efficiency
	4	Sales Effectiveness	Marketing cost	Sales Service
	4	Shipping Efficiency	Total order fulfillment time	Shipping Quality
	4	Annual training hours per employee	Employee perception of work environment	Work Environment Quality
	5	Inventory	Quantity of non-compliant supplies	Procurement
	5	Production Line Utilization	Production Efficiency	Production
	5	Sales Service	Shipping Quality	Distribution
	5	Customer satisfaction	Work Environment Quality	Reverse Logistics
Agile	1	Delivery error rate (%)	Delivery frequency (No. of actual deliveries / No. of scheduled deliveries)	Successful deliveries
	1	Delivery punctuality	Timeliness	Delivery accuracy
	2	Successful deliveries	Delivery accuracy	Delivery accuracy
	3	Supplier flexibility	Supplier response time (supplier lead time)	Supplier efficiency
	3	Quantity of defective products	Number of bottlenecks	Production inefficiencies
	3	Total production time	Overtime hours	Production timing
	3	Speed of inventory turnover to sales	Inventory turnover ratio	Inventory management
	3	Delivery accuracy	Delivery flexibility	Delivery efficiency
	4	Supplier efficiency	Proximity to suppliers	Supplier evaluation
	4	Production inefficiencies	Production timing	Production operational efficiency
	4	Production mix flexibility	Supplier involvement in product development	Product development

	4	Customer service rating	Problem resolution time after service request	After-sales service
	4	Inventory management	Delivery efficiency	Shipping
	5	Number of nodes in the supply chain	Supplier evaluation	Procurement
	5	Production operational efficiency	Product development	Production
	5	After-sales service	Shipping	Distribution
	5	Flexibility defined as the ability to process and recover parts/products even from different origins (Return flexibility)	Response time to return request	Reverse logistics
Resilient	1	Product range breadth	Product customization	Production flexibility
	2	Average downtime	Average time for preventive maintenance	Scheduled downtime
	2	Mean time between failures	Mean time to repair failures	Failure management
	2	Production flexibility	Percentage of component standardization	Product range
	2	Demand satisfaction	Percentage of lost sales	Sales effectiveness
	3	Availability of alternative supplies	Inventory adjustment time	Inventory management
	3	Supplier lead time	Supplier flexibility	Supplier timing and flexibility
	3	Scheduled downtime	Failure management	Downtime
	3	Product range	Percentage of reworked or modified products	Product quality
	3	Safety stock quantity	Inventory coverage time	Inventory management
	3	Sales effectiveness	Distribution channel resilience	Sales service
	3	Average customer tenure	Customer retention (CRR)	Customer base
	4	Inventory management	Supplier timing and flexibility	Procurement
	4	Downtime	Product quality	Production
	4	Inventory management	Sales service	Distribution
	4	Customer satisfaction and loyalty	Customer base	Reverse Logistics
Green	1	Energy consumed from fossil and renewable resources	Energy consumed	Electric energy
	2	Water consumed	Electric energy	Utilities
	2	Suppliers with environmental certifications	Use of renewable materials	Sustainable sourcing
	2	Sanitation costs	Human capital	Human factor
	2	Number of compliant products	Number of smart-performed activities	Production efficiency
	3	Cost of raw materials	Sustainable sourcing	Procurement
	3	Utilities	Human factor	Resources required for production
	3	Waste index	Production efficiency	Efficiency
	3	CO ₂ emission	Fuel consumption	Environmental impact
	3	Route efficiency	Vehicle load rate	Distribution efficiency
	3	Waste cost	Quantity of recyclable packaging	Reverse logistics

4	Resources required for production	Efficiency	Production
4	Environmental impact	Distribution efficiency	Distribution

For the sake of brevity, Figure 30 shows an example of hierarchical aggregation for the green KPIs. Starting from the outermost part of the diagram, two final-level indicators are aggregated at a time, proceeding progressively inward until reaching the green category. This category represents the overall evaluation, which is derived from the indicators at the preceding levels. The diagram includes two types of indicators: those highlighted in blue represent the final-level indicators used for the assessment, while those highlighted in red are intermediate indicators required for the correct functioning of the tool according to the proposed logic.

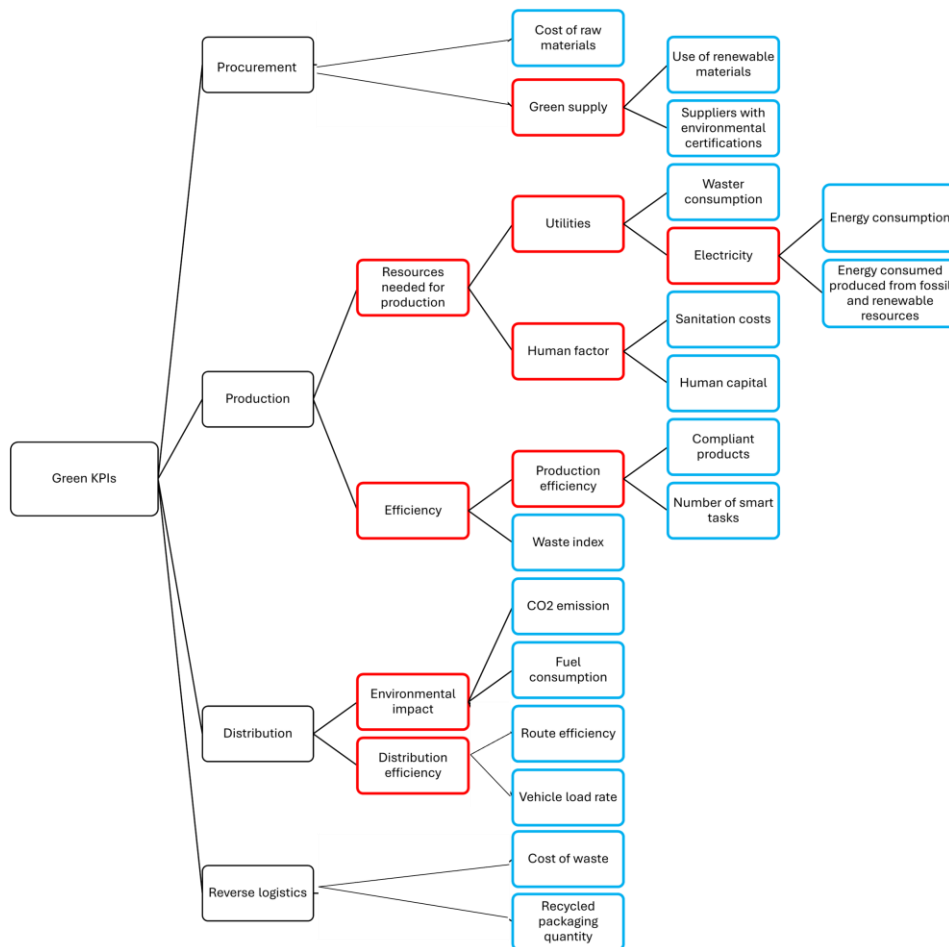


Figure 30. Example of a hierarchical aggregation structure for KPIs within the green dimension, used in the fuzzy logic framework (source: (Monferdini, Casella, et al., 2025)).

The linguistic judgments and the memberships degree for each KPI are shown in Table 24.

Table 24. Linguistic judgment and membership degree of KPIs.

	KPI	Linguistic Judgment	Degree of Membership
Lean	Quantity of non-compliant supplies	Very High	0
		High	1
	Inventory level (raw materials)	High	1
	Inventory cost	Very High	1

	Productivity	Low	1
	Production capacity utilization	Low	1
	Overall equipment effectiveness	Low	1
	Impact of setup change on total production hours	Very High	1
	Operational production time	Very High	0.5
		High	0.5
	Cycle time	Very High	1
	Design time	Very High	1
	Development costs	Very Low	0
		Low	1
	Stock level (consumables and semi-finished materials)	High	1
	Rework and defect costs	Very High	0
		High	1
	Material loss due to operations (transfer to other containers)	Very High	1
		High	0
	Full truckload (ftl) deliveries vs. Less-than-truckload (ltl)	High	1
	Total order fulfillment time	High	1
		Low	0
	Marketing cost	Low	0
		High	1
	Average monthly sales	Low	0
		High	1
	Sales effectiveness	High	0.43
		Very High	0.57
	Profit margin on sales	High	1
		Very High	0
	Stock level (finished goods)	High	0
		Very High	1
	Customer satisfaction	High	1
	Annual training hours per employee	High	0
		Very High	1
	Employee perception of the work environment	High	1
	Proximity to suppliers	Very Low	1
	Number of nodes in the supply chain	Very Low	1
	Supplier flexibility	Low	0
		High	1
	Supplier response time (lead time)	Very High	1
		High	0
	Supplier involvement in product development	High	0.87
		Very High	0.13
	Production mix flexibility	High	0.63
		Very High	0.37
	Total production time	Very High	1
	Overtime hours	Very High	1
		High	0
Agile	Quantity of defective products	Very Low	1
		Low	0
	Number of bottlenecks	Very Low	1
	% Delivery errors	Very Low	1
	Delivery frequency (actual deliveries / scheduled deliveries)	Very High	1
	Delivery punctuality	High	0.71
		Very High	0.29
	Delivery flexibility	Low	1
	Promptness	High	1
	Speed of inventory turnover	Very Low	1
	Inventory turnover index	Very Low	1
	Time to resolve service request	Very Low	1
	Service evaluation	High	0.08
		Very High	0.92

	Flexibility understood as the ability to handle and recover parts/products even from different origins (return flexibility)	High	0.51
		Very High	0.49
	Response time to return request	Very High	0
		High	1
	Supplier lead time	Very High	1
	Supplier flexibility	High	1
	Availability of alternative supplies	High	1
	Inventory adjustment time	Very High	1
	Average time for preventive maintenance	High	1
	Average time for preventive maintenance	Low	0
	Mean time between failures	Very High	1
		High	0
	Average repair time for failures	Very High	1
	Average downtime	Very High	0.3
		High	0.7
	Percentage of reworked or modified products	Very High	1
	Percentage of component standardization	Very High	1
	Product customization	Very Low	0.33
		Low	0.67
	Product range breadth	High	1
	Resilience of distribution channels	High	0.29
		Very High	0.71
	Demand satisfaction	Very Low	1
	Average customer tenure	High	1
	Percentage of lost sales	Very High	1
		High	0
	Inventory coverage time	Low	0
		High	1
	Quantity of safety stock	High	0.83
	Customer retention (CRR)	High	0.56
		Very High	0.44
	Customer satisfaction and loyalty	High	1
	Cost of raw materials	Very low	1
	Use of renewable materials	Low	1
		High	0
	Suppliers with environmental certifications	Very high	1
	Water consumption	Low	0.83
		Very low	0.17
	Energy consumed produced from fossil and renewable resources	High	1
	Energy consumption	Low	0,6
		High	0,4
	Human capital	High	0.97
		Very high	0.03
	Waste index	Very high	1
	Compliant products	High	0
		Very high	1
	Number of smart tasks	High	1
	Sanitation costs	Low	0.6
		High	0.4
	CO2 emission	Low	1
	Fuel consumption	Very low	1
	Route efficiency	High	0.71
		Very high	0.29
	Vehicle load rate	Low	0
		High	1
	Cost of waste	Low	0.6
		High	0.4
	Recycled packaging quantity	Very high	1

Considering the final KPIs, listed during the aggregation phase of KPIs (Table 23), Table 25 reports the inference results for the dimensions (lean, agile, resilient and green).

Table 25. Inference results of KPIs.

	Indicator	Linguistic Judgment	Final Truth Value
Lean	Design and development	Average	0
		High	1
	Operational timing	Very High	1
		Design timing	High
	Sales	Very High	1
		Average	0
		High	0.43
	Finished product	Very High	0.57
		High	0
	Production line efficiency	Very High	1
		Low	1
	Production time	Very High	1
		Work-in-progress product	Very High
	Sales quality	High	1
		High	0
		Very High	1
	Shipping efficiency	Very High	1
		High	0
	Inventory	Very High	1
		Production line utilization	Low
	Production efficiency	Very High	1
		Sales service	Average
	Shipping quality	High	0.43
		Very High	0.57
		Very High	1
	Work environment quality	High	0
		Average	0
		High	0
	Procurement	Very High	1
		Very High	1
High		1	
Production	High	1	
	High	0	
	Average	0	
Reverse logistics	Very High	1	
	High	0	
	Very High	1	
Agile	Deliveries Successfully Completed	Average	1
	Delivery Precision	High	0.71
		Very High	0.29
	Delivery Accuracy	High	1
		High	0
	Supplier Efficiency	Average	0
		Very High	1
	Production Inefficiencies	Very Low	1
		Production Timing	Very High
	Inventory Management	Very Low	1
		Delivery Efficiency	Average
	Supplier Evaluation	Low	0
		Average	1
	Operational Production Efficiency	Average	1
		Product Development	High
After-Sales Service	Very High	0.45	
	Low	0.08	
	Average	0.92	

	Shipping	Low	1
	Procurement	Very Low	0
		Low	1
	Production	High	1
	Distribution	Low	1
	Reverse Logistics	Very High	0.49
		High	0.51
Resilient	Production Flexibility	Low	0.33
		Average	0.67
	Scheduled Downtimes	Very High	0.3
		High	0.7
		Average	0
	Breakdown Management	Very High	1
	Product Range	High	1
	Sales Effectiveness	Average	1
		Low	0
	Inventory Management	Very High	1
	Supplier Timing And Flexibility	Very High	1
	Downtimes	Very High	1
		High	0
	Production Quality	Very High	1
	Stock Management	Average	0
		High	0.83
	Sales Service	High	1
		Average	0
	Customer Base	High	0.56
		Very High	0.44
	Procurement	Very High	1
	Production	Very High	1
	Distribution	High	0.83
		Average	0
	Reverse Logistics	High	0.56
		Very High	0.44
Green	Electricity	Average	0.6
		High	0.4
	Utilities	Low	0.67
		Average	0.333333
	Sustainable procurement	High	1
		Very high	0
	Human factor	Average	0.58
		High	0.41
		Very high	0.01
	Production efficiency	High	0
		Very high	1
	Procurement	Low	1
		Average	0
	Resources required for production	Low	0.39
		Average	0.46
		High	0.15
	Efficiency	Very high	1
	Environmental impact	Very low	1
	Distribution efficiency	Average	0
		High	0.71
	Very high	0.29	
Reverse logistics	High	0.6	
	Very high	0.4	
Production	High	0.85	
	Very high	0.15	
Distribution	Low	0.71	
	Average	0.29	

The objective of the tool is to achieve a final evaluation, broken down by LARG dimension and process part (procurement, production, distribution, reverse logistics), which includes “linguistic judgment,” “truth value,” “fuzzy average,” and “final linguistic judgment (Table 26).

Table 26. Final evaluation by process part for each indicator group, expressed through linguistic judgment and truth value.

	Indicator	Truth value	Xk	FM	Final linguistic judgmentl
Lean	Procurement	1	0.90	0.90	Very high
	Production	1	0.65	0.65	High
	Distribution	0	0.65	0.90	Very high
	Distribution	0	0.45		
	Distribution	1	0.90		
	Reverse Logistics	0	0.65	0.90	Very high
	Reverse Logistics	1	0.90		
Agile	Procurement	0	0.15	0.25	Low
	Procurement	1	0.25		
	Production	1	0.65	0.65	High
	Distribution	1	0.25	0.25	Low
	Reverse Logistics	0,494773519	0.90	0.77369338	Very high
	Reverse Logistics	0,505226481	0.65		
Resilient	Procurement	1	0.90	0.90	Very high
	Production	1	0.90	0.90	Very high
	Distribution	0,8333333333	0.65	0.65	High
	Distribution	0	0.45		
	Reverse Logistics	0,5555555556	0.65	0.7611111111	Very high
	Reverse Logistics	0,4444444444	0.90		
Green	Procurement	1	0.25	0.25	Low
	Procurement	0	0.45		
	Production	0,850980392	0.65	0.687255	High
	Production	0,149019608	0.90		
	Distribution	0,714285714	0.25	0.307142857	Low
	Distribution	0,285714286	0.45		
	Reverse logistics	0,6	0.65	0.75	Very high
	Reverse logistics	0,4	0.90		

Figure 31 illustrates the fuzzy mean scores and corresponding linguistic evaluations obtained for each of the four LARG dimensions across the main operational areas of the supply chain.

