ResC4EU
RESILIENT SUPPLY CHAINS FOR EUROPE

# D4.1
# Risk and Alerts Framework for Multimodal Logistics and Supply Chain Resilience

Funded by
the European Union

LinkedIn ResC4EU www.resc4eu.com

| | |
|---|---|
| Project Acronym | ResC4EU |
| Project Title | Resilient Supply Chains for Europe |
| Project No.: | 101137643 |
| Project Start date | 01 January 2024 |
| Project duration | 36 months |

| | |
|---|---|
| Deliverable No. | D4.1 |
| Deliverable Title | Risk and Alerts Framework for Multimodal Logistics and Supply Chain Resilience |
| Work Package/Task | WP4 / Task 4.1 |
| Deliverable Type | R- Report |
| Dissemination level | Public |
| Version No. | 1.6 |
| Version Date | 2 June 2025 |

| | |
|---|---|
| Deliverable Lead | Institute of Maritime Economics and Logistics (ISL), Bremen, Germany |
| Lead Responsible | Aseem Kinra, ISL |
| Contributing Partners | FHG, MCN, AID, ATIM, SCA |
| Contributing Authors | Debarshee Bhardwaj, ISL; Sönke Matsch, ISL; Frida Schulze, FHG; Kunal Chaudhari, FHG; Holger Kramer, ISL; Aseem Kinra, ISL |
| Due month/date | M15 / 31 March 2025 |
| Submission date | M18 / 8 June 2025 |

| | |
|---|---|
| Public | Public, fully open, automatically published by EC as download in CORDIS ResC4EU project's page & published by ResC4EU Consortium as download on ResC4EU website |
| Confidential | Confidential or sensitive, only for members of the ResC4EU Consortium (including the Commission Services) |
| Copyright |  |
| Disclaimer | Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the granting authority (HADEA- European Health and Digital Executive Agency). Neither the European Union nor the granting authority can be held responsible for them. |

| History of Changes | | |
|---|---|---|
| Version no | Version date | Comment |
| 1.0 | 25.01.2025 | Initial internal draft send for review internally to the associated members in ISL |
| 1.1 | 15.02.2025 | Changes made in the draft based on the recommendations |
| 1.2 | 12.03.2025 | D4.1 send for review to REVIEWER 1 (Clemens Jasper Richard Gonnermann, FHG) |
| 1.2 | 12.03.2025 | D4.1 send for review to internal REVIEWER 2 (Violeta Damjanovic-Behrendt, GTW) |
| 1.3 | 10.04.2025 | D4.1 sent for second review to internal REVIEWER 1 (Clemens Jasper Richard Gonnermann, FHG) |
| 1.3 | 10.04.2025 | D4.1 sent for second review to internal REVIEWER 2 (Violeta Damjanovic-Behrendt, GTW) |
| 1.4 | 15.04.2025 | D4.1 pre-Final submission to Project Coordinator |
| 1.5 | 30.04.2025 | Adjustments to formatting and document layout. |
| 1.6 | 16.05.2015 | Final Update; Final version for submission |

| Quality Control | | |
|---|---|---|
| Version reviewed | Date of review | Review result – Approved or Request for changes |
| 1.2 | 13.03.2025 | D4.1 has been returned for improvements/adaptations – reviewed by REVIEWER 2 (Violeta Damjanovic-Behrendt, GTW) |
| 1.2 | 19.03.2025 | D4.1 has been returned for improvements/adaptations – reviewed by REVIEWER 1 (Clemens Jasper Richard Gonnermann, FHG) |
| 1.3 | 13.04.2025 | D4.1 has been returned and approved by REVIEWER 2 (Violeta Damjanovic-Behrendt, GTW) for pre-final submission to the project coordinator |
| 1.3 | 14.04.2025 | D4.1 has been approved by REVIEWER 1 (Clemens Jasper Richard Gonnermann, FHG) for final submission to the project coordinator |
| 1.6 | 08.06.2025 | Final review prior to submission by Project Coordinator (Tjark von Reden, CU); Approved and submitted |

# Table of Contents

## List of Tables



## List of Figures

# List of Abbreviations

| | |
|---|---|
| API: | Application Programming Interface |
| BIV: | Business Impact Value |
| CAD: | Adaptability |
| CAN: | Anticipation |
| CC: | Capacity |
| CCT: | Collaboration and Trust |
| CD: | Dispersion |
| CDC: | Digital Capabilities |
| CE: | Efficiency |
| CEMT: | Conférence Européenne des Ministres des Transports (European Conference of Ministers of Transport) |
| CES: | Ecological Sustainability |
| CFS: | Financial Strength |
| CFSO: | Flexibility in Sourcing |
| COF: | Flexibility in Order Fulfilment |
| CR: | Recovery |
| CRAC: | Risk Appetite and Culture |
| CS: | Security |
| CSS: | Social Sustainability |
| CV: | Visibility |
| DES: | Discrete Event Simulation |
| DRMKC: | Disaster Risk Management Knowledge Centre |
| EP: | Ecological Performance |
| ERP: | Enterprise Resource Planning |
| FHG: | Fraunhofer IGCV |
| FOP: | Financial and Operational Performance |
| GDACS: | Global Disaster Alert and Coordination System |
| GHG: | Greenhouse gases |
| GIS: | Geographic Information System |
| GWP: | Global Warming Potential |
| HILF: | High-Impact-Low-Frequency |
| IMF: | International Monetary Fund (context: IMF PortWatch) |
| ISL: | Institute of Maritime Economics and Logistics |
| IWW: | Inland Waterway |
| KPI: | Key Performance Indicator |
| LCA: | Life Cycle Assessment |
| MCN: | Maritime Cluster Northern Germany eV |
| PLS-SEM: | Partial Least Squares Structural Equation Modeling |
| PML: | Possible Maximum Loss |
| RBIT: | Residual Business Interruption Time |
| REE: | Ripple Effect Exposure |
| SE: | Supplier Exposure |
| SME: | Small and Medium-sized Enterprises |
| SMEs: | Small and Medium-Sized Enterprises |
| SP: | Social Performance |
| SR: | Supply Chain Resilience |
| TTR: | Time-To-Recovery |
| VC: | Connectivity |
| VDT: | Deliberate Threats |
| VEP: | External Pressures |
| VMM: | Man-made Vulnerabilities |
| VRL: | Resource Limits |
| VS: | Sensitivity |
| VT: | Turbulence |

# 1 Executive Summary

**Purpose**

This document, D4.1: Risk and Alerts Framework for multimodal logistics and supply chain resilience of the ResC4EU project aims to enhance the resilience of supply chains across diverse European industries through a comprehensive, data-driven resilience assessment methodology. It demonstrates a risk and alerts framework that serves as a foundation for a toolset that can help companies assess and improve their resilience, covering their multimodal logistics and supply chain. There are various ways in which the toolset can help companies improve their resilience:

- Self-assessment scoring establishing benchmarks for improvement,
- Identifying and aligning weakness and capability gaps,
- Supply chain and logistics check and the risk alerts to avoid disruptions or shorten the recovery time,
- Carbon footprint analysis to assess the environmental impact of logistics operations and enable companies to align their strategies with sustainability goals, etc.

The framework presented in D4.1 is structured around the following three model methodologies:

a) **Supply chain resilience self-assessment methodology:** This methodology is a data-driven analytical framework developed to support organizations in evaluating, benchmarking, and strengthening their capacity to anticipate, respond to, and recover from supply chain disruptions. It offers a structured approach for assessing vulnerabilities, capabilities, and their interdependencies within the supply chain, enabling firms to pinpoint critical weaknesses and strengths for strategic improvement. Built on the Partial Least Squares Structural Equation Modeling (PLS-SEM) technique, the methodology quantifies resilience through latent variable scoring derived from survey data. This survey data is based on ordinal Likert-scale perceptual ratings collected from participants across a range of Small and Medium-sized Enterprises (SMEs), allowing for a multidimensional and statistically robust assessment of supply chain resilience.

b) **Multimodal transport model:** This model is based on identifying, assessing, and alerting stakeholders to potential risks in transportation and multimodal logistics systems, ensuring proactive mitigation strategies. This model employs a routing-based risk alert system to dynamically identify potential risks in multimodal logistics networks. It leverages GIS data to monitor routing decisions, notify users of potential disruptions and provide recommendations.

c) **Global Warming Potential (GWP) assessment model:** This evaluates the environmental impact of supply chain activities, particularly their contribution to global warming, thereby enabling the integration of sustainability into resilience strategies. This graph-based theoretical model evaluates the environmental impact of supply chain activities, with a focus on global warming potential. It integrates production process-specific data for different operational variants and incorporates country-specific energy mix data to ensure accurate impact assessments.

This risk and alerts framework combines both proactive and reactive approaches to safeguarding supply chains from disruptions. The supply chain resilience self-assessment methodology focuses on proactive risk preparedness and strategic resilience-building, enabling organizations to anticipate risks, identify vulnerabilities, and enhance preparedness before disruptions occur. Additionally, this methodology establishes a preliminary structure for risk and resilience assessment, setting a benchmarking standard that allows organizations to evaluate their resilience relative to industry and operational norms. The methodology acts as an entry-point diagnostic tool for SMEs to evaluate current resilience levels, identify gaps, and benchmark against industry standards. Given its role in providing a starting baseline measurement, this methodology is categorized as basic in the risk and alerts framework.

In contrast, the multimodal transport model serves as a reactive and advanced risk mitigation tool, offering a real-time response mechanism that helps organizations address disruptions as they emerge. This model leverages real-time data and Geographic Information System (GIS)-based risk monitoring to detect transportation bottlenecks, geopolitical risks, environmental hazards, and infrastructure vulnerabilities that could impact multimodal logistics networks. By integrating dynamic rerouting strategies and risk alerts, it enables stakeholders to adapt quickly and minimize operational disruptions.

The multimodal transport model also plays a pivotal role in both the supply chain resilience self-assessment methodology and the GWP assessment model and is methodically connected to both. For the resilience self-assessment methodology, it provides critical transportation-related parameters (refer to Annex) that feed into the resilience scoring system, enhancing the accuracy of risk evaluations. Additionally, it acts as a foundation for sustainability assessments, directly linking to the GWP assessment model, which ensures that resilience strategies incorporate environmental considerations. The GWP assessment model is also classified as advanced because it integrates complex environmental impact assessments, utilizing country-specific energy mix data and carbon footprint analytics to guide organizations toward more sustainable logistics practices.

While the GWP assessment model and the supply chain resilience self-assessment methodology are not methodologically linked, they function synergistically as complementary scoring systems—one focused on sustainability, the other on operational resilience. Resilience ensures continuity during disruptions, while sustainability embeds long-term ecological and social responsibility into supply chain strategies. Together, they form an integrated framework that balances adaptability with environmental accountability, enhancing both competitiveness and future readiness (Warmbier et al., 2022; 2023)[1].

It is important to clarify that while alert generation is primarily focused on transport-related vulnerabilities, the resilience self- and GWP assessments serve a different function. These assessments are primarily designed for evaluation, benchmarking, and strategic planning, with a stronger emphasis on production and supplier-oriented operational vulnerabilities.

Thus, the combination of methodology and models creates a holistic, data-driven framework that balances operational efficiency, risk mitigation, and sustainability, ensuring that organizations can both proactively strengthen their resilience and reactively manage disruptions in real time.

[1] Warmbier, P., Kinra, A. and Ivanov, D. (2022), "Supply chain sustainability and resilience-relationship and congruent capability analysis based on paradox theory", IFAC-PapersOnLine, Vol. 55, No. 10, pp. 311-316, doi: 10.1016/j.ifacol.2022.09.625.
Warmbier, P., Kinra, A., & Ivanov, D. (2023). Supply chain sustainability and resilience under uncertainty: paradoxes and responses. In Academy of Management Proceedings (Vol. 2023, No. 1, p. 19461). Briarcliff Manor, NY 10510: Academy of Management.

**Methodological adaptation**

During the iterative development process, the project evolved beyond the initial scope outlined in the Grant Agreement.

a) Initially, the risk and alerts framework was structured around two distinct models: one for production systems and another for multimodal logistics and transportation systems (Task 4.1, page 11– Grant Agreement). However, as the project progressed, it became clear that resilience must be addressed holistically, integrating supplier and customer networks, production processes, and logistics into a unified framework (Buer et al., 2019)[2].

To better reflect the complexities and interdependencies inherent in modern supply chains, the project transitioned to a three-model system. This refined approach includes:

- The multimodal transport model primarily focuses on real-time risk identification and mitigation on **multimodal logistics and transportation.**
- The GWP assessment model, which evaluates the environmental impact of activities, primarily focuses on **production systems.**
- The supply chain resilience self-assessment methodology integrates elements of **both transport and production resilience and supplier-customer network** to provide a comprehensive, system-wide evaluation of supply chain robustness.

These changes also reflect that data availability was a hindrance to project development for certain clusters and end users involved in the project. Consequently, the methodologies originally proposed were adapted to better align with the overarching objectives and practical constraints.

b) Initially, the sustainability aspect, represented by the GWP assessment model, was not explicitly integrated into the risk and alerts framework (Task 4.1, page 11 & 12– Grant Agreement), as the primary focus was on risk identification and resilience-building within supply chains. However, as the project evolved, it became evident that risk, resilience, and sustainability are inherently interconnected and must be addressed collectively rather than as isolated elements. A resilient supply chain is not only one that can anticipate and mitigate disruptions but also one that operates sustainably, reducing its environmental footprint while maintaining long-term operational efficiency.