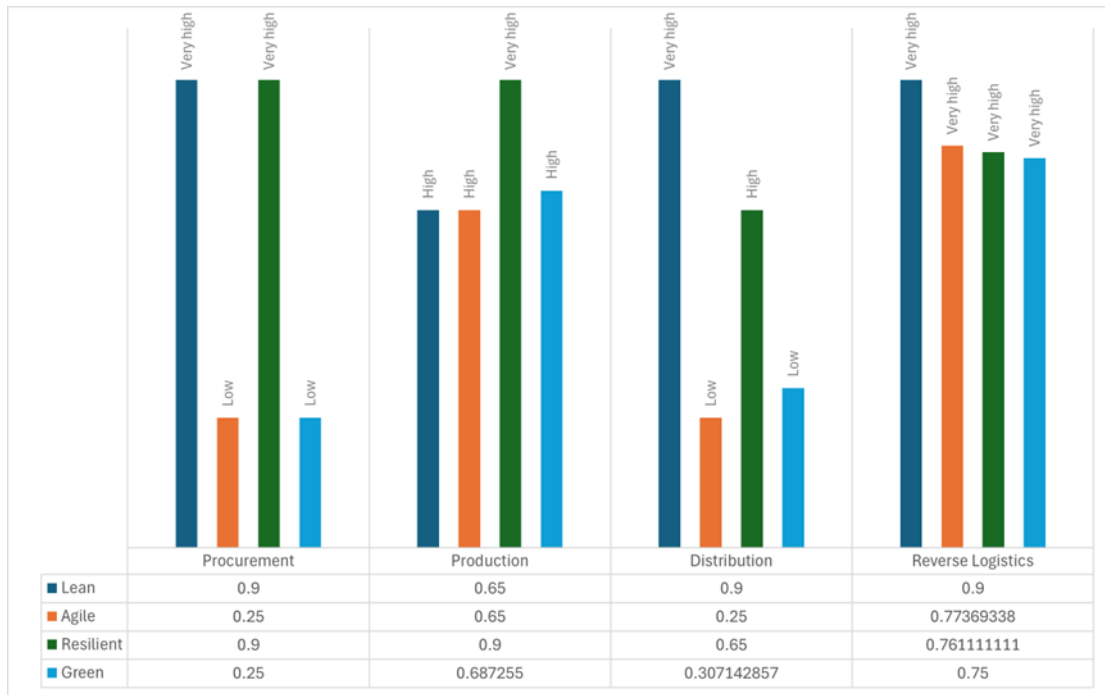


Figure 31. Final results - fuzzy mean and linguistic judgments of each dimension (source:(Monferdini, Casella, et al., 2025)).

In the Lean dimension, performance is consistently high across all activities. Procurement, distribution, and reverse logistics have fuzzy averages close to 0.9, which corresponds to a linguistic rating of “very high,” while the production phase shows a slightly lower score ($FM = 0.65$), associated with a “high” performance level. The Agile dimension shows a more irregular trend. Procurement and distribution have relatively lower fuzzy averages ($FM \approx 0.25$), interpreted as “low” performance, while production reaches 0.65 (‘high’) and reverse logistics achieves the highest value, 0.77, indicating “very high” agility. In terms of resilience, the results are more balanced across processes. Both procurement and production achieve very high performance ($FM = 0.90$, “very high”), while distribution shows a moderate value ($FM = 0.65$, “high”). Here too, reverse logistics performs well, with a fuzzy average of 0.76, which also corresponds to a “very high” rating. Finally, the Green dimension reveals strong environmental performance in production ($FM \approx 0.68$ and reverse logistics ($FM \approx 0.75$), highlighting the integration of sustainable practices in these phases. In contrast, procurement and distribution score lower ($FM \approx 0.25$ and 0.31, respectively), reflecting the limited adoption of green measures in the upstream and downstream stages of the supply chain.

The results obtained for the green dimension further confirm the hypothesis that sustainable practices are more easily implemented within internal operations (e.g., production and reverse logistics), where companies exercise direct control over resources and processes. In contrast, integrating sustainability into procurement and distribution (i.e., external operations) remains more complex and presents some critical issues.

4.4 Extending the LARG framework to LARGS: The Sustainable dimension

The fuzzy model discussed in section 4.3, highlighted a significant limitation in the green dimension: while sustainability-oriented practices appear to be effectively integrated into internal processes, their implementation in external operations remains limited. This imbalance reveals a structural gap in the LARG framework, suggesting that environmental performance alone (green dimension) cannot fully capture the broader concept of sustainability. To fill this gap, the research further explored the supplier selection process, introducing the sustainability dimension (S) into the model, thus expanding the LARG paradigm into LARGS (Bottani, Nardo, et al., 2025). Unlike the green perspective, which focuses primarily on environmental aspects, the sustainability dimension explicitly incorporates economic and social criteria, providing a more comprehensive view of supply chain performance.

Based on the above, a hybrid Fuzzy Delphi-DEMATEL-ANP model was developed to map the interdependencies between the LARGS criteria and quantify their relative importance. The model integrates expert judgment with fuzzy logic to manage uncertainty and subjectivity. The methodology was applied to the problem of supplier selection.

A list of 50 criteria (10 for each dimension), typically used for supplier selection under LARGS paradigm, are presented in Table 27.

Table 27. LARGS criteria for supplier selection.

Perspective	Criteria	Source
Lean	Price	(Ku et al., 2010), (Y. Li & Dong, 2015), (Abdollahi et al., 2015), (Beikhhakhian et al., 2015), (Galankashi et al., 2016), (Sahu et al., 2016), (T. K. Wang et al., 2017), (Sureeyatanapas et al., 2020)
	Transportation cost	(Abdollahi et al., 2015), (Ku et al., 2010), (Y. Li & Dong, 2015), (Valipour Parkouhi & Safaei Ghadikolaei, 2017) (Valipour Parkouhi et al., 2019), (Matawale et al., 2016)
	Quantity discount	(Ye et al., 2024), (Fallahpour et al., 2017), (Galankashi et al., 2016)
	Terms of payment	(Valipour Parkouhi & Safaei Ghadikolaei, 2017)(Girubha et al., 2016)(Abdollahi et al., 2015)
	Warranties and claims policies	(Kannan et al., 2015)(Abdollahi et al., 2015)
	Lead time	(Valipour Parkouhi et al., 2019) (Valipour Parkouhi & Safaei Ghadikolaei, 2017) (Alimardani et al., 2014)(Alimardani et al., 2013)(Galankashi et al., 2016)
	Zero inventory	(Sonar et al., 2022)(Rezaei et al., 2020)(Kannan et al., 2015)(Ghazvinian et al., 2024)
	Geographic location	(Mohammed et al., 2021), (Ku et al., 2010), (Galankashi et al., 2016)
	Quality management system	(Valipour Parkouhi & Safaei Ghadikolaei, 2017) , (Valipour Parkouhi et al., 2019), (Galankashi et al., 2021)(Rezaei et al., 2020), (Abdollahi et al., 2015)
	Experience in supply	(Birgün Barla, 2003) (Valipour Parkouhi & Safaei Ghadikolaei, 2017), (Valipour Parkouhi et al., 2019)
Agile	Customer satisfaction	(Haldar et al., 2014)(Alimardani et al., 2013), (Alimardani et al., 2014), (Sahu et al., 2016), (Beikhhakhian et al., 2015)
	Volume flexibility	(Valipour Parkouhi et al., 2019), (Valipour Parkouhi & Safaei Ghadikolaei, 2017) , (Alimardani et al., 2013), (Alimardani et al., 2014)
	Mix flexibility	(Valipour Parkouhi et al., 2019) , (T. K. Wang et al., 2017) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)
	Process flexibility	(Alimardani et al., 2014) , (Alimardani et al., 2013) , (Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)
	Emergency order processing	(Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017), (Y. Li & Dong, 2015)
	Customization	(Hasan et al., 2008)(Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)
	After-sales support	(Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017) (Rezaei et al., 2020) (Galankashi et al., 2016)
	R&D	(Alimardani et al., 2013), (Abdollahi et al., 2015; Alimardani et al., 2014; Fallahpour et al., 2017; Y. Li & Dong, 2015; Luthra et al., 2017; Rajesh & Ravi, 2015)
	IT infrastructure	(Rezaei et al., 2020)(Alimardani et al., 2014)(Alimardani et al., 2013) , (T. K. Wang et al., 2017) (Beikhhakhian et al., 2015) (Matić et al., 2019)
	Information sharing	(Abdollahi et al., 2015)(Galankashi et al., 2016)

Resilient	Vulnerability	(Rajesh & Ravi, 2015)(Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)
	Risk awareness	(Rajesh & Ravi, 2015)(Valipour Parkouhi et al., 2019) , (T. K. Wang et al., 2017) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017) (Mohammed et al., 2021) (Sureeyatanapas et al., 2020)
	Collaboration	(Rajesh & Ravi, 2015) (Y. Li & Dong, 2015) (Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)
	Safety stock level	(Gan et al., 2019; Hosseini & Khaled, 2019; Pramanik et al., 2017; Sureeyatanapas et al., 2020)
	Capability to hold strategic stock	(Gan et al., 2019; Haldar et al., 2012, 2014; Hosseini & Khaled, 2019; Sahu et al., 2016)
	Outsourcing contracts	(Hoseini et al., 2021; Hosseini & Khaled, 2019; Mohammed et al., 2021; Sureeyatanapas et al., 2020)
	Rerouting deliveries	(Gan et al., 2019; Hosseini & Khaled, 2019; Sureeyatanapas et al., 2020)
	Robustness	(Gan et al., 2019; Hoseini et al., 2021; Hosseini & Khaled, 2019; Sureeyatanapas et al., 2020)
	Recovery	(Gan et al., 2019; Hosseini & Khaled, 2019; Sureeyatanapas et al., 2020)
	Invulnerable location	(Mohammed et al., 2021; Rajesh & Ravi, 2015; Sureeyatanapas et al., 2020)
Green	Environmental management system	(Hashemi et al., 2015; Keshavarz Ghorabae et al., 2016; Nie et al., 2019; Wang Chen et al., 2016; Yazdani, 2014)
	Pollution production	(Haeri & Rezaei, 2019; Kannan et al., 2015; Keshavarz Ghorabae et al., 2016; Kuo et al., 2015; Qin et al., 2017; Wang Chen et al., 2016; Wu et al., 2019)
	Pollution control	(Bali et al., 2013; Haeri & Rezaei, 2019; Hashemi et al., 2015; Kannan et al., 2015; Rouyendegh et al., 2020; Wang Chen et al., 2016)
	Resource consumption	(Haeri & Rezaei, 2019; Keshavarz Ghorabae et al., 2016; Kuo et al., 2015; Qin et al., 2017; Wu et al., 2019)
	Recycle	(Fallahpour et al., 2017; Kannan et al., 2015; Lee et al., 2009; Rahardjo et al., 2023; Rao et al., 2017; Sen et al., 2018b; Yazdani, 2014; Yu et al., 2019)
	Disposal cost	(Kannan et al., 2015; Lee et al., 2009; Sen et al., 2018b)
	Green packaging	(Fallahpour et al., 2017; Kannan et al., 2015; Lee et al., 2009; Luthra et al., 2017; Nguyen et al., 2022; Sen et al., 2018b)
	Eco-design	(Bali et al., 2013; Hashemi et al., 2015; Kannan et al., 2015; Lee et al., 2009; Matić et al., 2019; Sen et al., 2018b; Wang Chen et al., 2016; Yu et al., 2019)
	Green warehouse	(Büyükoçkan & Ifi, 2012; Haeri & Rezaei, 2019; Hashemi et al., 2015; Kannan et al., 2015; Keshavarz Ghorabae et al., 2016; Lee et al., 2009; Qin et al., 2017; Rouyendegh et al., 2020; Sen et al., 2018b; Wang Chen et al., 2016; Wu et al., 2019)
Eco-efficient transport	(Fallahpour et al., 2017; Nie et al., 2019)	
Sustainable	Financial stability	(Abdollahi et al., 2015; Birgün Barla, 2003; Büyükoçkan & Ifi, 2012; Galankashi et al., 2021; Girubha et al., 2016; Leong et al., 2022; Matić et al., 2019; Wang Chen et al., 2016)
	Long-term relationships	(Sonar et al., 2022)(Valipour Parkouhi et al., 2019) , (Valipour Parkouhi & Safaei Ghadikolaei, 2017)

Life cycle assessment system	(Ghazvinian et al., 2024; Sonar et al., 2022)
Employee training	(Ecer & Pamucar, 2020; Fallahpour et al., 2017; Hashemi et al., 2015; Kuo et al., 2015; Matic et al., 2019; Menon & Ravi, 2022; Qin et al., 2017; Wang Chen et al., 2016; Yazdani, 2014) (Alimardani et al., 2013)
Workers' rights	(Ecer & Pamucar, 2020; Fallahpour et al., 2017; Girubha et al., 2016; J. Li et al., 2019; Lu et al., 2018; Luthra et al., 2017; Matic et al., 2019; Menon & Ravi, 2022; Nguyen et al., 2022; Rahardjo et al., 2023; Yu et al., 2019)
Occupational health and safety	(Ecer & Pamucar, 2020; Fallahpour et al., 2017; J. Li et al., 2019; Luthra et al., 2017; Matic et al., 2019; Menon & Ravi, 2022; Nguyen et al., 2022; Rahardjo et al., 2023; Rani et al., 2020; Rao et al., 2017; Yu et al., 2019)
Inclusion	(Fallahpour et al., 2017; J. Li et al., 2019; Menon & Ravi, 2022)
Stakeholder involvement	(Ecer & Pamucar, 2020; Luthra et al., 2017; Nguyen et al., 2022; Rao et al., 2017)
Information disclosure	(Ecer & Pamucar, 2020; Luthra et al., 2017; Matic et al., 2019; Yu et al., 2019)
Reputation	(Abdollahi et al., 2015; Girubha et al., 2016; Matic et al., 2019; Rani et al., 2020; Sureeyatanapas et al., 2020; Valipour Parkouhi et al., 2019; Valipour Parkouhi & Safaei Ghadikolaei, 2017; T. K. Wang et al., 2017)

A set of 49 experts analyse the KPIs through FDM questionnaires, resulting in 33 valid responses (67.35%). Most experts work in manufacturing (33%), logistics and transportation (15%), and chemicals and metals (approximately 12% each), while the remaining participants represent the automotive, energy, food and beverage, cosmetics, and electromechanical sectors. More than half of respondents (52%) have more than five years of experience in supply chain or production management, including senior managers, general managers, team leaders, and supply chain planners. Approximately 24% of participants have more than ten years of experience. Most experts (67%) hold a master's degree, followed by bachelor's degrees (21%) and secondary school diplomas (12%). The panel is predominantly composed of managers (60%), along with specialists, engineers, directors, and analysts.

The experts' assessments of the 50 supplier selection criteria were expressed as triangular fuzzy numbers (TFN) and then processed using the mathematical steps defined in the Fuzzy Delphi method. The defuzzification procedure, carried out using Eq. 7 - Eq. 8, allowed the fuzzy judgments to be transformed into clear numerical values representing the overall relevance of each criterion. A threshold value ($\rho = 0.6$) was established to filter the most significant factors: only criteria with a final defuzzified score equal to or greater than this threshold were considered important enough to be included in the subsequent FDANP phase. The subset of criteria retained together with their final importance values derived from the FDM process is listed below.

- Price (L_1): Fuzzy importance: (0.25, 0.59, 1.00), Final importance: 0.61
- Warranties and claims policies (L_2): Fuzzy importance: (0.25, 0.71, 1.00), Final importance: 0.65
- Lead time (L_3): Fuzzy importance: (0.25, 0.74, 1.00), Final importance: 0.66
- Quality management system (L_4): Fuzzy importance: (0.09, 0.73, 1.00), Final importance: 0.66
- Customer satisfaction (A_1): Fuzzy importance: (0.25, 0.72, 1.00), Final importance: 0.66
- Emergency order processing (A_2): Fuzzy importance: (0.25, 0.69, 1.00), Final importance: 0.65
- After-sales support (A_3): Fuzzy importance: (0.25, 0.73, 1.00), Final importance: 0.66
- Vulnerability (R_1): Fuzzy importance: (0.25, 0.65, 1.00), Final importance: 0.63
- Collaboration (R_2): Fuzzy importance: (0.25, 0.68, 1.00), Final importance: 0.64
- Safety stock level (R_3): Fuzzy importance: (0.25, 0.68, 1.00), Final importance: 0.64
- Environmental management system (G_1): Fuzzy importance: (0.25, 0.69, 1.00), Final importance: 0.65
- Pollution control (G_2): Fuzzy importance: (0.25, 0.67, 1.00), Final importance: 0.64
- Recycle (G_3): Fuzzy importance: (0.25, 0.67, 1.00), Final importance: 0.64

- Financial stability (S_1): Fuzzy importance: (0.25, 0.72, 1.00), Final importance: 0.66
- Long-term relationships (S_2): Fuzzy importance: (0.25, 0.71, 1.00), Final importance: 0.65
- Occupational health and safety (S_3): Fuzzy importance: (0.25, 0.73, 1.00), Final importance: 0.66
- Reputation (S_4): Fuzzy importance: (0.25, 0.64, 1.00), Final importance: 0.63

A second questionnaire, FDANP, was distributed to experts who had expressed their willingness to participate in this second phase of the study to investigate the interrelationships between the previously selected criteria. 21 valid responses were obtained.

The expert evaluations were first organized into initial direct matrices for both criteria and dimensions (Table 28 - Table 29).

Table 28. Initial direct matrix of criteria for expert 1.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0	2	2	3	1	1	1	1	1	1	3	1	3	4	2	2	1
L_2	2	0	2	2	1	2	2	1	1	1	1	1	1	1	2	2	3
L_3	3	2	0	2	5	2	2	3	2	2	2	3	2	2	2	2	4
L_4	5	3	2	0	4	1	2	2	1	1	2	3	2	2	2	2	4
A_1	2	2	2	2	0	2	2	1	2	1	2	2	1	2	2	2	3
A_2	3	2	4	2	5	0	2	4	1	1	2	4	2	3	3	1	4
A_3	2	3	2	2	3	2	0	2	1	2	2	1	1	2	3	1	3
R_1	1	1	2	2	2	2	1	0	3	3	1	1	1	3	3	3	2
R_2	2	1	1	1	2	3	1	5	0	2	1	3	1	3	4	1	3
R_3	3	1	2	1	3	3	2	5	1	0	1	3	1	3	3	1	3
G_1	2	1	1	2	2	3	3	2	1	3	0	4	2	4	2	2	5
G_2	1	1	2	1	2	2	1	2	2	2	3	0	3	3	1	1	2
G_3	3	2	1	3	3	1	3	2	1	1	3	5	0	3	1	1	3
S_1	3	2	1	3	1	1	1	2	1	2	3	2	2	0	2	2	3
S_2	2	2	1	1	2	2	2	2	2	1	1	1	2	3	0	1	3
S_3	1	2	2	2	2	2	3	3	1	2	1	1	1	2	2	0	5
S_4	4	2	2	1	2	2	2	2	2	2	2	1	1	2	2	1	0

Table 29. Initial direct matrix of dimensions for expert 1.

	L	A	R	G	S
L	0	4	3	3	3
A	3	0	5	3	4
R	3	2	0	2	3
G	2	2	3	0	4
S	2	3	2	5	0

These individual fuzzy matrices were then combined to generate the aggregated direct fuzzy matrices (Table 30 - Table 31).

Table 30. Initial direct fuzzy matrix of criteria for expert 1.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)
L_2	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)
L_3	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.5, 0.75, 1)
L_4	(0.75, 1, 1)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0)	(0.5, 0.75, 1)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.5, 0.75, 1)
A_1	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)
A_2	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0, 0, 0)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.5, 0.75, 1)
A_3	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
R_1	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)
R_2	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.75, 1, 1)	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
R_3	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0, 0, 0.25)	(0, 0, 0)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
G_1	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0, 0)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.75, 1, 1)
G_2	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)
G_3	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0.75, 1, 1)	(0, 0, 0)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
S_1	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)
S_2	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0)	(0, 0, 0.25)	(0.25, 0.5, 0.75)
S_3	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0)	(0.75, 1, 1)
S_4	(0.5, 0.75, 1)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0.25)	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0, 0, 0.25)	(0, 0, 0)

Table 31. Initial direct fuzzy matrix of dimensions of expert 1.

	L	A	R	G	S
L	(0, 0, 0)	(0.5, 0.75, 1)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)	(0.25, 0.5, 0.75)
A	(0.25, 0.5, 0.75)	(0, 0, 0)	(0.75, 1, 1)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)
R	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0, 0, 0)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)
G	(0, 0.25, 0.5)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0, 0)	(0.5, 0.75, 1)
S	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0, 0.25, 0.5)	(0.75, 1, 1)	(0, 0, 0)

The transformation from fuzzy values to crisp values was performed using the CFCS procedure. Specifically, the fuzzy numbers were normalized (Eq. 9) and their left and right normalized components were calculated (Eq. 10) and then combined into single crisp values (Eq. 11). These values were further normalized (Eq. 12), and the final aggregated crisp matrix was derived as the arithmetic mean of all normalized scores (Eq. 13).

The resulting direct relationship matrices for both criteria and dimensions (Table 32 - Table 33) were then analyzed to assess the level of consensus among the experts.

Table 32. Direct relationship matrix of criteria.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.000	0.324	0.318	0.358	0.156	0.113	0.16	0.03	0.03	0.15	0.32	0.06	0.30	0.52	0.32	0.09	0.111
L_2	0.089	0.000	0.123	0.070	0.133	0.09	0.17	0.05	0.07	0.07	0.03	0.03	0.04	0.03	0.12	0.06	0.24
L_3	0.389	0.102	0.000	0.144	0.800	0.33	0.10	0.35	0.10	0.09	0.113	0.56	0.12	0.14	0.15	0.10	0.58
L_4	0.889	0.334	0.297	0.000	0.644	0.17	0.16	0.34	0.07	0.10	0.13	0.62	0.16	0.39	0.40	0.12	0.611
A_1	0.156	0.143	0.122	0.145	0.000	0.13	0.13	0.06	0.09	0.06	0.113	0.12	0.12	0.15	0.17	0.14	0.35
A_2	0.644	0.185	0.581	0.112	0.811	0.00	0.36	0.86	0.15	0.17	0.20	0.611	0.13	0.42	0.65	0.12	0.811
A_3	0.100	0.334	0.123	0.123	0.378	0.13	0.00	0.14	0.09	0.17	0.09	0.10	0.15	0.16	0.34	0.12	0.33
R_1	0.122	0.123	0.210	0.123	0.122	0.15	0.13	0.00	0.34	0.33	0.15	0.13	0.14	0.37	0.34	0.36	0.40
R_2	0.389	0.132	0.113	0.101	0.156	0.38	0.14	0.911	0.00	0.35	0.08	0.311	0.12	0.64	0.86	0.13	0.35
R_3	0.367	0.154	0.308	0.133	0.367	0.37	0.26	0.83	0.14	0.00	0.14	0.611	0.13	0.38	0.36	0.16	0.36
G_1	0.389	0.144	0.146	0.369	0.389	0.38	0.34	0.37	0.14	0.34	0.00	0.92	0.16	0.64	0.35	0.10	0.82
G_2	0.122	0.070	0.156	0.144	0.311	0.34	0.13	0.14	0.13	0.16	0.39	0.00	0.30	0.31	0.111	0.10	0.37
G_3	0.655	0.154	0.079	0.326	0.567	0.13	0.34	0.10	0.07	0.08	0.35	0.85	0.00	0.39	0.111	0.10	0.43
S_1	0.367	0.134	0.145	0.369	0.078	0.15	0.18	0.18	0.08	0.29	0.37	0.17	0.16	0.00	0.33	0.32	0.42
S_2	0.400	0.345	0.199	0.123	0.089	0.14	0.20	0.16	0.32	0.12	0.08	0.17	0.14	0.34	0.00	0.112	0.411
S_3	0.111	0.165	0.198	0.165	0.156	0.18	0.36	0.32	0.10	0.10	0.09	0.17	0.13	0.36	0.17	0.00	0.83
S_4	0.578	0.249	0.220	0.208	0.156	0.17	0.19	0.13	0.16	0.18	0.29	0.15	0.15	0.211	0.211	0.20	0.00

Table 33. Direct relationship matrix of dimensions.

	L	A	R	G	S
L	0.000	0.537	0.478	0.622	0.589
A	0.423	0.000	0.800	0.578	0.644

R	0.402	0.394	0.000	0.267	0.400
G	0.370	0.264	0.322	0.000	0.900
S	0.370	0.515	0.378	0.833	0.000

The disagreement indices calculated (Eq. 14), equal to 2.44% for the criteria and 0.81% for the dimensions, are well below the conventional threshold of 5%, indicating a high degree of consistency in the experts' judgments (corresponding to confidence levels of 97.56% and 99.19%, respectively).

Finally, normalized direct relationship matrices (Table 34 - Table 35) were obtained using Eq. 15 - Eq. 16, and total relationship matrices for criteria and dimensions were calculated according to Eq. 17.

Table 34. Normalized direct relationship matrix of dimensions.

	L	A	R	G	S
L	0.000	0.212	0.189	0.246	0.233
A	0.167	0.000	0.316	0.228	0.254
R	0.159	0.156	0.000	0.105	0.158
G	0.146	0.104	0.127	0.000	0.355
S	0.146	0.203	0.149	0.329	0.000

Table 36 and Table 37 show the total relationship matrix of the criteria and dimensions, which summarize the influences exerted and received.

Table 35. Normalized direct relationship matrix of criteria.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.000	0.043	0.043	0.048	0.021	0.015	0.022	0.004	0.005	0.021	0.043	0.009	0.041	0.070	0.043	0.012	0.015
L_2	0.012	0.000	0.016	0.009	0.018	0.012	0.024	0.007	0.009	0.009	0.005	0.004	0.005	0.005	0.016	0.008	0.033
L_3	0.052	0.014	0.000	0.019	0.107	0.045	0.014	0.048	0.014	0.012	0.015	0.076	0.016	0.019	0.021	0.014	0.079
L_4	0.119	0.045	0.040	0.000	0.086	0.024	0.022	0.046	0.009	0.014	0.018	0.083	0.022	0.053	0.053	0.016	0.082
A_1	0.021	0.019	0.016	0.019	0.000	0.018	0.018	0.009	0.012	0.008	0.015	0.016	0.016	0.021	0.024	0.019	0.048
A_2	0.086	0.025	0.078	0.015	0.108	0.000	0.049	0.116	0.021	0.024	0.028	0.082	0.018	0.056	0.088	0.016	0.108
A_3	0.013	0.045	0.016	0.016	0.051	0.018	0.000	0.019	0.012	0.024	0.012	0.013	0.021	0.022	0.046	0.016	0.045
R_1	0.016	0.016	0.028	0.016	0.016	0.021	0.018	0.000	0.046	0.045	0.021	0.018	0.019	0.050	0.046	0.049	0.053
R_2	0.052	0.018	0.015	0.014	0.021	0.051	0.019	0.122	0.000	0.048	0.011	0.042	0.016	0.086	0.116	0.018	0.048
R_3	0.049	0.021	0.041	0.018	0.049	0.049	0.035	0.111	0.019	0.000	0.019	0.082	0.018	0.052	0.049	0.022	0.049
G_1	0.052	0.019	0.020	0.049	0.052	0.051	0.046	0.051	0.019	0.046	0.000	0.123	0.022	0.086	0.048	0.014	0.110
G_2	0.016	0.009	0.021	0.019	0.042	0.047	0.018	0.019	0.018	0.022	0.052	0.000	0.041	0.041	0.015	0.014	0.051
G_3	0.088	0.021	0.011	0.044	0.076	0.018	0.046	0.013	0.009	0.011	0.048	0.114	0.000	0.053	0.015	0.013	0.058
S_1	0.049	0.018	0.019	0.049	0.010	0.021	0.025	0.025	0.011	0.039	0.051	0.024	0.022	0.000	0.045	0.043	0.056
S_2	0.053	0.046	0.027	0.016	0.012	0.019	0.028	0.022	0.043	0.016	0.011	0.024	0.019	0.046	0.000	0.015	0.055
S_3	0.015	0.022	0.026	0.022	0.021	0.025	0.049	0.043	0.014	0.014	0.012	0.024	0.018	0.049	0.024	0.000	0.111
S_4	0.077	0.033	0.029	0.028	0.021	0.024	0.026	0.018	0.022	0.025	0.039	0.021	0.020	0.028	0.028	0.027	0.000

Table 36. Total relationship matrix of criteria.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4	R	C	R+C	R-C	
L_1	0.05	0.07	0.07	0.07	0.06	0.04	0.05	0.04	0.02	0.04	0.07	0.05	0.06	0.11	0.08	0.03	0.07	0.97	1.60	2.57	-0.63	NR
L_2	0.03	0.01	0.03	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.03	0.02	0.05	0.40	0.90	1.30	-0.49	NR
L_3	0.10	0.04	0.03	0.05	0.15	0.07	0.04	0.08	0.03	0.04	0.05	0.12	0.04	0.07	0.06	0.04	0.14	1.15	0.96	2.11	0.19	NR
L_4	0.18	0.08	0.08	0.04	0.14	0.06	0.06	0.09	0.03	0.05	0.06	0.13	0.05	0.11	0.10	0.05	0.15	1.45	0.88	2.33	0.57	NC
A_1	0.05	0.04	0.03	0.04	0.03	0.03	0.04	0.03	0.02	0.02	0.03	0.04	0.03	0.05	0.05	0.03	0.08	0.63	1.42	2.05	-0.79	NR
A_2	0.16	0.07	0.12	0.06	0.17	0.05	0.09	0.17	0.06	0.07	0.08	0.15	0.06	0.13	0.15	0.05	0.20	1.83	0.95	2.78	0.88	NC
A_3	0.05	0.06	0.04	0.04	0.08	0.04	0.02	0.05	0.03	0.04	0.03	0.04	0.04	0.05	0.07	0.03	0.09	0.79	0.95	1.73	-0.16	NR
R_1	0.06	0.04	0.06	0.04	0.05	0.05	0.05	0.04	0.06	0.07	0.05	0.06	0.04	0.09	0.09	0.07	0.11	1.03	1.30	2.32	-0.27	NR
R_2	0.11	0.06	0.06	0.05	0.07	0.09	0.06	0.17	0.03	0.08	0.05	0.10	0.05	0.15	0.17	0.05	0.13	1.46	0.62	2.08	0.83	NC
R_3	0.11	0.06	0.08	0.05	0.10	0.09	0.07	0.16	0.05	0.03	0.06	0.13	0.05	0.11	0.10	0.05	0.13	1.41	0.81	2.22	0.60	NC
G_1	0.13	0.06	0.07	0.09	0.12	0.10	0.09	0.11	0.05	0.08	0.05	0.18	0.06	0.15	0.11	0.05	0.20	1.68	0.91	2.58	0.77	NC
G_2	0.06	0.03	0.05	0.05	0.08	0.07	0.05	0.06	0.04	0.05	0.08	0.05	0.06	0.08	0.05	0.03	0.11	0.99	1.47	2.46	-0.49	NR
G_3	0.14	0.05	0.05	0.08	0.12	0.05	0.08	0.05	0.03	0.04	0.08	0.16	0.03	0.11	0.06	0.04	0.13	1.30	0.74	2.04	0.56	NC
S_1	0.10	0.05	0.05	0.08	0.05	0.05	0.06	0.06	0.03	0.06	0.08	0.07	0.05	0.05	0.09	0.06	0.12	1.09	1.52	2.61	-0.42	NC
S_2	0.09	0.07	0.05	0.04	0.05	0.04	0.05	0.05	0.06	0.04	0.04	0.06	0.04	0.08	0.04	0.03	0.10	0.93	1.38	2.31	-0.44	NR
S_3	0.06	0.05	0.05	0.05	0.06	0.05	0.07	0.08	0.03	0.04	0.04	0.06	0.04	0.09	0.06	0.02	0.16	1.01	0.70	1.71	0.31	NC
S_4	0.12	0.06	0.06	0.05	0.06	0.05	0.05	0.05	0.04	0.05	0.06	0.06	0.04	0.07	0.07	0.05	0.06	0.99	2.01	3.00	-1.02	NR

Table 37. Total relationship matrix of dimensions.