Recognizing this interdependence, the GWP assessment model was integrated into the risk and alerts framework, ensuring that sustainability considerations are embedded within risk mitigation and resilience strategies. This model evaluates carbon emissions, energy consumption, and resource efficiency, providing organizations with data-driven insights to align their supply chain operations with sustainability goals. By incorporating environmental impact assessments alongside risk and resilience analysis, the framework now offers a comprehensive approach that enables businesses to make informed, balanced decisions that enhance both supply chain robustness and ecological responsibility. Moreover, the GWP assessment in Task 4.1 serves as a foundational step for the broader sustainability initiatives planned under WP6 (Task 6.1), which focuses on the Life Cycle Assessment (LCA) model and tools for Resources, Energy & Net-Zero as part of its integration into the B2B platform. The work conducted in T4.1 establishes the initial

[2] Buer, T., Hassis, H.-D., Kinra, A. and Kotzab, H. (2019),"An overview to contemporary maritime logistics and supply chain management decision areas",

methodological framework for sustainability analysis, ensuring a seamless transition into the LCA-driven decision-support tools in later project phases.

c) Initially, the framework relied on holistic Possible Maximum Loss (PML) modeling, incorporating traditional methodologies such as Discrete Event Simulation (DES). This approach was based on hard data, including supplier performance metrics, operational records, and structured datasets from industry clusters, end-users, and SMEs. However, as the project evolved, interactions with cluster companies and SMEs revealed the need for a more flexible, perceptual, and data-driven approach to better reflect the complex and dynamic nature of modern supply chains.

To address this, the supply chain resilience self-assessment methodology transitioned from the initially proposed PLM modeling to PLS-SEM. This shift introduced a latent variable score analysis, which leverages perceptual data collected from SMEs by project-affiliated cluster partners as part of WP3. Unlike traditional deterministic models, PLS-SEM allows for the analysis of complex interdependencies, integrating both quantitative resilience indicators. These methodological refinements were driven by data availability limitations of participating clusters and end-users, which initially hindered project development. As a result, the adapted approach now allows for a more nuanced and reliable assessment of supply chain resilience. This perceptual, survey-driven method was better suited for SME clusters, enabling easier data collection, enhanced analytical flexibility, and lower computational demands. The methodology evaluates parameters on the various risks and vulnerabilities companies' face, the capabilities they possess to mitigate these risks, and the interdependencies among resilience factors. By integrating these multidimensional resilience parameters, the methodology offers a comprehensive, adaptable, and industry-specific assessment framework, ensuring more realistic, actionable insights for organizations seeking to strengthen their supply chains. This adaptation is further elaborated in detail in Section 3.2.

# 2 Introduction

## 2.1 Purpose of this document

The purpose of D4.1: Risk and Alerts Framework for Multimodal Logistics and Supply Chain Resilience is to provide a comprehensive, data-driven model for enhancing supply chain resilience across European industries. The focus is on building resilient supply chains in 14 industrial sectors in Europe, as outlined in the ecosystem division in the Annual Single Market Report 2021:[3] (1) aerospace and defence, (2) agri-food, (3) construction, (4) cultural and creative industries, (5) digital, (6) electronics, (7) energy intensive industries, (8) energy-renewables, (9) health, (10) mobility, transport and automotive, (11) proximity, social economy and civil security, (12) retail, (13) textile, and (14) tourism. D4.1 presents the model designed to serve as a strategic foundation toolset for organizations seeking to assess, strengthen, and sustain their supply chain and logistics networks against disruptions. By integrating three interrelated model methodologies—the supply chain resilience self-assessment methodology, multimodal transport model, and GWP assessment model—this approach enables Small and Medium-sized Enterprises (SMEs) to adopt both proactive and reactive risk management strategies. The model not only identifies vulnerabilities and capacity gaps but also alerts stakeholders to real-time risks and promotes sustainability considerations in logistics operations.

This risk and alerts framework supports businesses in improving their adaptability, operational efficiency, and environmental responsibility by offering tools for self-assessment, dynamic risk mitigation, and carbon footprint analysis.

- The supply chain resilience self-assessment methodology equips organizations with the ability to pre-emptively evaluate risks and fortify supply chains;
- The multimodal transport model ensures that stakeholders can respond swiftly to emerging disruptions through GIS-based monitoring and real-time rerouting. Additionally, the multimodal transport model plays a critical role in sustainability as it feeds into the GWP assessment model.
- Finally, the GWP assessment model integrates sustainability considerations by quantifying emissions and guiding greener logistics strategies.

This comprehensive, integrated framework ultimately enables organizations to strengthen supply chain resilience, optimize risk response mechanisms, and align their operations with sustainability goals, ensuring long-term competitiveness and stability in an increasingly complex global supply chain landscape.

## 2.2 Key features

The risk and alerts framework that serves as a strategic foundation toolset consists of the following key features (Figure 1):

**1) Resilience self-assessment scoring system:** Quantifying

[3] Annual Single Market Report 2021. Retrieved from https://commission.europa.eu/system/files/2021-05/swd-annual-single-market-report-2021_en.pdf (accessed 9.07.2024)

- Vulnerabilities that expose supply chains to potential disruptions, and
- Capabilities present within SMEs or those that need to be developed to mitigate risks effectively.

**2) Strategic alignment:** Ensuring that identified supply chain and logistics vulnerabilities are effectively matched with existing or developable capabilities to formulate actionable resilience strategies.

**3) Prioritization of weaknesses and strengths:** Identifying the most critical vulnerabilities and capabilities that significantly impact organizations, based on their industry characteristics and company size.

**4) Dynamic risk identification:** Monitoring routing decisions and hazards (via external global databases), for notifying users/companies of potential disruptions that may potentially affect

**5) Proactive risk mitigation:** Offering general guidance and recommendations on the next steps to effectively address and minimise potential risks.

**6) Carbon footprint analysis:** Establishing a structured approach for evaluating GWP over the supply chain. The approach is oriented on the information known by later users (companies) and enables simple integration of data from individual industry sectors.

**7) GWP contribution breakdown:** Identifying and addressing high-emission areas, referring to a hotspot-analysis.


**Figure 1: Key Features**

## 2.3 Key concepts

This segment outlines the key concepts and definitions essential for understanding D4.1, specifically in regards to the three interrelated model methodologies:

a) For supply chain resilience self-assessment methodology:

- **Resilience** is the capacity of an enterprise to survive (withstand), adapt and grow (recover) in the face of turbulent change (disruptions) to meet customer demand and target performance (Fiksel, 2006, Ivanov 2018a)[4].
- **Vulnerabilities** refer to weaknesses, gaps (complexities) within an organization's operations that make it more susceptible to disruptions, risks, or negative impacts (Pettit et al., 2013)[5]. The different parameters for vulnerabilities are:
  1. Turbulence: Environment characterized by frequent changes in external factors beyond company's control
  2. Deliberate Threats: Intentional attacks aimed at disrupting operations or causing human or financial harm
  3. External Pressures: Influences, not specifically targeting the company, that create business constraints or barriers
  4. Resource Limits: Constraints on output based on availability of the factors of production.
  5. Sensitivity: Importance of carefully controlled conditions for product and process integrity
  6. Connectivity: Degree of interdependence and reliance on outside entities
  7. Man-made Vulnerabilities: Vulnerabilities resulting from human activities or accidents
- **Risk** is the measure of the potential for events having adverse (negative) effects on the organization's objectives (Pettit et al.,2013, 2010; Tang 2006; Chopra et al. 2007, Ivanov, D., 2021)[6], e.g., natural risks, process risks, financial risks, supply risks, demand risks, information risks, law and cultural risk.
- **Disruptions** are unexpected events that interrupt normal operations (normal flow of goods and materials) within the supply chain limits and have a severe negative impact (Pettit et al., 2013, Ivanov, D., 2021), e.g., terrorism, piracy, natural disasters, man-made disasters, political crises, strikes, legal contract disputes, epidemics and pandemics (Ivanov, D., 2021)
- **Capabilities** refer to attributes such as skills, resources, competencies, and capacities that enable an enterprise to anticipate and overcome disruptions. (Pettit et al., 2013, Ivanov, 2018a). The different parameters for capabilities are:
  1. Flexibility in Sourcing: Ability to quickly change inputs or the mode of receiving inputs
  2. Flexibility in Order Fulfilment: Ability to quickly change outputs or the mode of delivery
  3. Capacity: The ability to change manufacturing processes or adapt to new products, mix, or volumes efficiently
  4. Efficiency: Capability to produce outputs with minimum resource requirements

---

[4] Fiksel, J. (2006). Sustainability and resilience: toward a systems approach. Sustainability: Science, Practice and Policy, 2(2), 14-21.
Ivanov, D. (2018). Structural dynamics and resilience in supply chain risk management (Vol. 265). Berlin, Germany: Springer International Publishing.

[5] Pettit, T. J., Croxton, K. L., & Fiksel, J. (2013). Ensuring supply chain resilience: development and implementation of an assessment tool. Journal of business logistics, 34(1), 46-76.

[6] Tang, C. S. (2006). "Perspectives in supply chain risk management." International Journal of Production Economics, 103(2), 451-488. REPEC IDEAS
Chopra, S., & Meindl, P. (2007). Supply Chain Management: Strategy, Planning, and Operation. Upper Saddle River, NJ: Prentice Hall. INDUSTRI FATEK UNPATTI
Ivanov, D. (2021). Supply Chain Viability and the COVID-19 Pandemic: A Conceptual and Formal Generalisation of Four Major Adaptations Strategies. International Journal of Production Research, 59(12), 3535-3552.

5. Visibility: Knowledge of the status of operating assets and the environment
6. Adaptability: Ability to modify operations in response to challenges or opportunities
7. Anticipation: Ability to discern potential future events or situations
8. Recovery: Ability to discern potential future events or situations
9. Dispersion: Broad distribution or decentralization of assets
10. Collaboration and trust: Ability to work effectively with other entities for mutual benefit
11. Security: Defense against deliberate intrusion or attack
12. Financial strength: Capacity to absorb fluctuations in cash flow
13. Digital capabilities[7]: Skills, technologies, processes, and resources that enable an organization to effectively leverage digital technologies
14. Risk Appetite and Culture: Ability to recognise, assess, and address risks and uncertainties in the supply chain
15. Social sustainability: Ability to ensure social sustainability of employees during production and delivery of products and meeting the requirements of stakeholders
16. Ecological sustainability: Ability to ensure ecological efficiency and sustainability during production and delivery of products and meeting the requirements of stakeholders.

- **Proactive vs. reactive resilience**[8]: Proactive resilience focuses on anticipating and mitigating risks before they occur, while reactive resilience deals with responding to and recovering from disruptions.
- **Supply chain performance metrics** are measures that assess the impact of resilience strategies on financial, social, and environmental outcomes. The supply chain performance[9] metrics include:
  1. Financial and Operational Performance: Company's results in terms of profitability and operational efficiency
  2. Social Performance: Company’s performance in terms of employee well-being and fair practices.
  3. Ecological Performance: Company’s performance in terms of ecological measures, focusing on the company’s environmental efficiency and sustainability.
- **Latent variables** (Hair et al., 2021)[10] are unobserved variables inferred from observed data, crucial for assessing complex resilience constructs.

---

[7] Baziyad, H., Kayvanfar, V., & Kinra, A. (2024). A bibliometric analysis of data-driven technologies in digital supply chains. Supply Chain Analytics, 100067.
Baziyad, H., Kayvanfar, V., & Kinra, A. (2022). The Internet of Things—an emerging paradigm to support the digitalization of future supply chains. In The Digital Supply Chain (pp. 61-76). Elsevier.

[8] Gruchmann, T., Stadtfeld, G. M., Thürer, M., & Ivanov, D. (2024). Supply chain resilience as a system quality: survey-based evidence from multiple industries. International Journal of Physical Distribution & Logistics Management, 54(1), 92-117

[9] Liu, C.-L., Shang, K.-C., Lirn, T.-C., et al.: Supply chain resilience, firm performance, and management policies in the liner shipping industry. Transp. Res. Part A-Policy Pract. 110, 202–219 (2018).
Tondolo, V.A.G., D’Agostini, M., Camargo, M.E., et al.: Sustainable operations practices and sustainable performance: relationships and moderators. IJPPM 70, 1865–1888 (2021)
Hong, J., Zhang, Y., Ding, M.: Sustainable supply chain management practices, supply chain dynamic capabilities, and enterprise performance. J. Clean. Prod. 172, 3508–3519.

[10] Hair Jr, J. F., Hult, G. T. M., Ringle, C. M., Sarstedt, M., Danks, N. P., & Ray, S. (2021). Partial least squares structural equation modeling (PLS-SEM) using R: A workbook (p. 197). Springer Nature.