	L	A	R	G	S	R	C	R+C	R-C	
L	0.55	0.77	0.82	0.98	1.04	4.16	3.06	7.21	1.10	NC
A	0.73	0.63	0.94	1.01	1.09	4.39	3.29	7.68	1.11	NC
R	0.53	0.56	0.47	0.65	0.73	2.92	3.64	6.56	-0.72	NR
G	0.60	0.61	0.67	0.69	1.00	3.56	4.32	7.89	-0.76	NR
S	0.65	0.73	0.75	1.00	0.81	3.93	4.66	8.59	-0.72	NR

The prominence-relation (P-R) maps (Figure 32 - Figure 33) consists of four quadrants:

- First quadrant: factors with high prominence and high relation
- Second quadrant: factors with low prominence and high relation
- Third quadrant: factors with low prominence and low relation
- Fourth quadrant: factors with high prominence and low relation

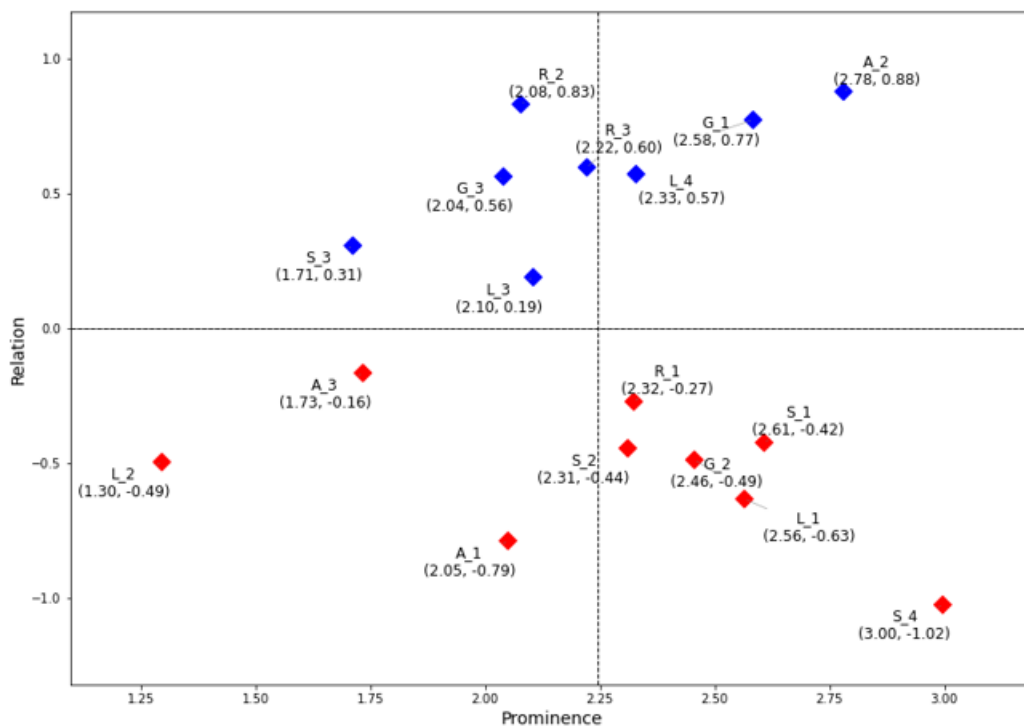


Figure 32. P-R map of the LARGS criteria (source:(Bottani, Nardo, et al., 2025)).

The first quadrant includes net causers factors, i.e., those that are fundamental within the network and significantly influence others. Among these, the most significant are “emergency order processing” (A_2) and “environmental management system” (G_1) (2.78 and 2.58 respectively), followed by “quality management system” (L_4). Furthermore, the criterion “emergency order processing” (A_2) has the highest positive relationship (0.88). Among the net causers we also find “safety stock level” (R_3), “lead time” (L_3), “collaboration” (R_2), “recycling” (G_3), and “occupational health and safety” (S_3). These criteria, located in the second quadrant, have low prominence and high relation, are less significant within the network of relationships but can still influence others. Among these, “safety stock level” (R_3) shows the greatest relevance (2.22), while “collaboration” (R_2) has the highest positive relationship (0.83) after the criterion “emergency order processing” (A_2). In the third quadrant, we find the net receivers: “customer satisfaction” (A_1), “after-

sales service” (A_3), and “guarantees and complaint policies” (L_2). Unlike the factors listed above (i.e., net causers), these factors are less relevant and are mainly influenced by other criteria. The criterion “guarantees and complaint policies” (L_2) has the least relevance in the network (1.30), while the criterion “customer satisfaction” (A_1) has the greatest relevance in this cluster (2.05). The fourth quadrant contains other net receivers: “reputation” (S_4), “financial stability” (S_1), “price” (L_1), “pollution control” (G_2), ‘vulnerability’ (R_1), and “long-term relationships” (S_2). These criteria are fundamental to the network and are influenced by others. The criterion “reputation” (S_4) has the highest absolute relevance (3.00) and also shows the highest negative relationship (-1.02).

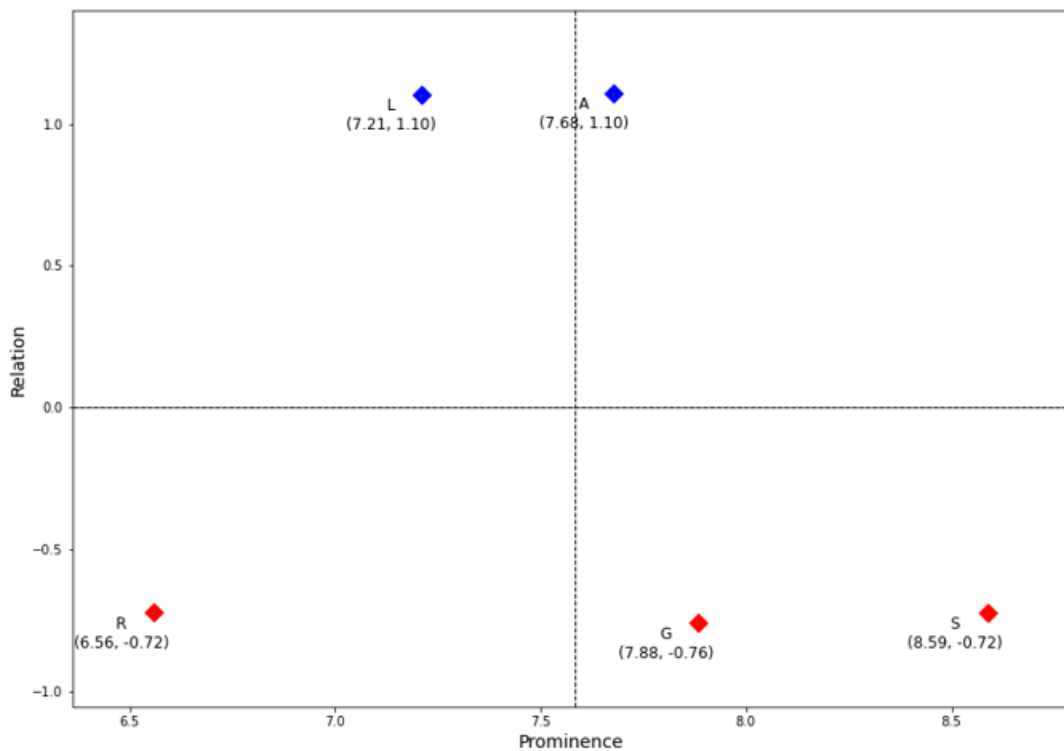


Figure 33. P-R map of the LARGS dimensions (source: (Bottani, Nardo, et al., 2025)).

In the first quadrant of the R-P map of LARGS dimension, we find the Agile dimension (A), with a prominence of 7.68 and a positive relationship of 1.10 (net cause). This suggests that the ability to respond quickly to changes in demand and market needs (i.e., agility) is critical and moderately influences the other LARGS dimensions. The Lean (L) perspective is in the second quadrant and is also a net cause (i.e., it significantly influences the remaining dimensions), with a relevance of 7.21 and a positive relationship of 1.10. The Resilient (R) dimension falls within the third quadrant, representing net receivers: its importance is positive (6.56), while its relationship is negative (-0.72). This indicates that resilience is less important than the other dimensions and can be significantly influenced by the remaining perspectives. The Sustainability (S) dimension also ranks among the net receivers, with a prominence of 8.59 (sustainability, in its environmental, social, and economic perspectives, ranks first in relative importance among the various dimensions) and a negative relationship of -0.72 (it is strongly influenced by the remaining dimensions). Alongside Sustainability (S), the fourth quadrant contains the Green dimension (G), with a prominence of 7.88 and a

negative relationship value of 0.34 (net receivers). This indicates that environmental practices are of considerable importance and are significantly influenced by the other dimensions.

Eq. 21 was used to calculate a threshold value (0.06 for the criteria and 0.76 for the dimensions) to graphically represent, using the INRM, the network of relationships between the various criteria and dimensions. Figure 34 shows the first INRM created to represent and analyze the relationships between the criteria within the five dimensions.

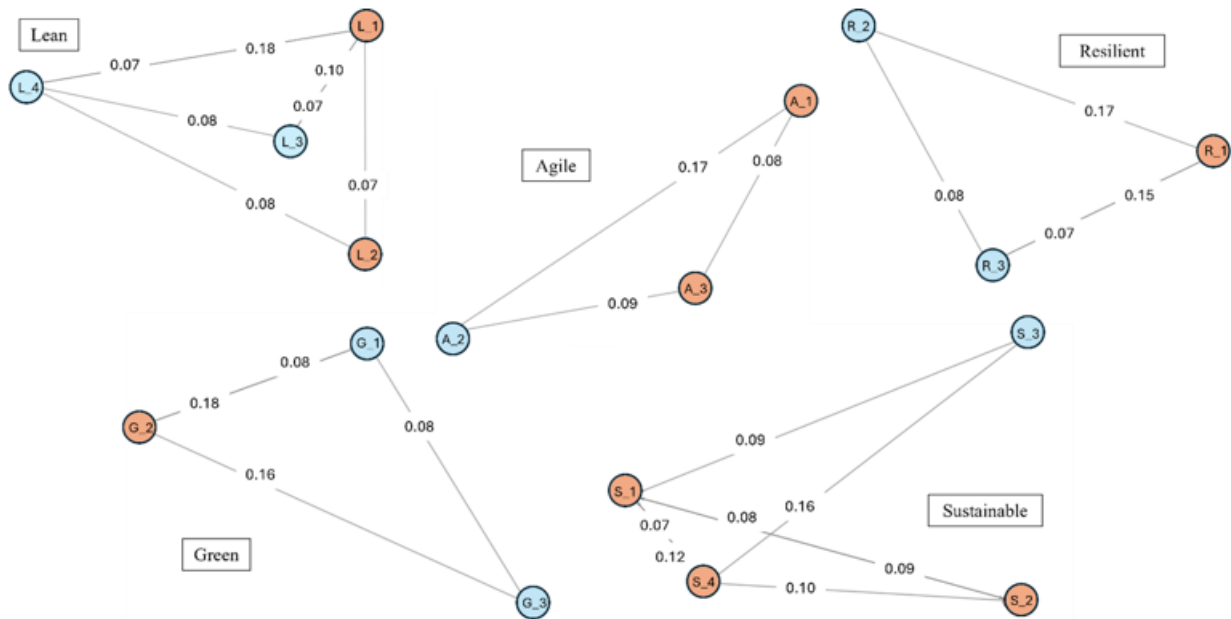


Figure 34. Network of the relationship between the criteria for the 5 dimensions (source:(Bottani, Nardo, et al., 2025)).

The “price” criterion (L_1) has a moderate influence on the parameters “warranties and complaint policies” (L_2), “delivery times” (L_3), and “quality management system” (L_4), with a value of 0.07. In turn, the “delivery times” criterion (L_3) has a moderate effect on “price” (L_1), as evidenced by a value of 0.10, suggesting a reciprocal relationship between time efficiency and economic competitiveness. Conversely, the “quality management system” (L_4) has a greater influence on several elements of the lean dimension, in particular on ‘price’ (L_1), “guarantees and complaint policies” (L_2), and “delivery times” (L_3), underlining the central role of quality as a lever for cross-cutting process improvement. Among the criteria of the Agile dimension (A), the criterion “customer satisfaction” (A_1) is influenced by the supplier's ability to handle urgent orders (A_2), with a value of 0.17, and the criterion “after-sales service” (A_3) is moderately influenced (0.09) by “processing of urgent orders” (A_2). Furthermore, “after-sales service” (A_3) affects “customer satisfaction” (A_1), with a value of 0.08. Within the Resilience (R) dimension, the “vulnerability” criterion (R_1) is significantly influenced (0.17) by the ‘collaboration’ criterion (R_2) and the “safety stock level” criterion (R_3), with a value of 0.15. Furthermore, the criterion “vulnerability” (R_1) moderately influences the criterion “level of safety stocks” (R_3), with a value of 0.07. The criterion ‘collaboration’ (R_2) exerts a moderate influence (0.08) on the criterion “level of safety stocks” (R_3).

Within the Green (G) dimension, the criterion “pollution control” (G_2) is the most influenced by the “environmental management system” (G_1) (0.18) and the criterion “recycling” (G_3), with values of 0.18 and 0.16, respectively. The criterion “environmental management system” (G_1) has a moderate influence on “pollution control” (G_2) and “recycling” (G_3), both of 0.08. The criterion “financial stability” (S_1) is influenced by “long-term relationships” (S_2) with a value of 0.08, and by “health and safety at work” (S_3), with a value of 0.09, and by “reputation” (S_4). “Reputation” (S_4) is significantly influenced (0.16) by the criterion “health and safety at work” (S_3) and by “long-term relationships” (S_2), with a value of 0.10. In turn, “reputation” (S_4) moderately influences (0.07) the criterion of “financial stability” (S_1).

Figure 35 illustrates the overall network of relationships between the criteria, considering only those relationships with a relevance value greater than the average relevance value (2.25). In addition, relationships with a strong intensity (greater than or equal to 0.15) are highlighted.

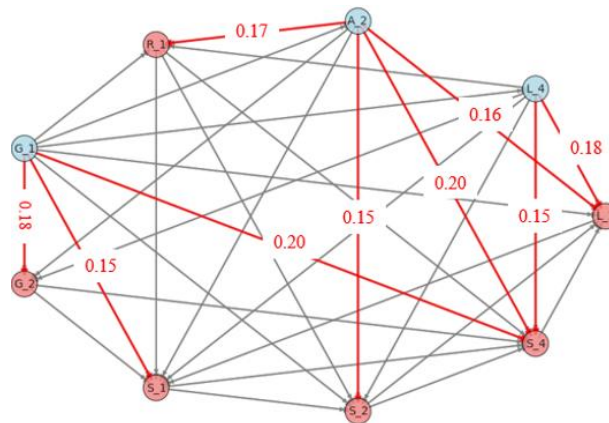


Figure 35. Overall network of relationships between the LARGS criteria based on the average value of Prominence (adapted from: (Bottani, Nardo, et al., 2025)).

The map shows that:

- The “price” (L_1) is strongly influenced by the “quality management system” (L_4), with a value of 0.18, and by the ability to “process urgent orders” (A_2), with a value of 0.16.
- The “vulnerability” criterion (R_1) is significantly influenced (0.17) by the ability to “process urgent orders” (A_2), with a value of 0.17.
- “Pollution control” (G_2) is significantly influenced by the “environmental management system” (G_1), with a value of 0.18.
- “Financial stability” (S_1) is strongly influenced (0.15) by the criterion “environmental management system” (G_1).
- The criterion “long-term relationships” (S_2) is significantly influenced by the criterion “processing of urgent orders” (A_2), with a value of 0.15.
- “Reputation” (S_4) is strongly influenced (0.20) by the criterion “processing of urgent orders” (A_2) and by environmental management (G_1), and by quality (L_4), with a value of 0.15.

Figure 36, which shows the network of relationships between the LARGS dimensions, highlights that the Agile and Lean dimensions strongly influence the remaining dimensions, with values ranging from 0.82 to 1.09. Furthermore, the Lean dimension exerts a moderate (0.77) influence on the Agile dimension.

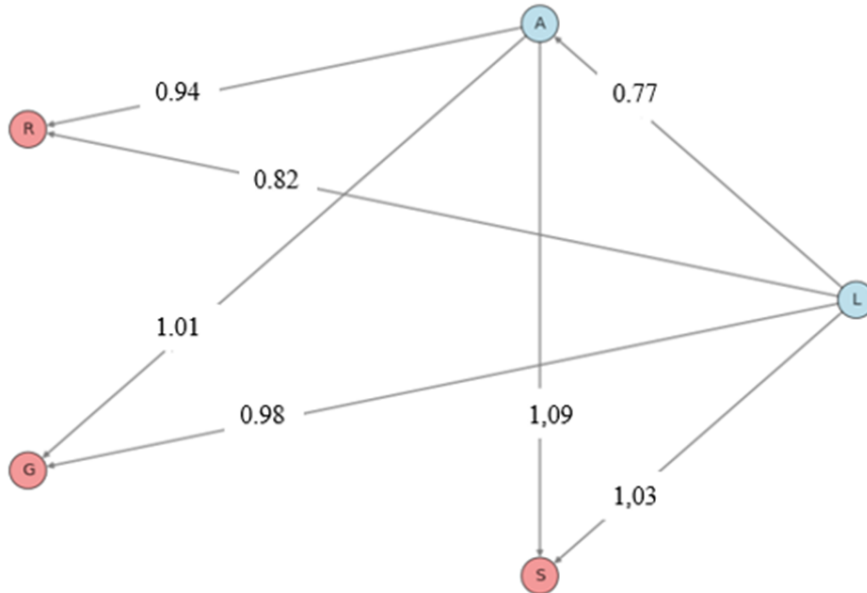


Figure 36. Network of relationship between LARGS dimensions (adapted from: (Bottani, Nardo, et al., 2025)).

The Normalized total criterion relation matrix (Table 38), Unweighted supermatrix (Table 39), Normalized total dimension relation matrix (Table 40) and weighted supermatrix (Table 41) are obtained as described in the methodology section and are shown below.

The weighted supermatrix was finally raised to successive powers (Eq. 23) until it reaches stability, obtaining the limit supermatrix (Table 42); that stable supermatrix provides the global priority vectors (influence weights).

Table 38. Normalized total criterion relation matrix.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.186	0.265	0.265	0.285	0.409	0.268	0.322	0.370	0.210	0.420	0.374	0.291	0.335	0.374	0.269	0.108	0.248
L_2	0.345	0.126	0.310	0.218	0.378	0.244	0.378	0.382	0.291	0.327	0.319	0.404	0.277	0.172	0.254	0.131	0.443
L_3	0.452	0.190	0.145	0.213	0.557	0.280	0.163	0.538	0.218	0.244	0.227	0.571	0.202	0.217	0.207	0.122	0.454
L_4	0.472	0.217	0.209	0.102	0.533	0.239	0.227	0.521	0.204	0.275	0.239	0.539	0.222	0.269	0.249	0.109	0.373
A_1	0.327	0.229	0.216	0.229	0.266	0.362	0.372	0.408	0.303	0.289	0.314	0.402	0.284	0.227	0.227	0.150	0.396
A_2	0.386	0.171	0.299	0.145	0.548	0.154	0.298	0.581	0.192	0.227	0.273	0.522	0.205	0.242	0.283	0.101	0.375
A_3	0.261	0.348	0.201	0.190	0.569	0.277	0.153	0.405	0.234	0.360	0.282	0.391	0.327	0.218	0.300	0.128	0.354
R_1	0.313	0.209	0.274	0.204	0.362	0.329	0.309	0.237	0.370	0.393	0.322	0.404	0.274	0.260	0.240	0.193	0.307
R_2	0.415	0.200	0.204	0.182	0.333	0.403	0.264	0.601	0.107	0.292	0.260	0.495	0.245	0.295	0.344	0.104	0.257
R_3	0.364	0.190	0.269	0.177	0.395	0.332	0.273	0.660	0.196	0.145	0.241	0.557	0.203	0.284	0.260	0.134	0.322
G_1	0.369	0.177	0.192	0.262	0.386	0.319	0.295	0.446	0.204	0.350	0.166	0.631	0.203	0.300	0.217	0.097	0.387
G_2	0.332	0.179	0.253	0.237	0.412	0.362	0.226	0.407	0.259	0.333	0.421	0.246	0.333	0.299	0.194	0.122	0.385
G_3	0.442	0.169	0.144	0.245	0.484	0.209	0.307	0.423	0.244	0.333	0.307	0.584	0.109	0.319	0.187	0.114	0.380
S_1	0.365	0.173	0.181	0.280	0.335	0.316	0.348	0.401	0.197	0.401	0.404	0.363	0.233	0.156	0.271	0.201	0.373
S_2	0.368	0.273	0.202	0.158	0.331	0.303	0.366	0.360	0.387	0.253	0.273	0.439	0.288	0.327	0.144	0.132	0.397
S_3	0.295	0.229	0.252	0.224	0.322	0.273	0.404	0.517	0.221	0.262	0.281	0.439	0.281	0.264	0.186	0.066	0.483
S_4	0.414	0.204	0.196	0.186	0.370	0.309	0.321	0.380	0.277	0.343	0.386	0.367	0.247	0.300	0.278	0.190	0.232

Table 39. Unweighted supermatrix.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.186	0.345	0.452	0.472	0.327	0.386	0.261	0.313	0.415	0.364	0.369	0.332	0.442	0.365	0.368	0.295	0.414
L_2	0.265	0.126	0.190	0.217	0.229	0.171	0.348	0.209	0.200	0.190	0.177	0.179	0.169	0.173	0.273	0.229	0.204
L_3	0.265	0.310	0.145	0.209	0.216	0.299	0.201	0.274	0.204	0.269	0.192	0.253	0.144	0.181	0.202	0.252	0.196
L_4	0.285	0.218	0.213	0.102	0.229	0.145	0.190	0.204	0.182	0.177	0.262	0.237	0.245	0.280	0.158	0.224	0.186
A_1	0.409	0.378	0.557	0.533	0.266	0.548	0.569	0.362	0.333	0.395	0.386	0.412	0.484	0.335	0.331	0.322	0.370
A_2	0.268	0.244	0.280	0.239	0.362	0.154	0.277	0.329	0.403	0.332	0.319	0.362	0.209	0.316	0.303	0.273	0.309
A_3	0.322	0.378	0.163	0.227	0.372	0.298	0.153	0.309	0.264	0.273	0.295	0.226	0.307	0.348	0.366	0.404	0.321
R_1	0.370	0.382	0.538	0.521	0.408	0.581	0.405	0.237	0.601	0.660	0.446	0.407	0.423	0.401	0.360	0.517	0.380
R_2	0.210	0.291	0.218	0.204	0.303	0.192	0.234	0.370	0.107	0.196	0.204	0.259	0.244	0.197	0.387	0.221	0.277
R_3	0.420	0.327	0.244	0.275	0.289	0.227	0.360	0.393	0.292	0.145	0.350	0.333	0.333	0.401	0.253	0.262	0.343
G_1	0.374	0.319	0.227	0.239	0.314	0.273	0.282	0.322	0.260	0.241	0.166	0.421	0.307	0.404	0.273	0.281	0.386
G_2	0.291	0.404	0.571	0.539	0.402	0.522	0.391	0.404	0.495	0.557	0.631	0.246	0.584	0.363	0.439	0.439	0.367
G_3	0.335	0.277	0.202	0.222	0.284	0.205	0.327	0.274	0.245	0.203	0.203	0.333	0.109	0.233	0.288	0.281	0.247
S_1	0.374	0.172	0.217	0.269	0.227	0.242	0.218	0.260	0.295	0.284	0.300	0.299	0.319	0.156	0.327	0.264	0.300
S_2	0.269	0.254	0.207	0.249	0.227	0.283	0.300	0.240	0.344	0.260	0.217	0.194	0.187	0.271	0.144	0.186	0.278
S_3	0.108	0.131	0.122	0.109	0.150	0.101	0.128	0.193	0.104	0.134	0.097	0.122	0.114	0.201	0.132	0.066	0.190

S_4	0.248	0.443	0.454	0.373	0.396	0.375	0.354	0.307	0.257	0.322	0.387	0.385	0.380	0.373	0.397	0.483	0.232
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Table 40. Normalized total dimension relation matrix.

	L	A	R	G	S
L	0.133	0.185	0.196	0.237	0.249
A	0.166	0.143	0.214	0.229	0.248
R	0.180	0.19	0.159	0.222	0.248
G	0.168	0.171	0.188	0.192	0.280
S	0.165	0.185	0.19	0.254	0.206

Table 41. Weighted supermatrix.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.025	0.046	0.060	0.063	0.054	0.064	0.043	0.056	0.075	0.066	0.062	0.056	0.074	0.060	0.061	0.049	0.068
L_2	0.035	0.017	0.025	0.029	0.038	0.028	0.058	0.038	0.036	0.034	0.030	0.030	0.028	0.029	0.045	0.038	0.034
L_3	0.035	0.041	0.019	0.028	0.036	0.050	0.033	0.049	0.037	0.048	0.032	0.043	0.024	0.030	0.033	0.042	0.032
L_4	0.038	0.029	0.028	0.014	0.038	0.024	0.032	0.037	0.033	0.032	0.044	0.040	0.041	0.046	0.026	0.037	0.031
A_1	0.076	0.070	0.103	0.099	0.038	0.078	0.081	0.069	0.063	0.075	0.066	0.070	0.083	0.062	0.061	0.060	0.068
A_2	0.050	0.045	0.052	0.044	0.052	0.022	0.040	0.063	0.077	0.063	0.055	0.062	0.036	0.058	0.056	0.051	0.057
A_3	0.060	0.070	0.030	0.042	0.053	0.043	0.022	0.059	0.050	0.052	0.050	0.039	0.052	0.064	0.068	0.075	0.059
R_1	0.073	0.075	0.105	0.102	0.087	0.124	0.087	0.038	0.096	0.105	0.084	0.077	0.080	0.076	0.068	0.098	0.072
R_2	0.041	0.057	0.043	0.040	0.065	0.041	0.050	0.059	0.017	0.031	0.038	0.049	0.046	0.037	0.074	0.042	0.053
R_3	0.082	0.064	0.048	0.054	0.062	0.049	0.077	0.062	0.046	0.023	0.066	0.063	0.063	0.076	0.048	0.050	0.065
G_1	0.089	0.076	0.054	0.057	0.072	0.063	0.065	0.071	0.058	0.054	0.032	0.081	0.059	0.103	0.069	0.071	0.098
G_2	0.069	0.096	0.135	0.128	0.092	0.120	0.090	0.090	0.110	0.124	0.121	0.047	0.112	0.092	0.112	0.112	0.093
G_3	0.079	0.066	0.048	0.053	0.065	0.047	0.075	0.061	0.054	0.045	0.039	0.064	0.021	0.059	0.073	0.071	0.063
S_1	0.093	0.043	0.054	0.067	0.056	0.060	0.054	0.064	0.073	0.070	0.084	0.084	0.089	0.032	0.067	0.054	0.062
S_2	0.067	0.063	0.052	0.062	0.056	0.070	0.074	0.060	0.085	0.064	0.061	0.054	0.052	0.056	0.030	0.038	0.057
S_3	0.027	0.033	0.030	0.027	0.037	0.025	0.032	0.048	0.026	0.033	0.027	0.034	0.032	0.041	0.027	0.014	0.039
S_4	0.062	0.110	0.113	0.093	0.098	0.093	0.088	0.076	0.064	0.080	0.108	0.108	0.106	0.077	0.082	0.099	0.048

Table 42. Limit supermatrix.

	L_1	L_2	L_3	L_4	A_1	A_2	A_3	R_1	R_2	R_3	G_1	G_2	G_3	S_1	S_2	S_3	S_4
L_1	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
L_2	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
L_3	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037	0.037
L_4	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035	0.035
A_1	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070
A_2	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053	0.053
A_3	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052	0.052
R_1	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082	0.082
R_2	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047
R_3	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060	0.060
G_1	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071	0.071
G_2	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098
G_3	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058	0.058
S_1	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067	0.067
S_2	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059	0.059
S_3	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033	0.033
S_4	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087	0.087

The local weights for each dimension were determined by adding together the global weights of the criteria belonging to the same category. Subsequently, for each dimension, the local weight of the individual criteria was calculated by comparing the global weight of the criterion to the total weight of the relevant dimension. Table 43 shows the results of this phase, displaying the local weights of the dimensions and their respective criteria, together with the global weight values obtained from the model.

Table 43. Local Weights of Dimensions/Criteria and Global Weights of Criteria.

Dimensions/Criteria	Local Weights	Global Weights	Ranking
Lean (L)	0.164		
Price (L_1)	0.354	0.058	10
Warranties and claims policies (L_2)	0.207	0.034	16
Lead time (L_3)	0.226	0.037	14
Quality management system (L_4)	0.213	0.035	15
Agile (A)	0.175		
Customer satisfaction (A_1)	0.400	0.070	5
Emergency order processing (A_2)	0.303	0.053	11
After-sales support (A_3)	0.297	0.052	12
Resilient (R)	0.189		
Vulnerability (R_1)	0.434	0.082	3
Collaboration (R_2)	0.249	0.047	13
Safety stock level (R_3)	0.317	0.060	7
Green (G)	0.227		
Environmental management system (G_1)	0.313	0.071	4
Pollution control (G_2)	0.432	0.098	1
Recycle (G_3)	0.256	0.058	9
Sustainable (S)	0.246		
Financial stability (S_1)	0.272	0.067	6
Long-term relationships (S_2)	0.240	0.059	8
Occupational health and safety (S_3)	0.134	0.033	17
Reputation (S_4)	0.354	0.087	2

Based on the results shown in Table 43:

- Lean: least influential dimension (weights: 0.164).
- Agile: higher importance (weights: 0.175)
- Resilient: mid-level relevance (weights: 0.189).
- Green: among the most important dimensions (weights: 0.227)
- Sustainable: highest weight overall (0.246)

The five key criteria are:

- Pollution control (G_2), with local weights equal to 0.432 and global weights equal to 0.098.
- Reputation (S_4), with local weights equal to 0.354 and global weights equal to 0.087.
- Vulnerability (R_1), with local weights equal to 0.434 and global weights equal to 0.082.

- Environmental management system (G_1), with local weights equal to 0.313 and global weights equal to 0.071.
- Customer satisfaction (A_1), with local weights equal to 0.400 and global weights equal to 0.070.

The global weights listed in Table 43 were applied to a real supplier selection case to demonstrate how interdependencies among criteria can significantly influence supplier ranking outcomes.

The case study concerns an Italian company, already analyzed in a previous study (Bottani et al., 2018), in which five potential suppliers of electronic components were evaluated to identify the best partners for the production of food machinery. This earlier study was performed using traditional MCDM approach, without considering the LARGS perspectives or the interrelationships among the criteria.

In the present study, the same supplier selection problem is revisited, integrating the global weights obtained from the FDANP model. These weights were used to evaluate the suppliers' performance and compute their final scores and ranking. The evaluation was conducted by the company's managers, in collaboration with academics and practitioners who had previously participated in the FDM and FDANP phases. Each supplier's performance was assessed for all criteria using a linguistic scale (Table 44), ranging from 1 (very low) to 5 (very high).

Table 44. Linguistic Scale for Evaluating a Supplier's Performance Against a Criterion.

Linguistic scale	Linguistic term set
5	Very high
4	High
3	Moderate
2	Low
1	Very low

After several consultations, the managers developed the performance matrix (Table 45), which includes the suppliers' scores for each LARGS criterion. These scores were normalized to account for the nature of the criteria, specifically distinguishing cost (C) criteria, such as price (L_1) and lead time (L_3), where lower values are preferred, from benefit (B) criteria, where higher values indicate better performance.

Table 45. Performance of each supplier against each criterion, normalized values and weights of the criteria.

Criteria	Global weight	B/C	Suppliers' performance					Normalized values				
			1	2	3	4	5	1	2	3	4	5
L_1	0.058	C	4	3	5	2	3	0.50	0.67	0.40	1.00	0.67
L_2	0.034	B	3	4	3	4	2	0.75	1.00	0.75	1.00	0.50
L_3	0.037	C	4	2	2	3	4	0.50	1.00	1.00	0.67	0.50
L_4	0.035	B	3	5	4	4	3	0.60	1.00	0.80	0.80	0.60
A_1	0.070	B	3	2	2	2	1	1.00	0.67	0.67	0.67	0.33
A_2	0.053	B	4	4	3	3	2	1.00	1.00	0.75	0.75	0.50
A_3	0.052	B	5	3	4	2	3	1.00	0.60	0.80	0.40	0.60
R_1	0.082	B	3	5	4	3	2	0.60	1.00	0.80	0.60	0.40
R_2	0.047	B	4	5	3	3	2	0.80	1.00	0.60	0.60	0.40
R_3	0.060	B	3	4	5	2	3	0.60	0.80	1.00	0.40	0.60
G_1	0.071	B	4	4	5	2	2	0.80	0.80	1.00	0.40	0.40
G_2	0.098	B	3	4	5	2	1	0.60	0.80	1.00	0.40	0.20
G_3	0.058	B	5	4	3	2	2	1.00	0.80	0.60	0.40	0.40
S_1	0.067	B	4	3	5	2	3	0.80	0.60	1.00	0.40	0.60
S_2	0.059	B	3	4	3	3	2	0.75	1.00	0.75	0.75	0.50
S_3	0.033	B	2	3	4	5	3	0.40	0.60	0.80	1.00	0.60
S_4	0.087	B	3	3	5	2	2	0.60	0.60	1.00	0.40	0.40

The normalized performance values and the corresponding global weights were combining using the Simple Additive Weighting (SAW) method to calculate the overall score of each supplier.