- **Constructs**, as abstract concepts or latent variables, represent key dimensions of supply chain resilience, while **items** are the measurable indicators/questions designed to assess these constructs. These **constructs and items** play a pivotal role in defining the conceptual framework and serve as the foundation for data collection, ensuring accuracy and relevance (Hair et al., 2021).
- **PLS-SEM** (Hair et al., 2021)[11] is a statistical technique used to model complex relationships between latent variables, enabling dynamic resilience assessment.
- **Correlation and covariance analysis** (Hair et al., 2021) is a method used to analyse the relationships between vulnerabilities and capabilities in supply chain resilience.

b) For the Multimodal transport Model:

- **Multimodal Routing Model (MRM):** The Multimodal Routing Model is a routing algorithm based on separate networks for each mode (road, rail, inland waterway, maritime and airborne) that are interlinked in intermodal terminals such as rail terminals, inland and maritime ports and airports.
- **GIS overlaying:** GIS overlaying is a database process that compares different types of geographic data (commonly called 'layers') and assess overlaps, distances between points, lines or areas across these layers.
- **Risk alert model:** The Risk alert model is based on the analysis of live or regularly updated data such as databases on earthquakes, extreme weather events or maritime traffic (AIS data). It generates notifications to inform all relevant users about specific events.

c) For the GWP Assessment Model:

- **GWP** is a metric employed to compare the potential of different greenhouse gases to contribute to global warming. It is expressed as a ratio of the warming caused by a given greenhouse gas to that caused by carbon dioxide ($CO_2$). This is characterized by the radiative forcing of a specific greenhouse gas. The time period over which the comparison is made is typically 100 years. By definition, the GWP of $CO_2$ is set at 1, and other gases are thus compared relative to $CO_2$. Therefore, it is quantified in the unit CO2 equivalent (eq.). For a specific product this can be relativised to kg CO2 eq./kg (product). The total GWP of a process refers to the total amount of emitted greenhouse gases caused directly or indirectly by the associated input and output flows (IPCC, AR6, The Physical Science Basis, 2021)[12]. Within the project context, the term GWP refers to the GWP metric used in the Production and Logistics GWP Assessment Model.
- **Greenhouse gases (GHG)** is defined as any gas that absorbs and emits infrared radiation within the infrared range. This property is the fundamental cause of the greenhouse effect, which in turn leads to the warming of the Earth's surface. GHGs are responsible for trapping heat in the atmosphere and are a key factor in climate change (Intergovernmental Panel on Climate Change (IPCC), Sixth Assessment Report (AR6), The Physical Science Basis, 2021.

[11] Hair Jr, J. F., Hult, G. T. M., Ringle, C. M., Sarstedt, M., Danks, N. P., & Ray, S. (2021). Partial least squares structural equation modeling (PLS-SEM) using R: A workbook (p. 197). Springer Nature.

[12] Intergovernmental Panel on Climate Change (IPCC). (2021). The Physical Science Basis. In V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. M. Berger, ... & W. W. L. Cheng (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press

- **Life Cycle Assessment (LCA)** method is defined as the systematic analysis of the potential environmental impacts of products or services during their entire life cycle. The environmental impact emphasized in the project is focused on GWP as defined by the following standards:
  - DIN EN ISO 14040:2021-02, Umweltmanagement – Ökobilanz – Grundsätze und Rahmenbedingungen (ISO_14040:2006_+ Amd_1:2020); German version EN_ISO_14040:2006_+ A1:2020.,
  - DIN EN ISO 14044:2021-02, Umweltmanagement_- Ökobilanz_- Anforderungen und Anleitungen (ISO 14044:2006 + Amd_1:2017 + Amd 2:2020); German version EN ISO 14044:2006 + A1:2018 + A2:2020.

There are additional concepts for resilience assessment (please refer to 3.2.1). Understanding these concepts will also provide a deeper insight into the methodological transition provided in Section 3.1:

- **Ripple effect in supply chains** is the cascading impact of a disruption across multiple tiers of the supply chain, which can amplify initial losses and delay recovery (Kinra et al., 2020)[13].
- **Supplier risk exposure** is the measure of the financial and operational impact a supplier's disruption can have on a supply chain. It considers factors such as supplier importance, financial impact, and inventory across different supply chain layers (Kinra et al., 2020).
- **Recovery effort assessment** focuses on the consequences of disruptions and the efforts required for recovery. It evaluates factors such as time-to-recovery (TTR) and time-to-survive (TTS) rather than attempting to predict disruption probabilities (Kinra et al., 2020).
- **Supplier Exposure (SE) Index** is a quantitative measure of the risk posed by a supplier, calculated based on the potential maximum financial loss and the importance of the supplier in the supply chain (Kinra et al., 2020).
- **Ripple Effect Exposure (REE) Index** is an extension of the SE index that accounts for multi-echelon disruption propagation effects, quantifying the overall impact across the supply chain (Kinra et al., 2020).
- **Possible Maximum Loss (PML)** is the estimated worst-case financial loss resulting from a supplier's disruption, used as a key variable in risk assessment models (Kinra et al., 2020).
- **Business Impact Value (BIV)** is a weighting factor in the SE and REE indices that reflects the financial importance of a supplier, based on spending and order quantities (Kinra et al., 2020).
- **Residual Business Interruption Time (RBIT)** is the net duration of disruption, accounting for mitigation strategies and inventory buffers available at different supply chain stages (Kinra et al., 2020).
- **Discrete-Event Simulation (DES)** is a method used to analyse the dynamics of disruption propagation in supply chains by modeling random disruption scenarios and recovery strategies (Kinra et al., 2020).

---

[13] Kinra, A., Ivanov, D., Das, A., & Dolgui, A. (2020). Ripple effect quantification by supplier risk exposure assessment. International Journal of Production Research, 58(18), 5559-5578.

## 2.4 Relevance for other work packages, tasks and deliverables in the project

This deliverable and document will be primarily used as follows:

- This deliverable is directly applicable to Work Package 5 (WP5): Building Alliances Between Tech-Savvy and Traditional SMEs, with a particular focus on Task T5.4: Launching ResC4EU Pilot Projects in Each Industrial Ecosystem Facilitated by Clusters. Task T5.4 involves initiating pilot projects across the 14 identified industrial ecosystems at risk. These pilots will serve to demonstrate the value of ResC4EU's insights, services, and tools for addressing specific challenges within each ecosystem and encourage broader adoption of these resources by additional SMEs, fostering resilience and sustainability across industries. This document, which presents a comprehensive model capable of generating actionable insights, innovative services, and user-friendly tools, will play a crucial role in achieving the objectives of Task T5.4. The document D4.1 will form as guiding report for the clusters in relevance to the pilot projects ensure its effectiveness in translating the framework into practical, impactful solutions for SMEs. The three interrelated models developed in D4.1—the supply chain resilience self-assessment methodology, multimodal transport model, and GWP assessment model—will serve as visualization of the core toolset demonstrator in line with the core features that the models would establish within the T5.4 pilot projects. It would ensure scalability and adaptability, allowing clusters to tailor the methodology to the specific needs of different industrial ecosystems. Beyond supporting T5.4 pilot projects, the D4.1 models will play a crucial role in the iterative refinement and validation of tools as part of B2B RESC4EU platform.
- This deliverable serves as a foundational step toward the development and deployment of assessment tools and a comprehensive platform for SMEs. Specifically, it lays the foundation for Work Package 6 (WP6), which focuses on creating and implementing practical solutions for SMEs to enhance their supply chain resilience and sustainability. WP6 includes the following key components:
    1) Eco Footprint Tool for Resources, Energy and Climate Neutrality: An easy-to-use tool designed to help SMEs optimize resource and energy usage while advancing climate neutrality. This corresponds to Deliverable D6.1
    2) Resilience Assessment Tool: A user-friendly tool to evaluate and enhance the resilience of a company's supply chain. This corresponds to Deliverable D6.2
    3) Platform Provision and Extension for Industrial Pilots: A platform created to meet emerging requirements identified during pilot projects (Task T5.4) and to integrate tools and services developed in Tasks T6.1 and T6.2. This corresponds to Deliverable D6.3

## 2.5 Document structure

The document proceeds with a detailed presentation of the framework, structured around the methodology. For each (a, b and c- refer to section 2.3), the methodology section elaborates on the applied approach, the development process, data collection techniques, operationalization, and validation.

Subsequently, the document presents the key outcome in alignment with the functionality and interpretation of each of the models and methodologies. These outcomes are particularly relevant to the following areas:

- Resilience assessment scoring for SMEs,
- Resilience-driven matchmaking of supply chain vulnerabilities and capabilities,
- Identification of key supply chain vulnerabilities and capabilities,
- Real-time risk alerts, and the
- GWP Score of supply chains.

The document concludes by summarizing the insights and findings, emphasizing their implications for advancing resilience strategies. It also outlines the next steps, transitioning into the tools and deliverables of Work Package 6 (WP6), while paving the way for practical implementation and further development.

## 2.6 Targeted group

The risk and alerts framework is designed to meet the specific needs of SMEs working with multimodal logistics, production and supply chain networks. These SMEs often face significant challenges in identifying, assessing, and mitigating risks, especially in dynamic and interconnected industrial environments.

The targeted group for this model includes, but is not limited to, the following:

a) **SMEs across critical supply chain functions:** production units such as SMEs engaged in production activities that are highly interdependent with supplier and customer networks and are particularly vulnerable to disruptions; Logistics and Transportation organizations involved in multimodal logistics and transportation systems, where disruptions can have cascading effects on overall supply chain performance; Supply Chain Integrators such as companies that manage the coordination of suppliers, manufacturers, and distributors, ensuring seamless operations in complex networks

b) **Industries with high vulnerability to disruptions:** The model specifically targets SMEs in industrial ecosystems at high risk, such as Energy-Intensive Industries, Health, Mobility, Transport and Automotive, Electronics, Agri-Food. These industries are characterized by complex supply chains, high interdependencies, and the potential for significant economic and operational losses during disruptions.

c) **Decision-managers and decision Makers:** European Supply Chain Managers responsible for designing, operating, and improving supply chain networks, risk management teams focused on identifying and mitigating risks related to logistics, production, and environmental sustainability, sustainability officers particularly interested in tools like the GWP Assessment model to align operational resilience with environmental goals.

d) **Policy makers:** EU policy makers responsible for regulating and legislating the areas of supply chain due diligence, sustainability reporting, and other existing green deal proposals like the omnibus and future ones related to the clean manufacturing deal.

# 3 Methodology

As stated in the previous section, the comprehensive integrated risk and alerts framework is based on the three models and methodologies (refer to Figure 2):

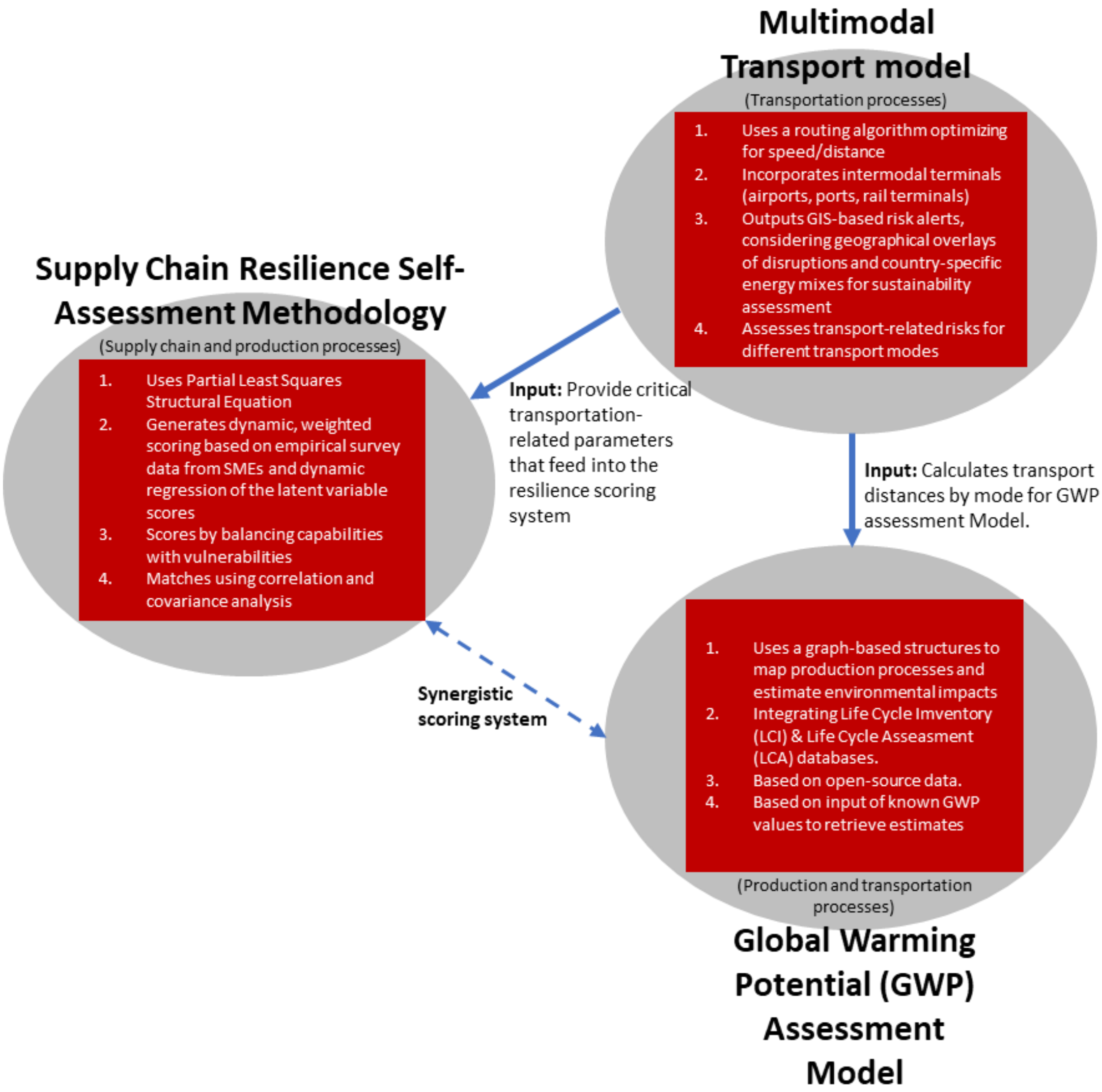



*Figure 2: Interconnection of the three models*

- **Supply chain resilience self-assessment methodology:** This methodology quantifies resilience by analysing the relationships between capabilities and vulnerabilities (see Section 2.3). A weighted scoring system dynamically evaluates resilience, allowing companies to benchmark their performance and identify critical gaps.

- **Multimodal transport model:** This component emphasizes identifying, evaluating, and alerting stakeholders to potential risks within multimodal logistics and transportation systems, enabling proactive and timely mitigation strategies.
- **GWP Assessment Model:** This sub-model assesses the environmental impact of supply chain activities, focusing on their contributions to global warming. It integrates sustainability considerations into resilience strategies, bridging the gap between operational efficiency and environmental responsibility.

As described in Section 2.2, the features (refer to Figure 1) can be classified into each of these model methodologies: features 1, 2 and 3 will be the output of supply chain resilience self-assessment methodology, features 4 and 5 for multimodal transport model and finally features 6 and 7 for GWP Assessment model. The supply chain resilience self-assessment methodology serves as the foundation for evaluating an organization's ability to anticipate, absorb, and recover from disruptions. As an entry-point diagnostic tool, it establishes benchmarking standards, helping SMEs and industry stakeholders identify vulnerabilities, capability gaps, and resilience strengths. Given its role in providing a starting baseline measurement, this methodology is categorized as basic within the risk and alerts framework, offering a structured, proactive approach for assessing supply chain robustness.

However, resilience is not only about preparedness and benchmarking- it also requires real-time responsiveness to emerging threats. This is where the multimodal transport model comes into play. Unlike the self-assessment model, which is proactive, the multimodal transport model is reactive and advanced, providing real-time risk mitigation to address disruptions as they occur. This model monitors transportation networks, detecting bottlenecks, geopolitical risks, environmental hazards, and infrastructure vulnerabilities through GIS-based risk monitoring and dynamic rerouting strategies. By providing timely risk alerts and adaptive routing recommendations, it enables organizations to minimize operational disruptions and optimize logistics flows.

The multimodal transport model also acts as a key data input for both the supply chain resilience self-assessment methodology and the GWP Assessment model. For the resilience self-assessment methodology, it provides critical transportation-related parameters, feeding into the resilience scoring system to enhance risk evaluation. By integrating real-time transportation risks into resilience assessments, this connection ensures that organizations can align their strategic planning with actual logistics vulnerabilities rather than relying solely on theoretical risk assessments.

Although there is no direct methodological relationship between the GWP assessment model (based on sustainability) and the supply chain resilience self-assessment methodology, they operate in a synergistic manner, both functioning as scoring systems that evaluate different dimensions of organisational performance. Sustainability and resilience are increasingly recognized as interdependent strategies in supply chain management; while resilience ensures operational continuity in the face of disruptions, sustainability extends this robustness by embedding long-term ecological, social, and economic responsibility into supply chain practices. A resilient supply chain safeguards operations against shocks, and when combined with sustainability practices, such as transparency, agility, and collaboration, it creates a congruent capability set that enhances long-term competitiveness and mitigates both economic and environmental risks (Warmbier et al., 2022)[14]. The resilience self-assessment methodology is basic, focusing on operational resilience and strategic preparedness, whereas the GWP assessment model is advanced, offering a comprehensive environmental impact analysis. While the self-assessment model helps organizations understand their ability to withstand disruptions, the GWP model ensures that these resilience strategies are aligned with sustainability objectives, using carbon footprint analytics and country-specific energy mix data. Together, they offer a comprehensive, data-driven risk and alerts framework that balances preparedness, adaptability, and environmental responsibility, ensuring that supply chains remain robust, responsive, and future-ready.

It is crucial to distinguish that while the generation of alerts predominantly targets transport-related vulnerabilities—such as delays, infrastructure failures, or geopolitical disruptions—the resilience and GWP assessments fulfil a fundamentally different purpose within the framework. These assessments are meticulously crafted to support evaluation, benchmarking, and long-term strategic planning, shifting the focus toward a broader spectrum of operational vulnerabilities. Specifically, they place greater emphasis on production-related challenges, such as manufacturing inefficiencies or resource constraints, and supplier-oriented vulnerabilities, including supply chain dependencies, procurement risks, and sustainability compliance. By addressing these dimensions, the resilience and GWP assessments provide organizations with a deeper understanding of systemic weaknesses including immediate transportation concerns, enabling them to prioritize investments on internal external capabilities and enhance operational stability, and align with both economic and environmental objectives. This complementary approach ensures a more holistic risk management strategy, balancing real-time responsiveness with proactive, forward-looking planning.

The next segments provide the changes that took place of the overall framework followed by overview of each of the model methodologies in detail.

## 3.1 Methodological adaptation of risk and alerts framework for multimodal logistics and supply chain resilience

To start with, the risk and alerts framework underwent significant methodological adaptations to ensure a more comprehensive, data-driven, and integrated approach to supply chain resilience. Initially, the framework was structured around two distinct models: one focused on production systems and another on multimodal logistics and transportation systems (Task 4.1, page 11 – Grant Agreement). However, as the project evolved, it became evident that resilience is not confined to isolated operational segments but rather depends on the interconnectedness of supplier networks, logistics, and production systems.

This realization led to a fundamental shift in methodology- from a compartmentalized approach to a three-model system designed to better capture the complexities and interdependencies of modern supply chains. This refined framework consists of:

[14] Warmbier, P., Kinra, A. and Ivanov, D. (2022),"Supply chain sustainability and resilience-relationship and congruent capability analysis based on paradox theory", IFAC-PapersOnLine, Vol. 55, No. 10, pp. 311-316, doi: 10.1016/j.ifacol.2022.09.625.

- The multimodal transport model, which focuses on real-time risk identification and mitigation within multimodal logistics and transportation networks.
- The GWP assessment model, which evaluates the environmental impact of supply chain activities, primarily within production systems.
- The supply chain resilience self-assessment methodology, which integrates elements of both transport and production resilience, as well as supplier-customer networks, to provide a comprehensive, system-wide evaluation of supply chain robustness.

By adopting this holistic, three-part structure, the project ensures that resilience is assessed not only in production and logistics but across the entire supply chain, allowing for a more nuanced and integrated understanding of risk, resilience, and sustainability.

Secondly, the sustainability aspect, represented by the GWP assessment model, was not explicitly incorporated into the risk and alerts framework (Task 4.1, pages 11 & 12 – Grant Agreement). The primary focus at the outset was on risk identification and resilience-building, addressing disruptions within supply chain operations and multimodal logistics. However, as the project progressed, it became increasingly clear that risk, resilience, and sustainability are deeply interconnected and must be treated as complementary elements rather than isolated components. A truly resilient supply chain is not only one that can anticipate and recover from disruptions but also one that is environmentally sustainable, minimizing its carbon footprint and resource consumption while maintaining long-term operational efficiency.

Recognizing this critical interdependence, the GWP assessment model was fully integrated into the risk and alerts framework, ensuring that sustainability considerations are embedded within resilience and risk mitigation strategies. This model evaluates carbon emissions, energy consumption, and resource efficiency, providing organizations with data-driven insights to align their supply chain strategies with sustainability objectives. By incorporating environmental impact assessments alongside risk and resilience analysis, the risk and alerts framework now offers a comprehensive decision-support system that enables businesses to balance supply chain robustness with ecological responsibility.

Furthermore, the GWP assessment in Task 4.1 serves as a foundational step for broader sustainability initiatives planned under WP6 (Task 6.1), which focuses on the Life Cycle Assessment (LCA) model and tools for Resources, Energy & Net-Zero as part of its integration into the ResC4EU B2B platform. The methodological groundwork laid in T4.1 ensures a seamless transition into the LCA-driven decision-support tools, allowing organizations to continuously assess and improve their sustainability performance. This alignment between resilience-building, real-time risk management, and sustainability objectives reinforces the project’s commitment to developing future-ready, adaptive, and environmentally responsible supply chains. Further refinements were also made at a more intrinsic level, particularly within the supply chain resilience self-assessment methodology. The specific modifications within this methodology, along with detailed discussions of the other models within the framework, will be explored in the following sub-sections.

## 3.2 Supply chain resilience self-assessment methodology

### 3.2.1 Initial Approach: Holistic Possible Maximum Loss (PML) Modeling

The original methodological approach aimed at assessing supply chain resilience by ripple effect quantification, which is the approach centred around supplier risk exposure assessment, without relying on traditional probability estimations of disruptions. Unlike conventional models that emphasize predicting disruption likelihood, this methodology introduced a consequence-based approach that evaluated financial and operational impacts instead.

The core objective of the holistic PML approach is to develop a Supplier Exposure (SE) model, integrating variables such as financial losses, business interruption time, inventory buffering, and supplier importance to analyse disruption propagation through multi-tiered supply chains. This would have served as a decision-making tool for supply chain managers, enabling them to identify high-risk suppliers, prioritize mitigation strategies, and enhance resilience, particularly in high-impact-low-frequency (HILF) events, where probability-based risk assessments are unreliable. The methodology was structured around two key indices:

- Supplier Exposure (SE): Measures financial losses due to supplier disruptions.
- Ripple Effect Exposure (REE): Quantifies disruption propagation across multiple supply chain tier
- The model would have incorporated key elements such as:
- Possible Maximum Loss (PML): Estimation of worst-case financial losses.
- Business Impact Value (BIV): Financial weight of disrupted suppliers.
- Residual Business Interruption Time (RBIT): Net disruption duration after inventory buffering.

By aggregating SE values across multiple supply chain levels, the REE index would have provided a structured quantification of disruption propagation. The methodology followed a cause-effect modeling approach, employing static analysis for predefined scenarios and dynamic discrete-event simulations to assess real-time disruptions and recovery behaviours.

### 3.2.2 Challenges in Data Collection and Model Execution with the PML Modeling approach

While the PML-based model was theoretically robust, practical challenges emerged during its execution, particularly in data collection and model feasibility. Periodic work with the cluster partners and SMEs revealed obstacles, particularly in obtaining reliable and comprehensive data. The key challenges were:

- Scarcity of Disruption Data: The focus on HILF events made it difficult to obtain comprehensive historical disruption records from clusters and SMEs. Most companies lacked structured data on past disruptions, making it challenging to estimate parameters like Business Interruption Time (BIT) and Time-to-Recovery (TTR).
- Supplier Data Transparency: Multi-tier supply chains involve upstream suppliers who often do not disclose risk-related data, leading to incomplete assessments of the ripple effect exposure (REE).
- ERP System Integration Issues: The PML approach required cross-functional operational data from various Enterprise Resource Planning (ERP) modules (procurement, finance, inventory, production planning). Many SMEs used fragmented IT systems, making data extraction, standardization, and integration challenging.

- Digital disparities among participating clusters and ecosystems: The PML modeling approach required comprehensive business and operational data from various platforms. However, the use of diverse digital platforms across different organizations created challenges in data collection and integration, potentially impeding the accuracy and effectiveness of the model.

### 3.2.3 Transition to PLS-SEM methodology

Given these obstacles and to arrive at a meaningful, standardised approach, an alternative methodological approach- PLS-SEM was introduced. This transition was driven by the need to adopt a perceptual data-based approach rather than relying solely on functional business and operational data[15], which was difficult to obtain.

PLS-SEM offered the following advantages:

- Suitability for SME Clusters: SMEs and cluster partners found it more feasible to provide perceptual data (e.g., survey-based risk assessments) rather than detailed operational records.
- Improved Data Accessibility: Unlike PML-based models requiring precise historical disruptions, PLS-SEM uses survey-based constructs, making it more practical for data collection.
- Enhanced Analytical Flexibility: The methodology allows for latent variable modeling, integrating factors such as supplier risk perceptions, disruption preparedness, and resilience strategies without requiring complete historical data.
- Lower Computational Demands: Unlike PML-based dynamic simulations, PLS-SEM relies on structural equation modeling, reducing the need for high computational power while still providing insights into causal relationships between resilience factors.