The results are presented in Table 46, which shows the total score and resulting ranking of the five suppliers.

Table 46. Final score and ranking of suppliers.

	Score	Ranking
Supplier 1	0.729	3
Supplier 2	0.805	2
Supplier 3	0.824	1
Supplier 4	0.583	4
Supplier 5	0.459	5

Supplier 3 achieved the highest overall score (0.729), primarily due to excellent performance in pollution control (G_2), reputation (S_4), environmental management system (G_1) and financial stability (S_1).

Supplier 2 ranked second, showing strong results in vulnerability (R_1) and pollution control (G_2), with positive contributions from long-term relationships (S_2), environmental management system (G_1) and emergency order processing (A_2).

Supplier 1 ranked third, performing well in agile criteria and recycling (G_3).

Supplier 4 ranked fourth, with satisfactory performance in lean criteria such as price (L_1) and warranties and claim policies (L_2), but weaker results in reputation (S_4), pollution control (G_2) and environmental management system (G_1).

Finally, supplier 5 ranked last, mainly due to poor performance in pollution control (G_2), customer satisfaction (A_1), vulnerability (R_1), environmental management system (G_1) and reputation (S_4).

The new ranking differs from the original results of (Bottani et al., 2018), in which supplier 2 was identified as the best option, followed by supplier 1. This shift demonstrates that considering interdependencies among criteria significantly affects the final ranking and provided a more realistic and holistic evaluation of supplier performance.

4.5 The role of green and sustainable activities in the supply chain

Building on previous quantitative findings, which highlighted the importance of ecological and sustainable perspectives in the LARGS framework, this section aims to provide a qualitative and operational understanding of how sustainability-oriented strategies can concretely support supply chain efficiency and waste reduction. To this end, the results of an ISM and MICMAC (Monferdini, Boza, Alemany, et al., 2025) analysis are presented, focusing on strategies to reduce food waste in perishable product supply chains.

To achieve the results, 16 papers were reviewed, leading to the identification of 13 key strategies (S1,...,S13) aim at reducing food waste in perishable supply chain. Table 47 lists these strategies along with their corresponding description and bibliographic references.

Table 47. 13 key strategies to reduce food waste in perishable supply chain.

No.	Strategy/Factor	Description	Source
1	Optimize inventory management	Implementation of advanced systems for real-time monitoring of inventories, expiration dates and movements in order to reduce overstocking and prevent product deterioration.	(Barto et al., 2024)
2	Enhanced cold chain management	Investment in technologies for precise temperature control during transport and storage, ensuring the quality of perishable products.	(Arriaga-Lorenzo et al., 2023; Qian et al., 2022)
3	Embracing "imperfect" produce	Promotion and sale of fresh products with aesthetic imperfections, reducing waste due to visual standards.	(van Giesen & de Hooge, 2019; Xiao et al., 2023)
4	Dynamic pricing	Offering discounts on products close to expiration date to incentivize purchasing and reduce waste.	(Kayikci et al., 2022)
5	Donation and food rescue programs	Partnering with charitable organizations to donate unsold but still consumable products, reducing waste and supporting communities.	(Montoli et al., 2023)
6	Staff training	Educating employees on best practices for handling and storing fresh produce, reducing errors that lead to waste.	(Montesdeoca-Calderón et al., 2024)
7	Collaboration with local farmers and producers	Partnerships with local producers to reduce transportation time and improve product freshness, decreasing losses during distribution	(Pimentel et al., 2022)

8	Smart demand forecasting	Using artificial intelligence to predict consumer demand, optimizing orders and reducing excess inventory.	(Makin et al., 2024)
9	Smart packaging	Use of packaging that monitors the freshness and quality of products, providing useful information for inventory management.	(Guarnieri et al., 2021)
10	Raising consumer awareness	Information campaigns to make customers aware of the importance of reducing food waste and how to properly store fresh produce.	(Szakos et al., 2021)
11	Waste-to-Energy and Composting	For waste that cannot be donated, composting and biogas production are viable sustainable solutions. It is important to focus on organic recycling technologies that allow waste to be turned into renewable energy or useful compost for agriculture.	(Sridhar et al., 2021)
12	Foster collaboration across the Supply Chain	By enhancing data transparency and real-time information sharing, supply chain partners can better align operations. For example, producers can update retailers on production volumes, while retailers share sales data to help forecast demand more accurately.	(Surucu-Balci & Tuna, 2022)
13	Adaptive delivery routing	Adjusting delivery routes in real time to prioritize the distribution of near-expiry or at-risk fresh products to closer or higher-turnover markets, helping reduce spoilage and improve sell-through.	(Avishan et al., 2025; Jedermann et al., 2014)

The survey returns a total of 145 valid responses from academic experts: PhD candidates (9), researchers (74) and lecturer (62). Figure 37. (a) Years and (b) level of experience of respondents (source: (Monferdini, Boza, Alemany, et al., 2025)). Figure 37 shows further information regarding experts' profile.

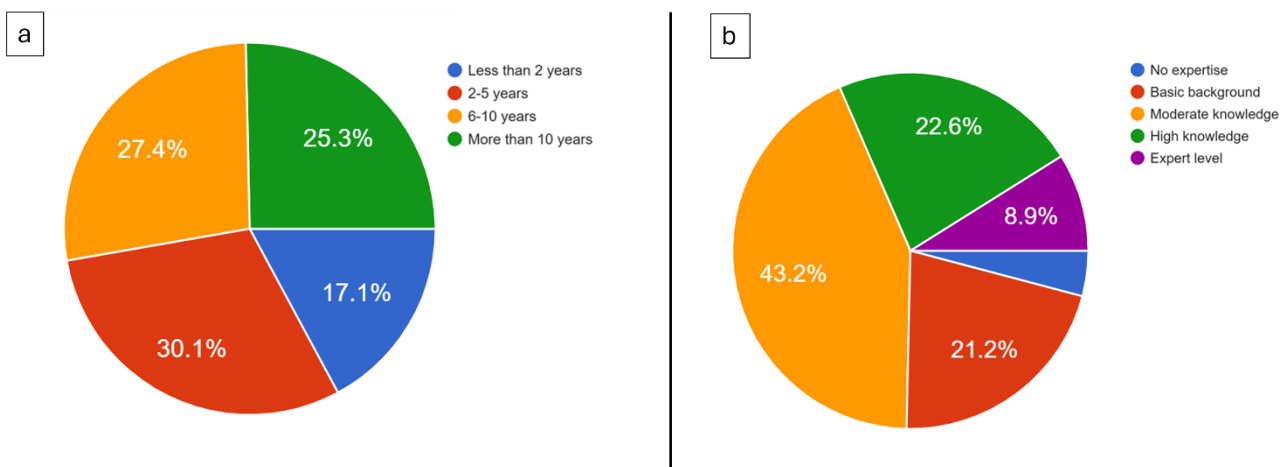


Figure 37. (a) Years and (b) level of experience of respondents (source: (Monferdini, Boza, Alemany, et al., 2025)).

The results show that among the strategies, five stand out as particularly impactful (Figure 38), having an average score above 4:

- Optimize inventory management (S1) – mean = 4.12
- Donation and food rescue programs (S5) - mean = 4.10
- Dynamic pricing (S4) - mean = 4.04
- Embracing “imperfect” product (S3) - mean = 4.00
- Collaboration with local farmers and producers (S7) - mean = 3.99

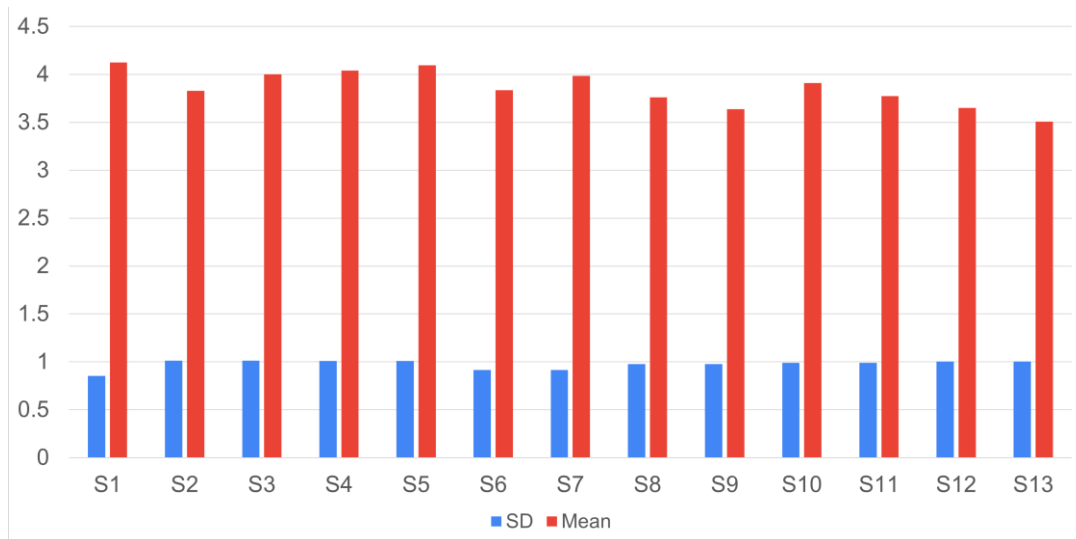


Figure 38. Mean and standard deviation of the effectiveness of strategies (source: (Monferdini, Boza, Alemany, et al., 2025)).

Four strategies receive evaluation with mean score below 3.8 (i.e., smart demand forecasting (S8), smart packaging (S9), forecasting collaboration across the supply chain (S12) and adaptive delivery routing (S13)). The standard deviation ranges between 0.85 and 1.01.

For the subsequent phase of the analysis (i.e., ISM and MICMAC) all strategies were considered because they received a mean score above 3.5, therefore they were all considered critical.

Based on experts' judgments, SSIM was developed based on experts' judgments. Some strategies influence each other, such as “acceptance of imperfect products”, “dynamic pricing” and “food donation and recovery programs”, as well as “collaboration with local farmers and producers” and “promotion of collaboration throughout the supply chain.”

Some factors, such as “adaptive delivery routes”, “staff training”, “smart demand forecasting” and “smart packaging”, act as influencing factors, while others (e.g., “inventory management optimization”, “consumer awareness” and “better cold chain management”) do not. “Waste-to-energy and composting” is the only factor that neither influences nor is influenced by other factors.

Table 48. Structural Self-Interaction Matrix.

	S13	S12	S11	S10	S9	S8	S7	S6	S5	S4	S3	S2	S1
S1	A	A	O	O	O	A	O	A	O	A	O	O	-
S2	O	O	O	O	A	O	O	A	O	O	O	-	
S3	O	O	O	V	O	O	V	O	X	X	-		
S4	O	O	O	O	O	O	O	O	O	-			
S5	O	O	O	O	O	O	O	O	-				
S6	O	O	O	O	O	O	O	-					
S7	O	X	O	O	O	O	-						
S8	O	O	O	O	O	-							
S9	O	O	O	O	-								
S10	O	O	O	-									
S11	O	O	-										
S12	V	-											
S13	-												

The SSIM matrix was converted into the initial reachability matrix and the transitivity was applied, to clearly show the direct (i.e., 1) and indirect (i.e., 1*) relationships between the factors (Table 49).

Table 49. Reachability matrix after transitivity.

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13
S1	1	0	0	0	0	0	0	0	0	0	0	0	0
S2	0	1	0	0	0	0	0	0	0	0	0	0	0
S3	1*	0	1	1	1	0	1	0	0	1	0	1*	1*
S4	1	0	1	1	1*	0	1*	0	0	1*	0	1*	1*
S5	1*	0	1	1*	1	0	1*	0	0	1*	0	1*	1*
S6	1	1	0	0	0	1	0	0	0	0	0	0	0
S7	1*	0	0	0	0	0	1	0	0	0	0	1	1*
S8	1	0	0	0	0	0	0	1	0	0	0	0	0
S9	0	1	0	0	0	0	0	0	1	0	0	0	0
S10	0	0	0	0	0	0	0	0	0	1	0	0	0
S11	0	0	0	0	0	0	0	0	0	0	1	0	0
S12	1	0	0	0	0	0	1	0	0	0	0	1	1
S13	1	0	0	0	0	0	0	0	0	0	0	0	1

Figure 39 shows the final hierarchical structure resulting from the ISM approach. The lower part consists of the most influential strategies (i.e., “acceptance of imperfect products”, “dynamic pricing” and “food donation and recovery programs”), while the upper part consists of the most dependent strategies (i.e., “optimization of inventory management”, “improvement of cold chain management” and “consumer awareness”).

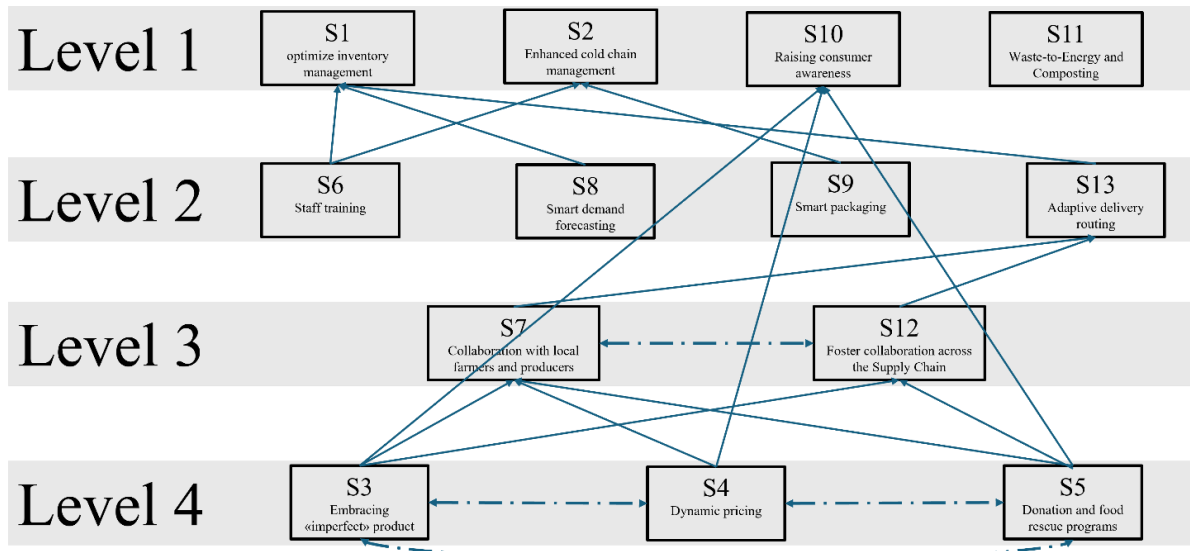


Figure 39. Final hierarchical structure of ISM approach (source: (Monferdini, Boza, Alemany, et al., 2025)).

At level 4, the most influential divers (i.e., embracing imperfect product (S3), dynamic pricing (S4), and donation and food rescue programs (S5)) emerge as concrete and effective actions capable of reducing waste directly at the retail stage, thus operating in the downstream portion of the supply chain. Their effectiveness, however, depends on the presence of enabling conditions provided by upper-level strategies; for this reason, although fundamental, they are positioned at the base of the hierarchy, as their impact is mediated by broader organizational and technological support.

Level 3 includes collaboration with local farmers and producers (S7) and foster collaboration across the supply chain (S12), emphasizing the critical role of cooperation and information exchange among stakeholders. These two strategies facilitate the alignment between supply and demand, improving flow coordination and reducing surplus or product deterioration. They function as connecting elements between the downstream practices (Level 4) and the operational enablers identified in level 2 (i.e. staff training (S6), smart demand forecasting (S8), smart packaging (S9), and adaptive delivery routing (S13)). Both collaboration with local farmers and producers (S7) and foster collaboration across the supply chain (S12) exert a direct influence on S13, as adaptive delivery routing depends strongly on transparent, timely and reliable data sharing across supply chain partners.