### 3.2.4 Methodological Transition

To illustrate the shift from PML-based modeling to PLS-SEM, the following framework outlines the key methodological differences and justifications for transition:

*Table 1: Methodological Transition from PML Modeling to PLS-SEM*

| Aspect | Holistic PML-Based Modeling | PLS-SEM Approach |
|---|---|---|
| Focus | Quantifying financial & operational impacts of disruptions | Assessing perceptual resilience & risk factors |
| Data Requirement | Historical disruption data, supplier risk metrics, financial loss data | Perceptual data from surveys, qualitative risk assessments |
| Modeling Technique | Cause-effect modeling with static & dynamic simulations | Structural equation modeling (SEM) with latent variables |
| Computational Demand | High (simulation-based) | Moderate (statistical modeling) |
| Feasibility for SMEs | Low – Data limitations & system integration issues | High – Data collected via surveys & expert assessments |
| Practical Decision Use | Real-time disruption risk quantification | Strategic risk management & resilience evaluation |

[15] Operational Data: Data curated through ERP systems, digital platforms, or business intelligence tools. It includes structured, real-time, and transactional data such as sales records, inventory levels, financial transactions, and process logs. Perceptual Data: Data collected via surveys, interviews, or self-reports, often capturing opinions, attitudes, and subjective experiences rather than measurable transactions.

### 3.2.5 Results

The transition from Holistic PML Modeling to PLS-SEM was a necessary step to widen the resilience self-assessment approach. While the PML-based model provided a rigorous quantitative framework for assessing supplier risk exposure, the practical challenges of data availability and execution made its implementation impossible for SME clusters. PLS-SEM, with its empirical, perceptual-data-driven approach, emerged as a more suitable alternative, ensuring better integration of SME perspectives, improved data accessibility, and enhanced practical application in supply chain resilience assessment.

### 3.2.6 Current Approach: Supply Chain Resilience Self-Assessment Methodology based on Partial Least Squares Structural Equation Modeling (PLS-SEM)

The Supply Chain Resilience Self-Assessment methodology was developed at ISL with significant contribution and support from MCN and FHG. The development process was iterative, relying on regular collaborative meetings to refine the framework, methodology, and functionality (see Figure 3). The methodology employs an integrative approach, utilizing Partial Least Squares Structural Equation Modeling (PLS-SEM) to capture and analyse complex relationships among variables. Software such as SmartPLS 4 was utilized for testing and initial validation.

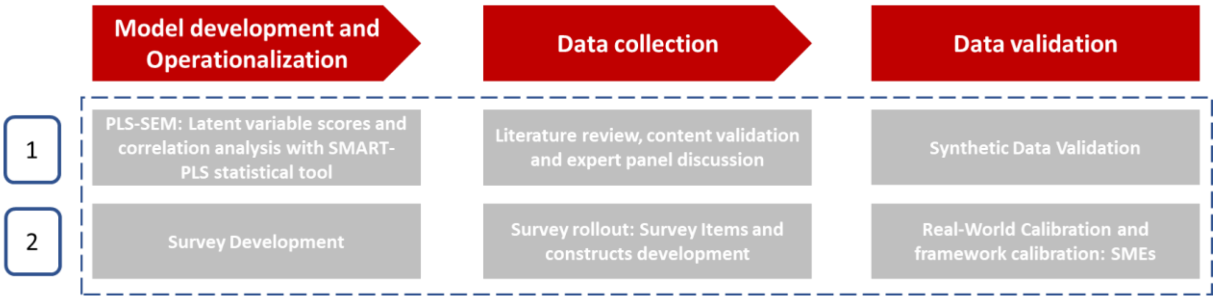


*Figure 3: Process steps for resilience self-assessment methodology*

Features of the Supply Chain Resilience Self-Assessment methodology:

a) Resilience self-assessment scores: The methodology enables companies to generate resilience self-assessment scores, offering a benchmarking system both within and across industries.
b) Critical capability-vulnerability identification: The methodology pinpoints the most critical vulnerabilities and capabilities that have a significant impact on organizations, tailored to their specific industry characteristics and company size.
c) Capability-vulnerability matching: By matching identified supply chain vulnerabilities to relevant organizational capabilities, the methodology helps companies pinpoint areas for improvement and prioritize interventions.

#### A. Methodology development and operationalization

This subsection focuses on the formulation and design of the Supply Chain Resilience Self-Assessment methodology, highlighting the following activities:

a) Framework Creation:

The methodology is developed using an integrative framework designed to capture the dynamic interplay between supply chain vulnerabilities and organizational capabilities.

- PLS-SEM was chosen as the core methodology for the Supply Chain Resilience Self-Assessment methodology due to its ability to handle complex relationships among variables and its flexibility in accommodating diverse data structures. Unlike traditional statistical methods, PLS-SEM provides a robust approach for exploring latent variables- concepts that are not directly observable but are measured through multiple constructs and indicators. This capability is particularly essential for assessing supply chain resilience, which involves intricate interactions between vulnerabilities, capabilities, and performance outcomes. Unlike static, non-weighted models, such as those proposed by Petit et al. (2013), PLS-SEM enables dynamic, weighted scoring, offering precise and adaptable evaluations through detailed path analysis and construct-level weighting. As a variance-based technique, PLS-SEM is particularly effective for predictive modeling and exploratory research, enabling insights into the most impactful factors driving supply chain resilience. It provides a forward-looking perspective, helping organizations anticipate and address risks before they escalate into disruptions.
- The framework and equations are implemented and tested using SmartPLS 4.

b) Survey Development:

- A detailed survey was designed to collect real-world data, targeting specific industries with customized questions to assess resilience parameters and supply chain characteristics. For these various constructs and items are considered and established through ad-hoc literature review (Wemmerlöv, 2021), supported by conceptual model development and validation techniques such as content validity checks (Forza, 2002) and expert panel discussions (Flynn et al., 1990).
- This process refined the conceptual model and defined key constructs and measurement items for assessing supply chain resilience. The whole process of survey development in line with the various parameters (constructs and items) is discussed in detail in the next section B. Data collection (refer to a) Survey Items and constructs development).

c) Data analysis

- Resilience self-assessment scoring based on PLS-SEM latent variable scoring is conducted.
- Identification of critical vulnerabilities and capabilities based on weighted scores calculation
- Matching vulnerabilities with capabilities based on correlation and covariance analysis complemented by an extensive scientific and practice-oriented literature base critically evaluated to validate the methodology's applicability and effectiveness.

## B. Survey creation & data collection:

The survey creation and data collection phase involved the survey parameter (item and constructs- refer to subsection B. a) Survey Items and constructs development) development and deployment of the survey parameters designed to gather meaningful inputs from industry clusters. This segment of the work was primarily conducted along with MCN as part of T3.2. Key activities include:

**a)** Survey Items and constructs development:

The development of parameters (survey items and constructs) by ISL involved around 150 initial items, aligning with the project's established Key Performance Indicator (KPI) (EO1: Number of tested parameters for identifying threats and disruptions >200). Through iterative refinement and analysis, 75 parameters (refer to the items in Table 2) were finalized to form the survey's final version. An ordinal likert rating scale of 1-7 (extremely irrelevant - extremely relevant) was considered. The items are based on the critical concepts on supply chain vulnerabilities, capabilities and resilience presented in Section 2.3.

**Fehler! Verweisquelle konnte nicht gefunden werden.** provides an extensive framework of constructs and their associated items used in a supply chain resilience self-assessment conceptual model. Here's an explanation of its key components:

a) Acronyms and constructs: The table organizes various constructs (abstract concepts like flexibility, capacity, and adaptability) that represent critical aspects of supply chain resilience. Each construct is assigned a code (e.g., CFSO for Flexibility in Sourcing) for easier reference.
b) Definitions: Constructs are defined to clarify their roles in the supply chain. For instance, "Flexibility in Sourcing" refers to the ability to adapt quickly to input changes or sourcing modes, ensuring adaptability during disruptions.
c) References: The constructs are grounded in research, with references to foundational studies or authors such as Pettit et al. (2010, 2013) and others. These sources validate the constructs and provide theoretical backing.
d) Formative/Reflective nature: Constructs are categorized as either reflective (measured by their indicators, e.g., Flexibility in Sourcing measured by modular product design, supplier flexibility, etc.) or formative, depending on the direction of causality between the construct and its indicators.
e) Measurement items: Each construct has a set of measurable indicators (items) that operationalize it. For example: Flexibility in Sourcing (CFSO) has items like modular product design (CFSO1) and supplier contract flexibility (CFSO3). Recovery (CR) includes items like communication strategy (CR1) and crisis management (CR2).
f) Purpose: The table enables organizations to assess their supply chain's strengths, weaknesses, and areas for improvement. The constructs and items are carefully curated to address various resilience aspects, ensuring holistic evaluations.

*Table 2: Various constructs and items in supply chain resilience self-assessment conceptual model*

| Acro-nyms | Constructs | Definition | References | Formative /Reflective | Measurement items |
|---|---|---|---|---|---|
| Supply chain capabilities | | | | | |
| CFSO | Flexibility in Sourcing | Ability to quickly change inputs or the mode of receiving inputs | Pettit et al., (2010; 2013), Choudhury (2017; 2019); Pu et al., (2023) | Reflective | CFSO1: Modular product design<br>CFSO2: Multiple uses<br>CFSO3: Supplier contract flexibility<br>CFSO4: Multiple sources |
| COF | Flexibility in Order Fulfilment | Ability to quickly change outputs or the mode of delivery | | Reflective | COF1: Alternate distribution channels and multisourcing<br>COF2: Delayed commitment/Production postponement<br>COF3: Inventory management<br>COF4: Rerouting of requirements |

| | | | | | |
|---|---|---|---|---|---|
| CC | Capacity | The ability to change manufacturing processes or adapt to new products, mix, or volumes efficiently | | Reflective | CC1: Reserve capacity<br>CC2: Backup energy sources and communications |
| CE | Efficiency | Capability to produce outputs with minimum resource requirements | | Reflective | CE1: Labor productivity and product variability reduction<br>CE2: Asset utilization and waste elimination |
| CV | Visibility | Knowledge of the status of operating assets and the environment | | Reflective | CV1: Information technology & product, equipment and people visibility<br>CV2: Information exchange |
| CAD | Adaptability | Ability to modify operations in response to challenges or opportunities | | Reflective | CAD1: Alternative technology development, strategic gaming and simulation<br>CAD2: Lead time reduction, |
| CAN | Anticipation | Ability to discern potential future events or situations | | Reflective | CAN1: Forecasting, deviation and near-miss analysis<br>CAN2: Monitoring early warning signals and risk management<br>CAN3: Recognition of opportunities |
| CR | Recovery | Ability to discern potential future events or situations | | Reflective | CR1: Communications strategy<br>CR2: Crisis management and resource mobilization<br>CR3: Consequence mitigation |
| CD | Dispersion | Broad distribution or decentralization of assets | | Reflective | CD1: Decentralization of key resources<br>CD2: Distributed decision-making, distributed capacity and assets, location-specific empowerment<br>CD3: Dispersion of markets |
| CCT | Collaboration and trust | Ability to work effectively with other entities for mutual benefit.” | | Reflective | CCT1: Collaborative forecasting and communications<br>CCT2: Risk sharing with partners and postponement of orders<br>CCT3: Relationship sincerity<br>CCT4: Trust with information accuracy |
| CS | Security | Defense against deliberate intrusion or attack | | Reflective | CS1: Layered defenses<br>CS2: Access restrictions,<br>CS3: Cyber-security and information security |
| CFS | Financial Strength | Capacity to absorb fluctuations in cash flow | | Reflective | CFS1: Insurance and financial reserves and liquidity<br>CFS2. Portfolio diversification and price margin |
| CDC | Digital capabilities | Skills, technologies, processes, and resources that enable an organization to effectively leverage digital technologies | Mishra et al., (2023); Christopher and Peak (2004); Jain et al. (2017), Negri et al. (2022); Hong et al. (2018) | Reflective | CDC1: System data analysis<br>CDC2: Enterprise Resource Planning<br>CDC3: Smart work procedures (real-time online storage, monitoring, tracking and control) and big data analysis<br>CDC4: Additive manufacturing<br>CDC5: Automated guided vehicles<br>CDC6: Digitally enabled global shipping platform<br>CDC7: Industry 4.0-based analytics techniques (machine learning/artificial intelligence)<br>CDC8: Sophisticated digital solutions-Inventory level and performance |
| CRAC | Risk Appetite and culture | Ability to recognise, assess, and address risks and | Choudhury (2017; 2019) | Reflective | CRAC1: High level of risk<br>CRAC2: Training and awareness |

| | | | | | |
|---|---|---|---|---|---|
| | | uncertainties in the supply chain | | | |
| CSS | Social sustainability | Ability to ensure social sustainability of employees during production and delivery of products and meeting the requirements of stakeholders | Gold et al. (2017); Jain et al., (2017); Tukamuhabwa et al., (2015); Umang Soni et al., (2014) | Reflective | OCSS1 Health and safety;<br>OCSS2 Human and labor rights |
| CES | Ecological sustainability | Ability to ensure ecological efficiency and sustainability during production and delivery of products and meeting the requirements of stakeholders | Avella et al. (2011); Gold et al. (2017); Jain et al., (2017); Tukamuhabwa et al., (2015); Umang Soni et al., (2014) | Reflective | OCSE1 Pollution prevention;<br>OCSE2 Recycling of materials;<br>OCSE3 Waste reduction |
| Supply chain vulnerabilities | | | | | |
| VT | Turbulence | Environment characterized by frequent changes in external factors beyond your control | Pettit et al., (2010; 2013), Choudhury (2017; 2019); Pu et al., (2023) | Reflective | VT1: Fluctuations in currencies and prices<br>VT2: Geopolitical disruptions<br>VT3: Natural disasters,<br>VT4: Technology failures<br>VT5: Pandemic |
| VDT | Deliberate Threats | Intentional attacks aimed at disrupting operations or causing human or financial harm | | Reflective | VDT1: Espionage<br>VDT2: Terrorism/sabotage and special interest groups<br>VDT3: Labor disputes<br>VDT4: Product liability<br>VDT5: Cyber-attacks |
| VEP | External Pressures | Influences, not specifically targeting the company, that create business constraints or barriers | | Reflective | VEP1: Competitive innovation and price pressures<br>VEP2: Social/Cultural change and Corporate responsibility<br>VEP3: Environmental change |
| VRL | Resource Limits | Constraints on output based on availability of the factors of production. | | Reflective | VRL1: Number of supplier and customers<br>VRL2: Production and Distribution capacity, Raw material and<br>VRL3: Utilities availability<br>VRL4: Human resources |
| VS | Sensitivity | Importance of carefully controlled conditions for product and process integrity | | Reflective | VS1: Safety hazards<br>VS2: Concentration of capacity<br>VS3: Product purity, restricted materials, fragility, complexity |
| VC | Connectivity | Degree of interdependence and reliance on outside entities | | Reflective | VC1: Scale of network and Import and Export channels<br>VC2: Reliance upon information |
| VMM | Man-made vulnerabilitie s | Vulnerabilities resulting from human activities or accidents | | Reflective | VMM1: Industrial accidents<br>VMM2: Infrastructure failures |
| Supply chain performance | | | | | |
| FOP | Financial and Operational Performance | Company's results in terms of profitability and operational efficiency | Tondolo et al. (2021); Chahal et al. (2020); Hong et al., (2018); Kaynak (2003); Kang et al. (2018) | Reflective | FOP1: Quality<br>FOP2: Lead time<br>FOP3: Sales growth<br>FOP4: Cost |
| SP | Social Performance | Company's performance in terms of employee well-being and fair practices. | Tondolo et al. (2021); Chahal et al. (2020); Hong et al., (2018); Kaynak (2003); Kang et al. (2018); | Reflective | SP1 Incident and accident rates<br>SP2 Employee satisfaction and engag |

| | | | | | |
|---|---|---|---|---|---|
| EP | Ecological Performance | Company's performance in terms of ecological measures, focusing on the company's environmental efficiency and sustainability. | Tondolo et al. (2021); Chahal et al. (2020); Hong et al., (2018); Kaynak (2003); Kang et al. (2018); | Reflective | EP1: Waste production levels and recycling rate EP2: CO2 emissions |
| Supply chain resilience | | | | | |
| SR | Supply chain resilience | Resilience can be defined as the (cap)ability of a supplier chain to absorb changes and the capacity of a system to return to a state of equilibrium after disturbance | Pettit et al., (2010; 2013), Choudhury (2017; 2019); Pu et al., (2023) | Reflective | SR1: Alternative solutions<br>SR2: Risk Evaluation |

This table serves as a foundational tool for designing and implementing surveys or methodology aimed at enhancing supply chain resilience.

**b)** Survey Rollout:

- The EU survey management platform (see https://ec.europa.eu/eusurvey/home/welcome) is selected by MCN and ISL to ensure secure, scalable, and accessible survey data collection by MCN as part of T3.2. The link to the ResC4EU survey is shared with SMEs covering all 14 industrial sectors – see Figure 4.
- Regular meetings held by MCN with cluster representatives facilitates the distribution and completion of the survey

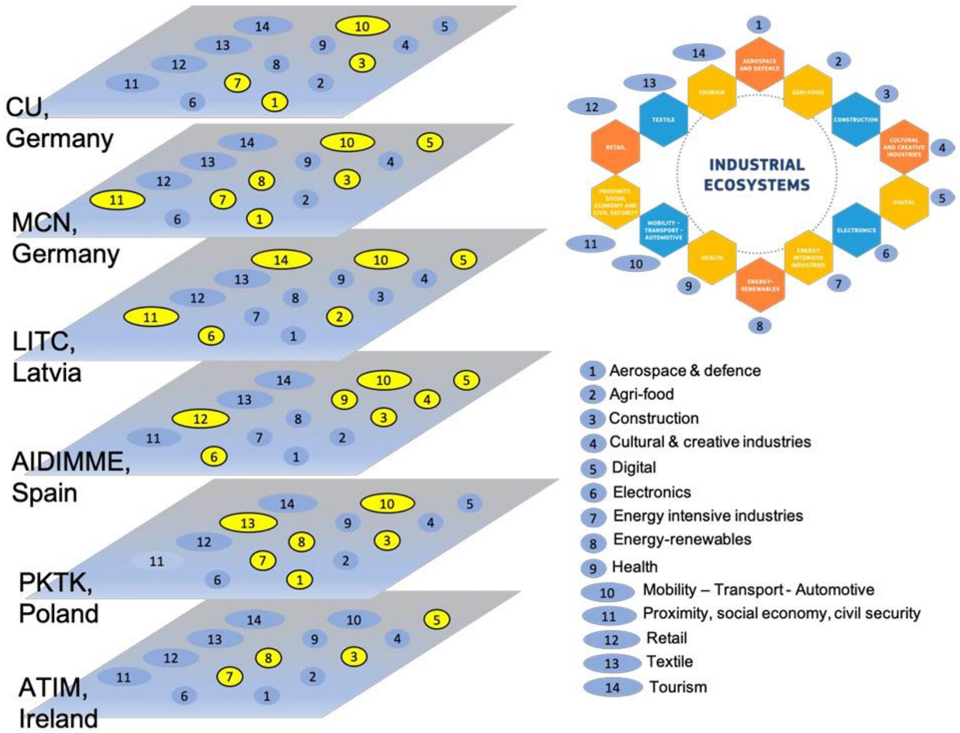



*Figure 4: Industry coverage by ResC4EU*

## C. Validation

The validation phase ensured the functionality, reliability, and adaptability of the methodology for real-world application:

### a) Synthetic Data Validation:

To ensure the robustness and reliability of the methodology, a comprehensive validation process was conducted using synthetic data, allowing for controlled testing under simulated supply chain scenarios. This evaluation was based on a dataset comprising 100 data points, with quantitative perceptual ratings on a scale of 1 to 7. The dataset was carefully designed to reflect realistic industry conditions, incorporating two primary sources:

1) Synthetic data generated via Large Language Models (LLMs)
   - Large language models were employed to replicate the characteristics of SMEs across different industries and ecosystems.
   - This data was designed to reflect a diverse range of supply chain structures, resilience challenges, and operational conditions, ensuring that the methodology could generalize across various industrial settings.
2) Empirical data from a controlled group of students and researchers
   - A controlled group of students and researchers provided additional perceptual responses, further validating the applicability of the dataset.
   - This input ensured that the dataset encompassed both theoretical and practical perspectives, enhancing its ability to simulate real-world decision-making scenarios within supply chains.

The synthetic dataset was specifically tailored to emulate a wide variety of supply chain disruptions, risk factors, and resilience-building strategies, creating a robust foundation for testing the operational capabilities of the methodology.

Link to the dataset:
https://docs.google.com/spreadsheets/d/1f5lN6dPny5YxZm1GQtw7WvKjewTgeBcYyAAt5J2Acj8/edit?usp=sharing

The validation focused on determining whether the methodology functions correctly based on its regression-based Partial Least Squares Structural Equation Modeling (PLS-SEM) approach. The model was evaluated against several key criteria:

1) Score generation and benchmarking
   - The methodology successfully generated resilience scores across various observations, ensuring that different supply chain entities could be benchmarked against industry norms.
   - The score outputs remained within expected ranges, confirming the methodology's ability to differentiate resilience levels among SMEs.
2) Item weighting and construct relationships
   - The PLS-SEM approach enabled the model to assign appropriate weights to different resilience factors, capturing their relative importance in determining supply chain resilience.

- The model also established correlations between different items and constructs, validating the expected interdependencies between resilience capabilities, vulnerabilities, and performance outcomes.

These functionalities confirm that the model performs as intended, aligning with the core methodological objectives outlined in the Grant Agreement. It is important to note that the focus of the project is the development of a resilience assessment methodology, not a standalone tool. The successful validation of methodological functionality ensures that the framework can serve as a foundation for further refinements, empirical validation, and future integration into decision-support platforms.

**b)** Real-world calibration:

- After data collection, the methodology then undergoes calibration to align its outputs with the real-world data collected from SMEs across various industrial clusters, within the tool that will be created as part of Task T6.2 in the next phase (M16-M36)
- This phase will ensure the methodology's accuracy and adaptability across diverse industries and scenarios.

**c)** Framework documentation:

- The methodology, parameters, and detailed equations have been documented comprehensively, enabling further refinement during validation and testing.

**d)** Discussions and validation meetings:

As part of the validation process, dedicated discussions and meetings were conducted with cluster partners LITC, MCN and AIDIMME to evaluate the resilience self-assessment methodology. The sessions were structured to facilitate in-depth analysis and feedback while ensuring that the methodology was clearly understood.

Feedback from these discussions provided valuable insights into the methodological framework, highlighting both areas of clarity and aspects requiring further refinement. Among the key areas of discussion were the structure of the regression logic, the process of weightage determination, and the feasibility of reassessing resilience scores following vulnerability mitigation.

A significant point of deliberation involved the extent of initial data collection, particularly regarding supplier and customer transportation details. Concerns were raised that the comprehensiveness of early-stage data requirements may discourage participation, especially among micro-companies with limited financial resources. In response, potential adjustments were considered, including the introduction of institutional funding schemes to enhance accessibility and engagement.

Further discussions explored the integration of the methodology with existing software platforms, particularly distinguishing between data analysis conducted via SmartPLS 4 and the eventual incorporation of SmartPLS 4 result data within the B2B platform in T6.3. Additionally, licensing considerations for third-party SmartPLS 4 software were highlighted as an area requiring further examination within the project timeframe.

Beyond survey-based insights, opportunities for supplementing resilience benchmarking with expert contributions from third-party supply chain professionals were also discussed. Incorporating external perspectives may provide an additional layer of validation and refinement, enhancing the robustness of the methodology.

The validation meetings played a crucial role in reinforcing the methodological soundness of the self-assessment methodology while identifying practical considerations for improving usability and industry applicability.

## 3.3 Multimodal Transport Model: Methodology

The multimodal transport model is specifically oriented towards multimodal logistics and provides the basis for the assessment of transport-related risks as well as for the assessment of the Global Warming Potential associated with transport. The model is based on ISL's Cargo Traffic Simulation tool, a routing model allowing route optimization on any given network based on Dijkstra's routing algorithm. The routing network is based on OpenStreetMaps data and has been complemented by a sea routes and intermodal terminals network developed by ISL. The model has been used in various project, e.g., to estimate the impact of the planned Fehmarn Belt tunnel on the nearby ferry routes[16] or to assess the competitiveness of ports in various hinterland regions (Figure 5).[17] It has also been used to compare the GWP of a seaport in different hinterland regions with that of other.

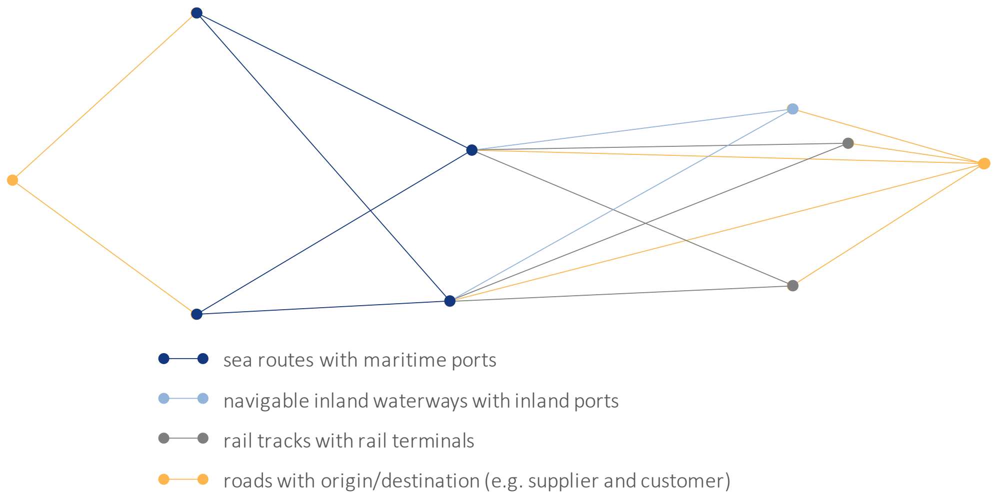



*Figure 5: Multimodal Transport Model (schematic view)*

The standard routing algorithm is based on the fastest or shortest route for each mode. Multimodal routes are generated by routing to/from intermodal terminals such as airports, maritime ports, inland waterway (IWW) ports or rail/road terminals.