The second level encompasses strategies that serve as key operational factors. Staff training (S6) provides employees with the skills needed to manage processes, supporting both inventory optimization (S1) and cold chain management (S2). Similarly, intelligent demand forecasting (S8) reduces uncertainty by aligning production and storage with actual

demand, while intelligent packaging (S9) extends shelf life and provides real-time quality information to facilitate decision-making. At the top of the hierarchy (Level 1) are inventory management optimization (S1), cold chain management improvement (S2), and consumer awareness (S10), which are the most dependent strategies. These depend on the influence of lower-level factors and supporting practices. Consumer awareness (S10) is directly influenced by S3, S4, and S5, as initiatives promoting imperfect products, dynamic pricing, and donation programs encourage more responsible purchasing behavior and raise awareness about reducing food waste. Finally, waste-to-energy and composting (S11) were found to be an autonomous factor, which neither influences nor is influenced by other strategies. This independence stems from the fact that it contributes to sustainable disposal rather than preventive waste management.

The MICMAC matrix was developed considering driving and dependence power of each factor. The strategies were divided into 4 categories: driver, linkage, autonomous and dependent.

Strategies S3 (imperfect products), S4 (dynamic pricing), and S5 (food donation and recovery programs) have high driving power and low dependency, confirming their fundamental role at the lower levels of the ISM hierarchy (Level 4).

In contrast, inventory management optimization (S1), consumer awareness (S10), and delivery route adaptation (S13) showed high dependency but limited influence, positioning themselves as dependent factors. These are significantly influenced by the implementation of other strategies, in line with their placement at the upper levels of the hierarchical model (Levels 1 and 2).

Two strategies, collaboration with local farmers and producers (S7) and promoting collaboration throughout the supply chain (S12), were classified as connecting factors, as they combine high driving power and high dependency. Their bidirectional influence highlights their bridging function between the upper and lower levels, in line with their intermediate position within the ISM structure (Level 3).

Finally, optimized cold chain management (S2), staff training (S6), smart demand forecasting (S8), smart packaging (S9), and waste-to-energy and composting (S11) were classified as autonomous factors. These strategies, having low driving power and low dependency, play a relatively independent role in the overall system.

5. Discussion

5.1 Answer to RQ1

The progressive integration of Lean, Agile, Resilient, Green, and Sustainable perspectives from a conceptual basis (Bottani et al., 2024), to the definition of hierarchical priorities (Bottani, Monferdini, et al., 2025), to the use of fuzzy logic to manage uncertainty (Monferdini, Casella, et al., 2025) and model interdependencies (Bottani, Nardo, et al., 2025), has made it possible to address research question RQ1 (i.e., “*How can Lean, Agile, Resilient, Green, and Sustainable (LARGS) paradigms be integrated into a unified decision-making framework, and what are the key criteria that most influence supply chain performance in these perspectives?*”).

With this approach, each phase resolves a limitation of the previous one and cumulatively enables a LARGS operational framework.

The LARG framework was developed to map supply chain performance across processes (procurement, production, distribution, and reverse logistics) and indicators.

By considering KPIs and grouping them into the four paradigms, the framework shows that the LARG dimensions interact dynamically across all supply chain processes, as follows.

- Procurement combines lean and agile dimensions, improving both supplier responsiveness and cost control; furthermore, this phase takes into account resilience and green activities, promoting risk diversification and low-impact sourcing.
- Production simultaneously uses lean and agile approaches to standardize and improve process adaptability, and resilience and ecological dimensions to manage system continuity and environmental efficiency.
- Distribution integrates lean principles to reduce waste, agile activities to improve responsiveness to customers, and the optimization of eco-friendly transportation.
- Reverse logistics closes the loop through the recovery and recycling of materials (focusing on the green dimension), linking cost efficiency (i.e., lean dimension) with resilience.

Based on the above, the AHP model represents the first application of the LARG framework.

The model translates the conceptual structure into a hierarchical system, organized into main dimensions (Lean, Agile, Resilient, and Green), sub-criteria (the related KPIs), and alternatives (the suppliers to be evaluated).

This phase provided an initial quantitative validation of the framework, demonstrating that:

- The four perspectives can be coherently integrated within a unified decision support structure.
- The application of AHP in the case study on supplier selection allows for the objective weighting of criteria based on their frequency and relevance, as defined in the previous conceptual framework.

- The resulting hierarchy ensures transparency and replicability, addressing one of the main limitations of qualitative decision-making processes.

The AHP model has some limitations: as the number of criteria and subcriteria increases, the pairwise comparison process becomes progressively more complex, requiring greater effort and potentially leading to inconsistencies in expert judgments. Furthermore, it can be difficult to define evaluation criteria with sufficient precision and assign reliable scores, especially in areas where supplier performance cannot be easily quantified, such as sustainability assessments.

To overcome the limitations identified in the application of AHP, the next phase of the research introduced a fuzzy logic-based decision support model to evaluate the LARG supply chain and implemented the tool using Excel™.

The model takes into account fluctuations in supplier delivery performance, reliability, and flexibility, factors that are typically uncertain in procurement activities. In the production phase, it detects variations in equipment effectiveness, processing times, and defect rates, thus helping to mitigate risks associated with capacity constraints or operational disruptions. For distribution, the approach integrates uncertainties related to delivery accuracy, vehicle loading efficiency, and fuel consumption, supporting more effective logistics planning under changing demand conditions. In reverse logistics, it accounts for the unpredictability of return times, quantities, and processing efficiency, which are inherently difficult to forecast.

The results of the model confirmed that:

- Lean practices remain the most established and standardized foundation across all stages of the supply chain, in line with their established role in ensuring process efficiency and stability.
- Agility, although conceptually transversal, appeared to be more concentrated in specific operational areas, particularly in manufacturing and reverse logistics, where flexibility and responsiveness are critical.
- Resilience emerged as a structural requirement rather than a reactive capability, demonstrating its integration as a permanent element in supply chain design, especially in upstream processes such as procurement and manufacturing.
- The ecological dimension turned out to be easier to implement in production and reverse logistics activities than in external activities (i.e., in procurement and distribution), where integration with partners and suppliers presents greater challenges.

By converting qualitative and variable information into fuzzy linguistic evaluations, the model allows for a more realistic assessment of supply chain performance.

Although green practices are well integrated into internal processes, their adoption in external operations remains limited. This result shows that the green dimension alone cannot represent the entire concept of sustainability. The sustainable dimension (S) has been integrated into the model, extending the LARG paradigm to LARGS and incorporating economic and social aspects.

The Fuzzy Delphi-DEMATEL-ANP model allowed for a more complete analysis of the complex relationship between LARGS criteria and managing uncertainty and subjectivity in expert judgments. The analysis revealed that the inclusion of the sustainability dimension significantly reshaped the internal balance of the model. Sustainability emerges as the most influential factor, reflecting its transversal nature and its role as an enabler for the other paradigms. The green and sustainable dimensions, while related, act at different levels: the former focuses on environmental practices, while the latter encompasses strategic, social and ethical issues.

At the criterion level, five key drivers were identified as having the highest global weights: pollution control (G_2), reputation (S_4), vulnerability (R_1), environmental management system (G_1) and customer satisfaction (A_1). These factors encompass environmental protection, social responsibility, risk management and customer orientation, linking these criteria within a single structure.

The comparison between local and global weights shows that, locally, lean and agile operations retain importance for short-term performance, while, globally, sustainable criteria gain relevance once interdependencies are considered. Sustainability has proven to be not an isolated goal, but an element integrated into the LARGS network that strengthens the entire structure and improves the performance of the supply chain.

More specifically, from a lean perspective, the criteria include price (L_1), delivery times (L_3), warranties and complaint policies (L_2), and the quality management system (L_4). On the one hand, price and delivery times are among the most commonly used indicators for supplier evaluation, while the inclusion of warranties and quality management systems links operational efficiency to product reliability and service quality. The Agile dimension includes customer satisfaction (A_1), urgent order processing (A_2), and after-sales service (A_3), reflecting the supplier's ability to respond quickly to customer needs and market fluctuations. The inclusion of after-sales service, increasingly recognized as a key component, introduces a customer-centric and service-oriented vision that was rarely emphasized in previous models. From a resilience perspective, vulnerability (R_1), collaboration (R_2), and safety stock level (R_3) were identified as the most relevant criteria. These criteria reflect preventive and adaptive capabilities, confirming that risk management and collaborative relationships are essential to ensuring continuity in the event of disruptions. This is also a consequence of recent global crises, which have made resilience a fundamental requirement. The green dimension includes environmental management systems (G_1), pollution control (G_2), and recycling practices (G_3). These practices aim to reduce emissions and waste while complying with environmental regulations. Their inclusion emphasizes that supplier evaluation increasingly extends beyond economic and operational performance to include measurable ecological impacts. Finally, the sustainable dimension integrates financial stability (S_1), long-term relationships (S_2), occupational health and safety (S_3), and reputation (S_4). Together, these criteria capture the economic, social, and ethical dimensions of sustainability. Financial stability and long-term partnerships promote supply chain continuity and strategic alignment, while occupational health and safety and reputation reflect suppliers' social responsibility and credibility among stakeholders.

The results obtained through the progressive development of the framework, the AHP model, and the fuzzy logic and FDANP methods demonstrate that the integration of lean, agile, resilient, green, and sustainable paradigms within a unified decision support structure can work, provided that each is modeled using appropriate analytical methods that capture their specific characteristics and address a different aspect of the complexity of the decision-making process. The hierarchical structure developed with AHP, the management of uncertainty made possible by fuzzy logic, and the analysis of interdependence obtained through FDANP collectively define a LARGS operational framework capable of linking conceptual paradigms with measurable performance results. Furthermore, the identification of key criteria covering economic, operational, environmental, social, and ethical aspects for supply chain assessment, with a specific focus on supplier selection, confirms that performance cannot be understood by considering efficiency alone. Rather, it emerges from the balanced interaction between efficiency, flexibility, robustness, and sustainability-oriented factors. The inclusion of sustainability as a cross-cutting and enabling dimension redefines the traditional LARG framework, transforming it into a dynamic and interconnected model (LARGS) in which performance improvement depends on the integration of all five paradigms.

5.2 Answer to RQ2

Based on the results discussed above, the analysis delves into the relationships between the criteria (Bottani, Nardo, et al., 2025) and enabling factors (Monferdini, Boza, Alemany, et al., 2025) that influence the implementation of the LARGS paradigm in the supply chain (answering RQ2: “*What are the main interdependencies, barriers, and favorable conditions that influence the implementation of LARGS strategies?*”).

The results of the FDANP model made it possible to represent the direct and indirect relationships between the LARGS dimensions/criteria. Table 50 summarized the classification as net receiver and net causers of the key criteria emerged and already discussed in the results section.

Table 50. Key criteria and relationships emerging from FDANP model.

Criteria	Description
Price (L_1)	Classified as <i>net receiver</i> , influenced by other criteria. Moderate influence on L_2, L_3 and L_4, with a value of 0.07. Moderate influenced by L_3 (0.10) and L_4 (0.18). It turns out to be the most important criterion within the Lean dimension (local weight=0.354, global weight=0.058).
Lead Time (L_3)	Classified as <i>net causer</i> , influencing other criteria. It is moderate influenced by L_1 (0.07) and L_4 (0.18) and it moderate influence L_1 (0.10). Emerged as the second most significant criterion within the Lean dimension (local weight=0.226, global weight=0.037).
After-Sales Support (A_3)	Classified as <i>net receiver</i> , influenced by other criteria. It is influenced by A_2 (0.09). It has local weight = 0.297 and global weight = 0.052, highlighting an important role within the agility perspective.
Environmental Management System (G_1)	Classified as <i>net causer</i> , influencing other criteria. It exhibits the highest prominence in this cluster (2.78 and 2.58, respectively). It influences G_2 (0.18), G_3 (0.08), S_4 (0.20) and S_1 (0.15). It is influenced by G_2 (0.08). It is the second most relevant criterion within the Green dimension (local weight=0.313, global weight=0.071) and is the fourth by importance among all LARGS criteria.
Long-Term Relationships (S_2)	Classified as <i>net receiver</i> , influenced by other criteria. It is influenced by S_1 (0.09), A_2 (0.15). The “financial stability” criterion (S_1) moderately influences “long-term

Reputation (S_4)	relationships" (S_2), with a value of 0.09, and "reputation" (S_4), with a value of 0.12. Classified as <i>net receiver</i> , influenced by other criteria. It has the highest absolute prominence (3.00) and also exhibits the highest negative relation (-1.02). It is influenced by S_1 (0.12), S_2 (0.10), L_4 (0.15) and S_3 (0.16) and, strongly, by G_1 (0.20) and A_2 (0.20). It influences S_1 (0.07). It is the most importance criterion within the Sustainable dimension, with local weight=0.354 and global weight=0.087, and the second by importance overall among the LARGS criteria.
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In addition, Figure 40 shows the structure of interactions between LARGS criteria.

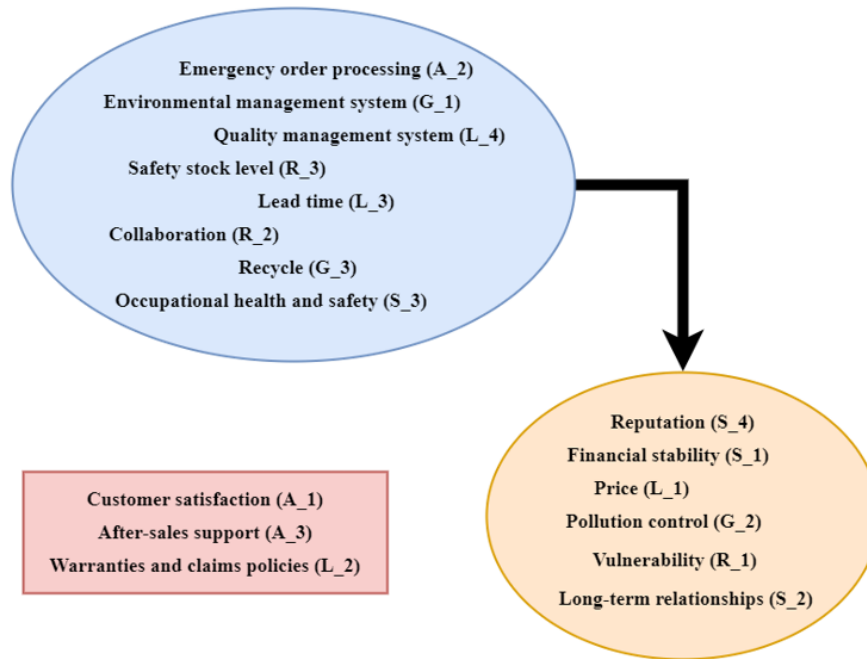


Figure 40. Structure of the interaction system among the LARGS criteria (source:(Bottani, Nardo, et al., 2025)).

The Agile dimension emerges as highly influential on the remaining perspectives: flexibility and responsiveness, factors that enable rapid adaptation to changing demand and market conditions in a volatile and uncertain supply chain environment, emerge as central elements within the network of relationships.

The key objectives are also productivity and cost reduction, placing the lean dimension as the second most critical factor and classifying it in the “causes” group, together with the agile dimension.

The results reveal that environmental sustainability is a key element in supply chain management and a strategic value for long-term competitiveness. Sustainability, together with the green dimension, are those most directly or indirectly influenced, constituting the “effects” group.

The Resilient dimension is highly independent, showing low interaction with the previously identified “causes” group.

The criteria "emergency order processing" (A_2), "environmental management system" (G_1), and "quality management system" (L_4) emerge as clear causal factors, strongly influencing the behavior of other elements within the network.

In contrast, the factors "pollution control" (G_2), "reputation" (S_4), and "vulnerability" (R_1) belong to the "effects" group. Furthermore, the criterion "customer satisfaction" (A_1) is highlighted as one of the most important, while remaining independent of the "causes" factors.

The numerical example presented in Section 4.4 highlights the importance of considering the interrelationships between LARGS dimensions and underlying criteria when selecting suppliers and determining the weights of evaluation factors. The analysis indicates that the most suitable supplier is the one that achieves the highest performance in key criteria such as pollution control (G_2), reputation (S_4), environmental management system (G_1), and financial stability (S_1). Specifically, three of these criteria, pollution control (G_2), reputation (S_4), and environmental management system (G_1), also emerged as the most influential LARGS criteria overall, underscoring their critical role in determining supplier evaluation outcomes. In contrast, Supplier 5, which achieved the lowest overall score, showed weak performance in these same critical areas, particularly pollution control (G_2), customer satisfaction (A_1), vulnerability (R_1), environmental management system (G_1), and reputation (S_4).