- The output of the routing algorithm includes the following:
- Distance by mode of transport

[16] see ISL: Trans-Baltic transport structures up to 2035: How the Fehmarnbelt Fixed Link will shape traffic flows, September 2018, available online at https://tentacle.eu/downloads/

[17] This type of analysis has been performed, among others, for aspiring ports such as Dunkirk and Wilhelmshaven as well as for a global terminal operator to assess its European seaport terminal network.

- Standard transport means (e.g., ship size for sea and IWW transport) per journey segment
- GIS data of the route

The GIS data of the route is used for the transport-related risk assessment as well as for risk alerts. This is done by overlaying risk-related GIS data such extreme weather events or earthquakes. The distance per mode of transport and the standard transport means information is used as an input for the assessment of the transport-related GWP in the GWP Assessment model. The distances calculated by the routing model are multiplied with emission factors per km (see 4.1 Functionality - GWP Assessment Model). In addition, the distance of land-based transport can be split by countries, e.g., in order to use the respective country's energy mix for the GWP assessment of electrified transport means.

### 3.3.1 Point-to-point routing algorithm (one mode)

The first step of the multi-modal routing model is the road routing. This includes two sets of origin/destination pairs (Figure 6):

1) Direct road routing between origin and destination
2) Routing to nearby intermodal terminals for origin and destination points

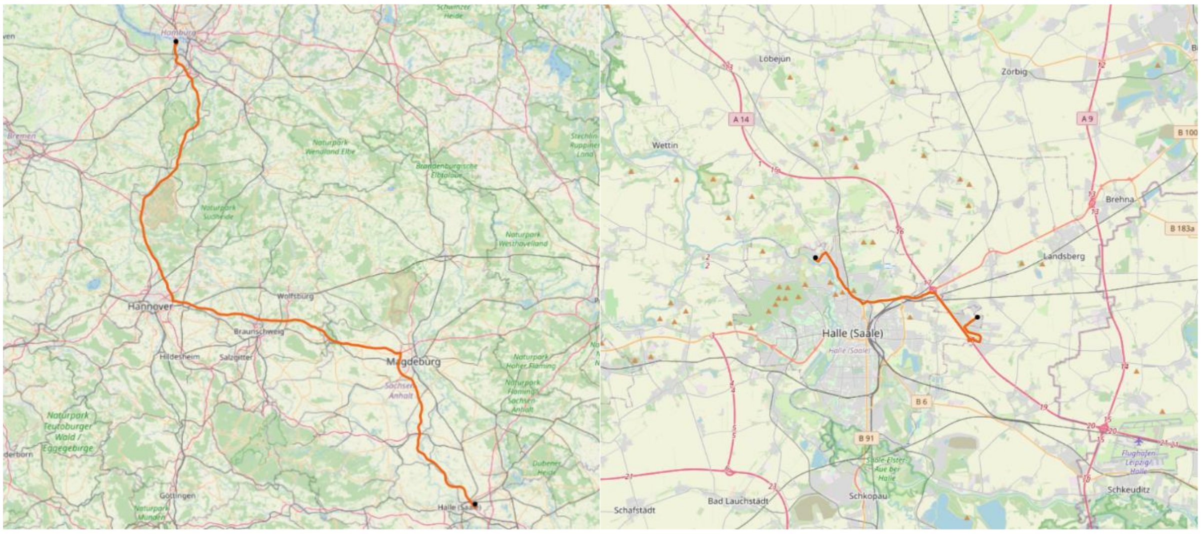



*Figure 6: Example for Origin-to-destination road routing (left) and routing to nearby terminal (right)*

For each origin/destination pair, there will be one single road routing result. In addition, for each origin and each destination, routings to all nearby terminals (e.g., air distance up to 100 km) will be performed.

Routing results include the following:

- Origin and destination of route
- GIS line string of route
- Distance in km
- Distance in each country (except airborne and maritime traffic)
- Road only: type of road and speed limit
- Inland waterway only: CEMT waterway class

For rail, inland waterway and maritime routings, there are two options. Option 1 is a complete routing between all possible combinations of terminals which are connected to the same mode. This includes rather short distances between two terminals in one region, but also long-distance transport between, e.g., China and Europe. Terminal pairs which are not connected to the same network (e.g., rail terminals in Ireland and in France or in North America and in Europe) will drop out due to missing connections.

Option 2 only includes routings between terminals that are connected with regular service, e.g., by a rail or barge operator, or by a regular maritime container service. This option is used for products that are typically transported in containers or trailers.[18]

For airborne traffic, air distances between airports are used instead of a routing algorithm.

### 3.3.2 Construction of multimodal transport chains

Multimodal transport chains are generated based on an optimization algorithm that can be freely defined (Figure 7). The routing model currently has three built-in optimization mechanisms:

- Shortest transport time
- Lowest modelled transport cost per cargo unit
- Shortest truck distances

For intercontinental transport chains, cost-based optimisation favours maritime transport while transport-time optimisation favours air transport. The actual means of transport depends on preferences of the company that is in charge of the transport, which is why the mode of transport is given by user input.

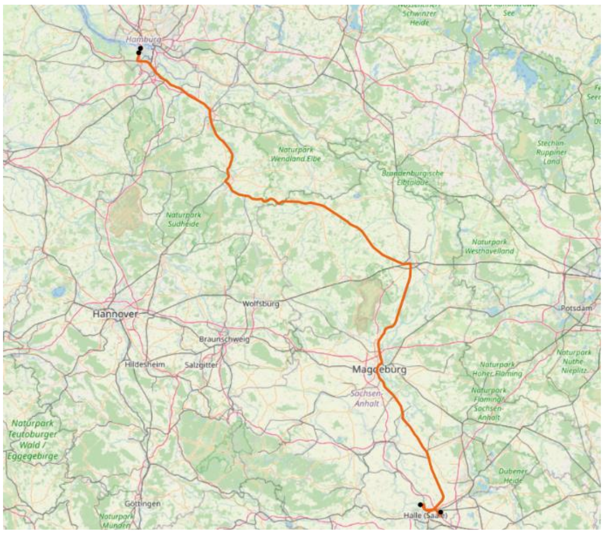



*Figure 7: Example for intermodal routing*

For airborne intermodal transport, transport-time optimization is used as the standard while for maritime intermodal transport, cost-based optimization is chosen as the default option.

The output of the intermodal transport routing includes:

[18] Data on regular rail and barge services is available for Europe only. Option 1 will be the fallback option for all regions with missing data.

- Origin and destination of route
- Intermodal terminals used
- GIS line string of route
- Distance in km per mode
- Vessel type for maritime and inland waterway transport

### 3.3.3 Overlaying risk and hazard data

The GIS data generated by the multimodal routing model can be used to overlay it with risk maps and with live GIS data of current events like earthquakes, tropical storms, etc. While the exposure to risks is used for an ex-ante evaluation of transport resilience, live data is used to generate risk alerts.

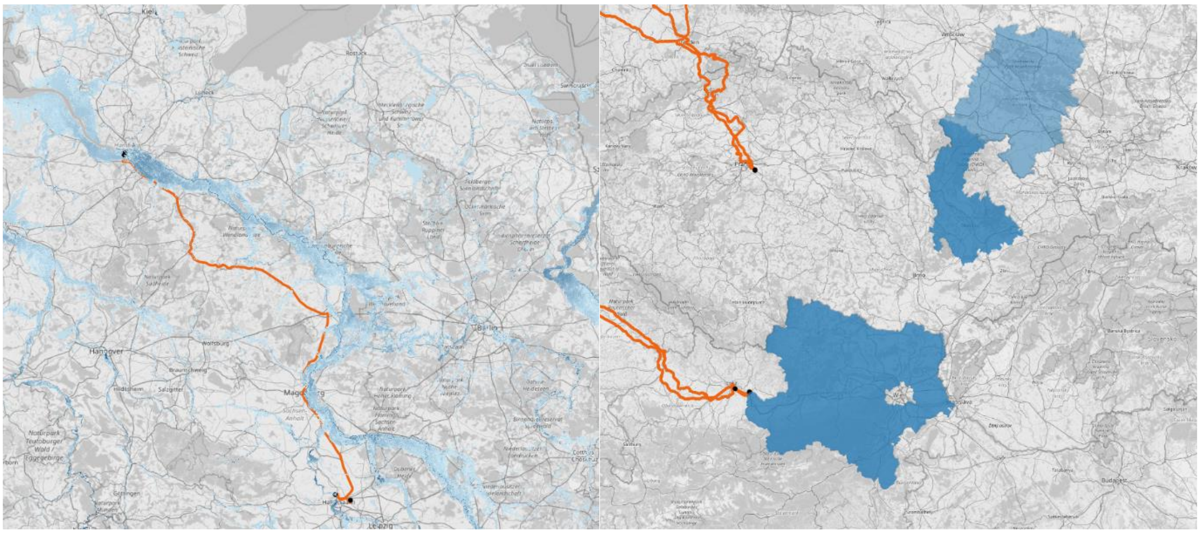


*Figure 8: River flooding risk areas (left) and actual river flooding event (right)*

Various data sources have been imported for the risk assessment in the GIS data model, including

- Country risks (DRMKC – INFORM, European Commission)
- Earthquakes and Earthquake risk areas (U.S. Geological Survey)
- Various hazards from Global Disaster Alert and Coordination System (GDACS)
- Fluidity of maritime traffic in ports and straits (IMF PortWatch)

Additional sources will be added during the implementation phase. The total number of parameters – which contribute to the project KPI EO1: "Number of tested parameters for identifying threats and disruptions" will initially be around 40 (selected country risks, earthquakes, selected disasters and 24 choke points from IMF PortWatch). In addition, all maritime ports that are included in one of the users' transport routes will be included in the monitoring for risk alerts. Additional datasets will be established in the second project phase.

### 3.3.4 Risk alert model

The risk alert model will focus on data with live or regular updates (at least daily). Several times a day (the frequency will be determined during the testing phase), the related databases will be queried and overlaid with all transport routes that have been modelled for users of the ResC4EU platform. The Risk alert model will generate data for alert messages to be sent to ResC4EU users that subscribed to the service. The data will contain (field types in square brackets):

- ID numbers for the concerned routes [integer, necessary to identify the concerned users]
- Event time or time of first occurrence in external dataset [timestamp]
- Location data (geocoordinates or concerned area) [geometry]
- Concerned suppliers/customers (based on the above route id, will be completed in the platform)
- Message header [character varying]
- Main body of text [text / html]

### 3.3.5 Data output for transport-related Global Warming Potential assessment

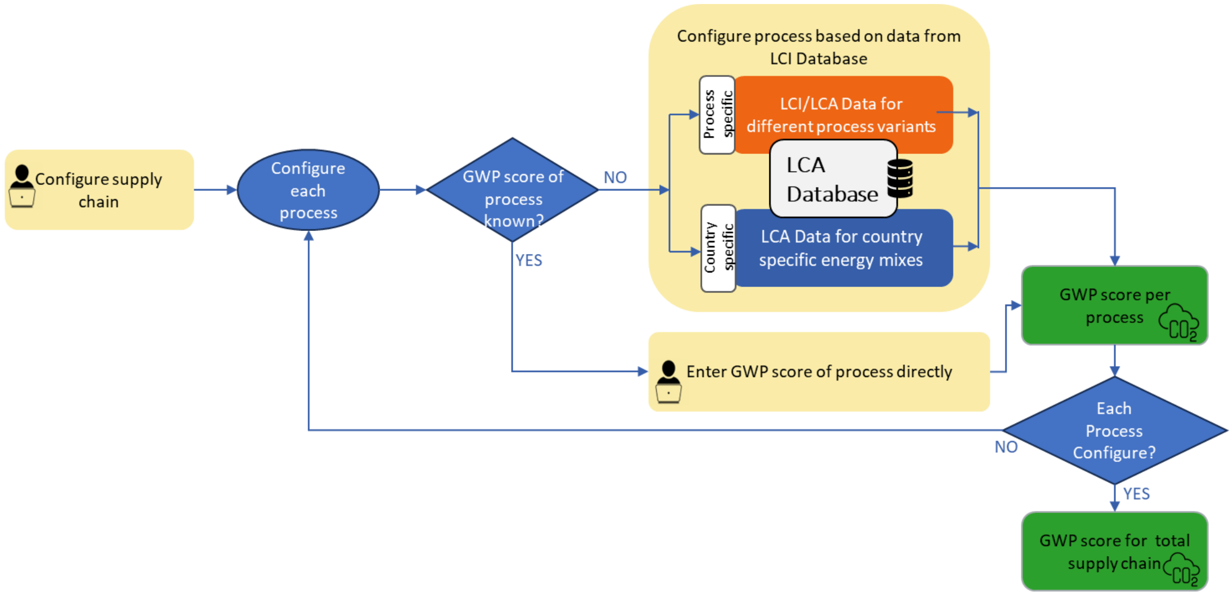
As a basis for the estimation of the transport-related GWP, the following data will be extracted from the routing results:

- Mode of transport
- Distance in km, grouped by countries for land transport (usable for country-specific energy mix or vehicle mix)
- Vessel types and emission factors for maritime transport
- Vessel types based on CEMT class for inland waterway transport
- Number and country of intermodal loading operations (if applicable)

## 3.4 GWP Assessment Model: Methodology

The GWP model implemented in this project is based on previous work within Fraunhofer IGCV, specifically a prior model developed for calculating costs and GWP for a given process route, with a focus on carbon manufacturing processes. In this previous project called “Öko Cup” (https://oekocap.org/), the model has been integrated as a backend service, allowing it to interact with users via a user interface where they can provide the necessary input data. To calculate the GWP, the model in “Öko Cup” utilized both open-source and commercial data. In ResC4EU, only the GWP part is considered for further developments and open-source data will be used for estimation of GWP. Additionally, the modeling is graph-based, which allows for the representation of related objects as well as the precise definition of their relationships and interaction rules. Especially, the abstract representation of the manufacturing process implanted in previous projects serves as the foundation for upcoming project-specific implementations. The model adaptation and extension are iterative processes, meeting the needs of potential users of the service (SMEs) and based on the technical exchange with the cluster members.