These results once again highlight the centrality of green and sustainable dimensions.

Sustainability strategies are further explored in the analysis of perishable products, analyzed using the ISM-MICMAC approach. In particular, the findings reveal that strategies such as the adoption of imperfect products (S3), dynamic pricing (S4), and food donation and recovery programs (S5) act as key factors in reducing waste by directly intervening in the downstream stages of the food supply chain. However, their effectiveness depends on the presence of enabling conditions provided by organizational and technological practices, represented by intermediate strategies such as collaboration with local farmers and producers (S7) and the promotion of collaboration throughout the supply chain (S12). The highest levels of the hierarchy include inventory optimization (S1), cold chain management (S2), and consumer awareness (S10), which emerge as interdependent strategies. Their success relies on the implementation of key factors and lower-level linkages. The MICMAC analysis complements this view by demonstrating that, while operational strategies (S3 - S5) exert a strong driving force, collaborative strategies (S7, S12) act as bridges connecting short-term operational initiatives with long-term sustainability goals. In turn, autonomous strategies such as employee training (S6), intelligent demand forecasting (S8), and intelligent packaging (S9) play a supporting yet independent role, improving efficiency and information accuracy across the network.

Overall, the FDANP analysis highlighted that the Lean and Agile dimensions act as key drivers, influencing the overall system through efficiency and flexibility, while the Green and Sustainable dimensions represent the main outcomes of these interactions, confirming their role as "receivers" within the network. Resilience, in turn, emerged as an independent yet stabilizing factor that ensures structural robustness throughout the supply chain.

Meanwhile, the ISM-MICMAC analysis identified the favorable conditions that translate these interdependencies into operational results. Strategies such as dynamic pricing, the adoption of imperfect products, and food donation programs proved to be the main drivers

of sustainability-oriented performance, supported by enabling mechanisms such as collaboration throughout the supply chain, partnerships with local producers, and staff training.

5.3 Theoretical implication

From a theoretical perspective, the present thesis contributes to the evolution of supply chain management models as follows:

- The development of the LARG framework represents an important advancement in supply chain performance literature: (i) It creates a structure capable of mapping performance across all supply chain processes, unifying the existing body of research on LARG paradigms. (ii) It provides a measurable and comparable basis for evaluating the four perspectives, considering KPIs drawn from the literature. (iii) It enables a process-oriented interpretation, aligning performance measurement with the dynamic nature of supply chain operations (procurement, production, distribution, and reverse logistics). (iv) It views green performance as a factor structurally linked to operational objectives, demonstrating that environmental and efficiency dimensions can coexist within a single evaluation model.
- The development of the LARG-AHP model: (i) operationalizes the previously defined conceptual framework through a structured MCDM approach, (ii) promotes the integration of LARG paradigms in supply chain management within a quantitative and hierarchical system, (iii) structures the evaluation process through pairwise comparisons and ratio scales, allowing for reproducible and evidence-based decision-making results, thus overcoming one of the limitations of qualitative evaluations (i.e., the difficulty of ensuring consistency and transparency in the experts' judgment) and (iv) demonstrates that a supplier can achieve good results from multiple perspectives simultaneously, confirming that the different LARG dimensions can work together in a complementary way within the supply chain.
- The fuzzy logic-based model improves the theoretical contribution of supply chain evaluation under LARG paradigm by introducing a flexible decision-making approach. Specifically: (i) it provides an analytical framework capable of modeling the ambiguity inherent in supply chain assessments. (ii) It distinguishes between internal processes (production and reverse logistics), where green practices are more easily implemented, and external ones (procurement and distribution), where integrating sustainability encounters greater obstacles. (iii) It transforms subjective judgments into quantitative outputs.
- The FDANP model extend the LARG paradigm into LARGS, incorporating the sustainable dimension. Theoretically: (i) the integration of Fuzzy Delphi, DEMATEL, and ANP provides a comprehensive analytical framework for capturing both causal relationships and the uncertainty inherent in expert judgment. (ii) It demonstrates that Lean and Agile dimensions remain key drivers of efficiency and responsiveness, while the Sustainable dimension emerges as the most influential and transversal factor, enabling long-term alignment between operational performance, environmental responsibility, and social value creation. (iii) It estimates how each

criterion influences the others and confirms that supply chain performance results from a network of cross-effects (not from isolated factors). (iv) It demonstrates that performance improvement depends on the balance and interaction between efficiency-based paradigms (Lean and Agile) and sustainability-oriented paradigms (Green and Sustainable). (v) It positions sustainability as both an integrative enabler and a strategic outcome within the LARGS framework.

- The ISM-MICMAC approach introduces a structured representation of the interrelationships among criteria within a specific context (i.e., perishable supply chain). The model: (i) provides a hierarchical and causal view of how operational, organizational, and technological factors interact to improve sustainable performance, (ii) highlights that waste reduction in perishable supply chains is not the result of isolated actions, but emerges from a network of interacting strategies and (iii) demonstrates that sustainability in supply chains arises from the practical application of theoretical paradigms, thanks to the combination of strategies and factors that work together at multiple levels of the system.

5.4 Managerial implication

- The LARG framework (i) provides practical guidance to managers for assessing and improving supply chain performance across all operational processes. (ii) It enables managers to map key performance indicators (KPIs) by process (procurement, manufacturing, distribution, and reverse logistics), helping them recognize which operational areas require intervention and which LARG dimension is most critical for improvement.
- From a managerial perspective, the LARG-AHP model (i) helps managers understand, in a structured and numerical way, which criteria are most important for supply chain performance and on which aspects to focus improvement efforts. (ii) It reduces subjectivity in expert assessments and improves the transparency and traceability of strategic procurement decisions. (iii) Managers can apply the model to simulate alternative supply scenarios, compare performance across different LARG dimensions, and select suppliers that can deliver both efficiency and sustainability.
- Some managerial suggestions emerge from the fuzzy logic model. Given the consistently positive results, lean practices appear to be well established and standardized throughout the supply chain. However, in manufacturing, where efficiency levels remain relatively lower, there is potential to strengthen lean initiatives by increasing process standardization, reducing variability, and promoting continuous improvement programs. The heterogeneous performance of the agile dimension indicates that agility is not uniformly integrated across all stages of the supply chain. Although reverse logistics and manufacturing show strong adaptability, its limited integration into procurement and distribution may hinder the company's ability to react quickly to unexpected market changes or supply disruptions. Managers are encouraged to invest in digital solutions such as real-time monitoring systems, demand forecasting tools, and flexible sourcing strategies to strengthen agility, particularly in upstream and downstream activities. The solid performance observed in purchasing and production confirms that upstream resilience has become a priority,

likely influenced by recent global disruptions. Managers should maintain this focus by fostering strong relationships with suppliers, while extending resilience downstream, particularly in distribution, where the ability to absorb shocks appears weaker.

The green dimension reveals a clear divide between internal operations (production and reverse logistics) and external operations (procurement and distribution). Managers should leverage positive results achieved internally to promote the spread of sustainable practices across the company. At the same time, lower scores in sourcing and distribution highlight the need for greater engagement with environmentally responsible suppliers and the adoption of sustainable logistics solutions, such as integrating environmental criteria into supplier selection and partnering with green logistics service providers. Based on these considerations, the following managerial actions are recommended:

- Maintain lean practices as standardized routines and extend them to production processes where performance is below average.
 - Strengthen lean implementation through process standardization, value stream mapping, and continuous improvement initiatives.
 - Adopt flexible transportation options and advanced demand forecasting technologies to improve distribution performance, especially from an “agile” perspective.
 - Improve supply chain responsiveness by applying flexible sourcing policies, improving demand perception, and adopting real-time monitoring systems.
 - Build downstream resilience through greater distribution flexibility, last-mile risk management, and contingency planning.
 - Promote the development of green suppliers, include sustainability metrics in procurement criteria, and collaborate with eco-friendly logistics partners to bridge the internal-external sustainability gap.
- The results of the FDANP model allow us to draw some management conclusions, including: (i) the strategies that managers and companies should adopt when selecting suppliers; (ii) indications on lean, agile, resilient, green, and sustainable dimensions and the related criteria to be prioritized to ensure business success. Specifically, the results of the FDANP model show that particular attention must be paid to factors such as “urgent order processing” (A_2), “environmental management system” (G_1), and “quality management system” (L_4) when selecting suppliers. A well-implemented environmental management system helps ensure compliance with regulatory standards throughout the supply chain, thereby preventing disruptions related to legal or environmental issues. In addition, a strong corporate reputation builds trust among existing and potential customers, facilitating the creation of new business partnerships and strengthening existing ones. The quality of products or services and the company's responsiveness in times of crisis, as well as its commitment to sustainable activities, improve supplier confidence. This also leads to increased sales, with a clear competitive advantage. As a result, end consumers, investors, and other stakeholders are more attracted to the supply chain and more inclined toward long-term growth opportunities. Companies must manage their ability to anticipate and mitigate risks arising from sudden events, preventing production

delays, material shortages, and other operational inefficiencies. Similarly, the ability to handle urgent or emergency orders demonstrates flexibility and adaptability, preserving business continuity and avoiding costly downtime. Market demand must be studied and managed in order to respond quickly to sudden changes. An effective environmental management system is a link between the entire system, capable of influencing and being influenced by other criteria. This also helps reduce environmental impact, improving both the performance and reputation of the supply chain. Sustainable activities are increasingly attractive to investors, customers, and stakeholders, who choose to do business with companies that demonstrate a clear commitment to this. Based on this, companies can adopt innovations in production processes that consider the circular economy: recycling activities lead to reduced production costs and increase the resilience, as well as sustainability, of the supply chain. The results also show that agility and leanness do not necessarily lead to improved resilience, but managers can recommend that their suppliers adopt lean and agile practices to improve green and sustainable dimensions. For example, concentrating a supply base in a specific geographic area (lean practices) reduces delivery times and, in addition, leads to a reduction in CO₂ emissions (thereby improving environmental practices). It also improves the social dimension, supporting local job creation. Companies should separately manage strategies focused on adaptability and recovery from disruptions (resilience dimension). The network of relationships shows that the adoption of Enterprise Resource Planning/Advanced Planning and Scheduling (ERP/APS) systems and environmental certifications can improve the ability to manage demand fluctuations (demand risk) and corporate reputation, respectively. Furthermore, some technologies could also be used to improve sustainability, reducing environmental impact through emissions treatment, wastewater management, and solid waste management. From this perspective, companies can demonstrate their commitment with environmental certifications (e.g., ISO 14001). It should be noted, however, that the use of these technologies, while having benefits, can also lead to negative impacts, such as increasing the company's vulnerability to technical failures. ERP systems unify logistics, production, and sales data, also enhancing a company's agile capabilities. Using ERP software, along with APS software, allows for real-time data management, predicting the consequences of any process changes and adapting promptly to these changes. Resilience is also improved thanks to these technologies, which, in addition to improving the ability to adapt to unexpected market changes, also enable a rapid and effective response to disruptions. Suppliers, as well as all personnel, must be adequately trained to respond quickly to logistical disruptions, natural disasters, or technical failures. For example, using local sourcing ensures that resources have a faster response in the event of an emergency.

- The ISM-MICMAC model applied to the perishable products supply chain has shown that dynamic pricing (S4), the valorization of imperfect products (S3), and food donation and recovery programs (S5) are driving factors. Managers should consider how these three strategies reduce food waste and influence consumer confidence. Companies should be aware that these strategies are effective when supported by

organizational and technological practices. Furthermore, managers should prioritize the creation of collaborative networks with local farmers and supply chain partners, as these relationships amplify the effectiveness of both downstream initiatives and upstream practices. If companies want to improve inventory and cold chain management, they must adopt strategies such as staff training and the use of demand forecasting technologies. Finally, regarding unavoidable waste, companies should seek to manage it sustainably, for example, by adopting the "waste-to-energy and composting" practices (S11).

5.5 Practical implication

From a practical perspective, the LARG-AHP model provides managers with a practical and replicable tool for supplier evaluation.

In addition, the fuzzy logic model, implemented in Excel™ (i) provides managers with a flexible and intuitive tool for evaluating supply chain performance under uncertain and variable conditions. (ii) It helps decision makers identify performance gaps in different operational areas (procurement, production, distribution, and reverse logistics) and understand how uncertainty affects each process. For example, it can highlight where demand variability, supplier reliability, or production efficiency have the greatest impact on overall performance. (iii) By translating qualitative assessments into quantitative scores, the model improves the objectivity and comparability of managerial assessments, reducing bias and facilitating continuous monitoring over time. (iv) Its adaptability makes it suitable for a wide range of industries. Managers can easily adjust KPIs, language variables, and reference values to align the tool with their strategic objectives and operational characteristics, ensuring its relevance and practicality.

Some practical implications emerge from the result of the FDANP model: (i) The importance of take into account the interconnections between LARGS dimensions and criteria in real-world supplier selection processes. (ii) The need to consider the relationships between perspectives and criteria in companies' current supplier selection processes, updating existing processes. (iii) The LARGS paradigm provides a robust framework for evaluating suppliers not only based on traditional metrics, but also considering their adaptability, environmental impact, and ability to withstand disruption. (iv) Finally, the developed tool can be adapted to any supplier selection context, and the results can therefore be integrated into any tool used by companies.

Considering the specific context of perishable products, this study offers a tool to support companies and stakeholders in improving food waste management. The ISM-MICMAC model allows for the assessment of the influence relationships between strategies and their individual effectiveness in reducing food waste. Thus, the framework supports stakeholders in identifying the most effective strategies and assigning priorities.

6. Conclusion

This doctoral thesis aimed to develop frameworks and tools for evaluating logistics processes and improving supply chain performance according to the Lean, Agile, Resilient, Green, and Sustainable (LARGS) paradigms. The work addressed two main research questions:

- RQ1 (i.e., *How can Lean, Agile, Resilient, Green, and Sustainable (LARGS) paradigms be integrated into a unified decision-making framework, and what are the key criteria that most influence supply chain performance in these perspectives?*) investigated how these paradigms could be integrated into a unified decision-making framework.
- RQ2 (i.e., *What are the main interdependencies, barriers, and favorable conditions that influence the implementation of LARGS strategies?*) explored the interdependencies between the criteria, obstacles, and enabling conditions that influence their implementation.

The research offers a progressive methodological path from the conceptualization of the LARG framework to its practical implementation through hybrid and fuzzy tools.

The LARG framework enabled the systematic mapping of KPIs in procurement, manufacturing, distribution, and reverse logistics, offering a complete view of supply chain performance.

The LARG-AHP model enabled hierarchical and quantitative prioritization of performance indicators, supporting objective supplier evaluation.

The fuzzy logic tool provided an effective solution for managing uncertainty and linguistic evaluations, translating qualitative judgments into quantitative results and ensuring flexibility across all areas.

The extension to the LARGS paradigm, developed through the hybrid Fuzzy Delphi - DEMATEL - ANP model, revealed strong interdependencies between the dimensions (lean, agile, resilient, green and sustainable) and between the criteria. Lean and Agile emerged as driving factors influencing the system through efficiency and flexibility, while Green and Sustainable acted as receiving dimensions reflecting the results of these interactions.

Finally, the ISM-MICMAC analysis highlighted the hierarchical relationships between strategies to reduce food waste in perishable supply chains, identifying dynamic pricing, the valorization of imperfect products, and food donation programs as key operational levers supported by collaborative and technological factors. This analysis further emphasized the importance of sustainability by focusing on a specific context.

Despite its contributions, the present study has some limitations. The empirical validation, of AHP and fuzzy model, relies primarily on expert judgments and numerical examples rather than large-scale industrial data. The number of experts involved, while adequate for methodological validation, may limit the generalizability of the results. Furthermore, fuzzy

models rely on subjective linguistic assessments that, while structured, remain partly influenced by individual perception. Finally, the analyses focus on selected industrial contexts; extending the approach to other sectors could reveal different dynamics or additional interdependencies.

Future research can overcome these limitations by expanding empirical validation through case studies and surveys across different sectors.

Moreover, several barriers to the implementation of LARG(S) strategies emerge from the literature; in this perspective, a combined Delphi and ISM–MICMAC approach could be applied to identify, validate, and prioritize these barriers. This extension would provide further evidence to support decisions for both companies and stakeholders, improving understanding of the critical factors that hinder or facilitate the transition towards sustainable, resilient and efficient supply chains.

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