Figure 9 outlines the general schematic approach for determining the GWP Score of a supply chain. Therefore, the configuration of the whole supply chain is required, where individual processes within the supply chain are identified and set up for the analysis. The next step is to configure each process of the supply chain by first assessing whether the GWP score for that process is already known. If the GWP score of the process is known, the user can directly enter the value into the system. This eliminates the need for further calculations and simplifies the process. However, if the GWP score for a process is unknown, the value can be determined by selecting the relevant process from a process dropdown list, which is then linked to a LCA database, providing the corresponding GWP value.




LCI=life cycle inventory data and LCA=life cycle assessment data

*Figure 9: GWP Assessment Model showing the general workflow of configuring the supply chain for estimating the total GWP score*

To obtain the required data, the system refers to the Life Cycle Assessment (LCA) Database. Available data from the Life Cycle Inventory (LCI) Database can be utilized to calculate the corresponding LCA data. The LCA Database provides two categories of data:

1) Process-specific LCI/LCA Data – This includes GWP values for different process variants, e. g. electrically or gas-heated ovens for curing processes. If process-specific LCI data is known, e. g. energy consumption, it is then linked to the corresponding LCA data of the country-specific energy mix.
2) Country-specific LCA Data for energy mixes – This data includes country-specific energy mixes. Since electricity generation and industrial processes vary depending on the energy mix of a country (e.g., fossil fuels vs. renewable energy sources), this category helps in refining the GWP score based on the location-specific factors.

If any process remains unconfigured, data collection continues iteratively until all processes are accounted for. After all the individual processes are configured, the final step is to calculate the total GWP Score for the entire supply chain. This cumulative score provides a comprehensive measure of the GWP Score of the entire supply chain. As the project progresses, the framework should be extended to include a function for estimating unknown supply chain processes based on predefined standard supply chain routes.

Benefits of the GWP Model:

Given the increasing importance of assessing and reducing the GWP of products and supply chains, the assessment model for GWP assessment serves as a valuable tool to support sustainable practices and informed decision-making of companies, including:

- Assessing the GWP-score for a given supply chain
- Identifying hotspots within their supply chain that significantly contribute to the GWP score
- Comparing different supply chain variants (suppliers, locations, transportation) in terms of their GWP scores
- Comparing different transportation routes or transportation means of their supply chain, in terms of their GWP scores

**Validation:**

a) The technical validation of the initial framework was proven in a previous project

b) The usability of the adopted framework was validated in a GWP training workshop, aligning the established framework with the conceptions of the cluster partners.

# 4 Output

As outlined in the previous sections, these three models offer a set of features that will be integrated with the RESC4EU B2B platform (in WP6). The output demonstrators of each feature are presented first, followed by a step-by-step demonstration of their functionality and the interpretation of results for each model based on examples.

To start with, the 1) The resilience scoring system (see Figure 10), as a part of the resilience self-assessment methodology, serves as a benchmarking tool for SMEs, enabling them to evaluate their resilience maturity in comparison to industry standards. This system categorizes businesses into three resilience tiers based on the scores -highly resilient, moderately resilient, and low resilience- helping organizations understand their current ability to anticipate, withstand, and recover from disruptions.

By generating a resilience score, the system signals whether a business has a balanced resilience profile or if gaps exist that require strategic intervention (the algorithm is provided in section 4.1 Functionality). If an SME is classified as highly resilient, it is understood that no immediate corrective action is needed, whereas a low resilience score signals the need for targeted improvements.

As an extended feature, for businesses with lower resilience scores, the next feature identifies key areas for improvement/capabilities and providing targeted recommendations to address critical weaknesses/vulnerabilities (weighted score calculation- refer to 4.1) and enhance supply chain resilience. The system offers tailored capability-matching insights, helping companies understand which specific vulnerabilities can be mitigated through internal and external capability improvements (correlation analysis between the different items and literature- refer to 4.1). These recommendations are personalized, considering both the company's individual characteristics and industry-specific benchmarks, ensuring relevance based on industry sector, company size.

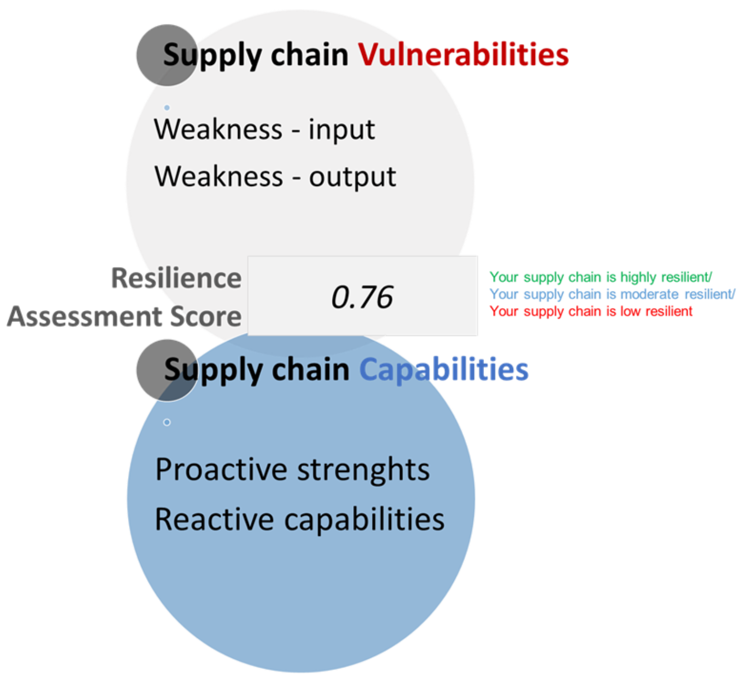



*Figure 10: Supply chain resilience self-assessment*

Notably, companies with high resilience scores can also leverage this feature to further optimize their supply chain strategies, refine their risk mitigation mechanisms, and maintain a competitive advantage. This structured, data-driven approach not only helps SMEs gain a clearer understanding of their resilience standing but also provides them with the necessary tools to fortify their operations.

As a next step, the feature of 2) Strategic alignment provides matching recommendations of the right capabilities that can fix a certain vulnerability, based on what industry and company size the company belong to (see Figure 11). By analysing the relationship between supply chain vulnerabilities and capabilities, businesses can develop targeted strategies to enhance resilience and build a more robust supply chain.

Feature 3) Prioritization of weaknesses and strengths (see Figure 12) focuses on identifying critical capabilities and vulnerabilities based on the specific industry or company size the user/company belong to. Participants receive guidance in recognizing key supply chain and transportation-related vulnerabilities, as well as potential operational disruptions. The tailored recommendations on how to leverage specific capabilities to address these challenges effectively, ensuring a more resilient and adaptive business operation, will be integrated with the ResC4EU B2B Platform using API calls.

To effectively demonstrate the features a), b), and c) within the RESC4EU B2B platform for users in WP6, the survey data is planned to be collected directly through the platform. Once collected, the data- linked to participant IDs- will be transmitted to the ISL data processing infrastructure, where it will be processed using SmartPLS 4 software.

- Utilizing the algorithm outlined in Section 4.1, the data analysis will include:
- Score generation to assess resilience levels,
- Weight allocation based on initial assumption and regression to determine the relative significance of different parameters, and
- Correlation analysis to identify relationships between vulnerabilities and capabilities.

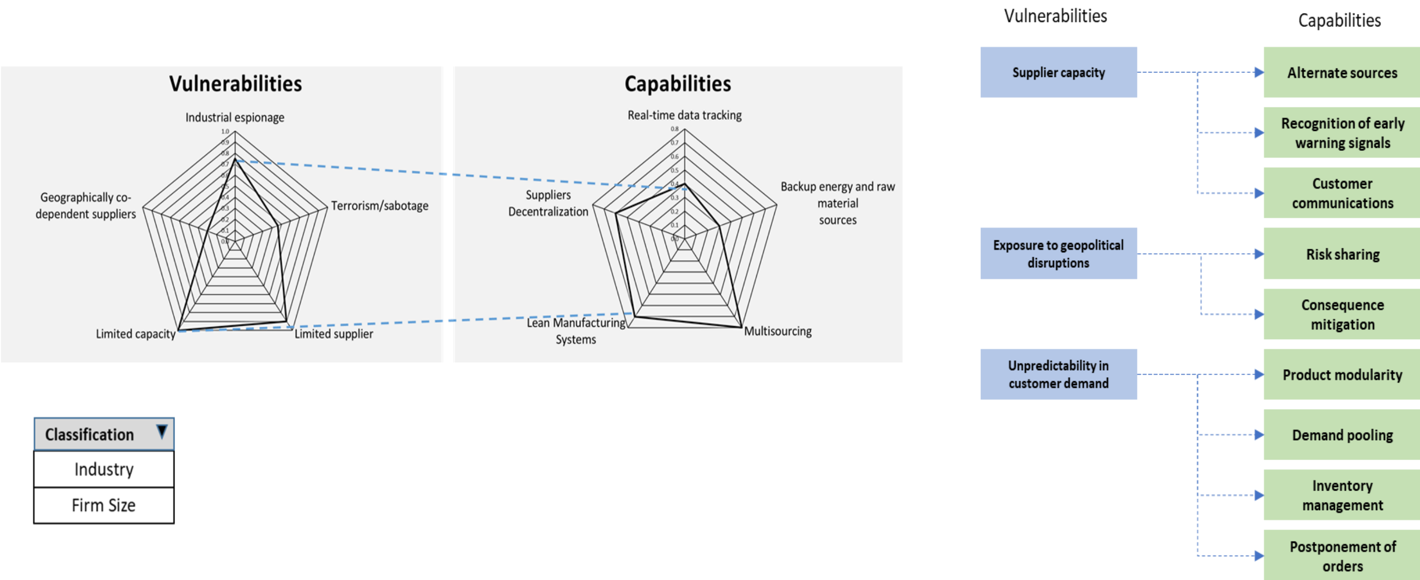



*Figure 11: Matching capabilities and vulnerabilities*

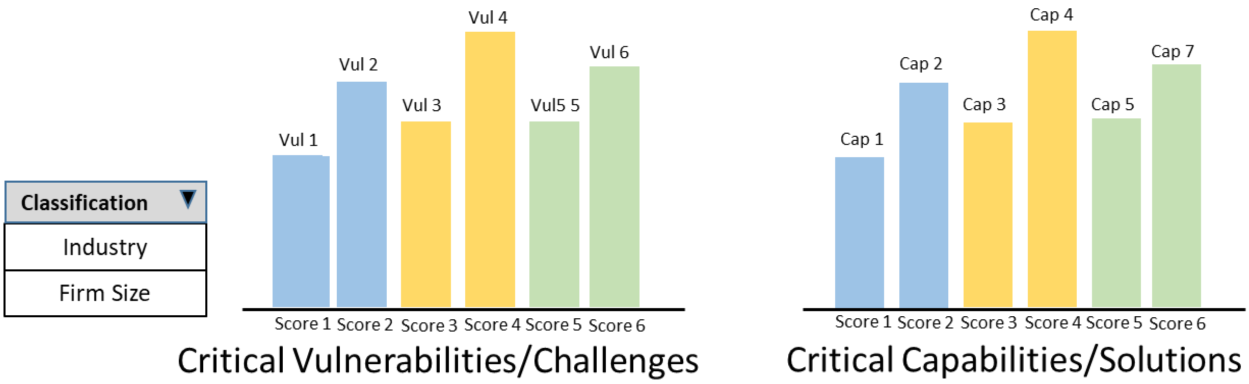



*Figure 12: Critical capabilities and vulnerabilities*

For seamless integration[19], Representational State Transfer (REST)[20] APIs will be developed to transmit the survey data from the user and collect the results of the analysis in order to present them, including graphical representations, on the ResC4EU B2B platform. This will enable immediate visualization of the outputs for features a), b), and c), ensuring an interactive and user-friendly experience for stakeholders engaging with the platform.

Next in line feature 4) and 5) (See Figure 13) enable continuous monitoring of hazards through external global databases, ensuring companies receive timely notifications if they are potentially affected. By identifying risks early, businesses can take proactive measures to safeguard operations. Additionally, guidance on the next steps for effectively addressing potential threats, helping organizations strengthen resilience and minimize disruptions, will be generated using the multimodal transport model through targeted API calls.

The process[21] begins with users providing route-related information (e.g., Route 1 from point A to point B) on the ResC4EU platform. This user-submitted data serves as the foundation for the multimodal transport model at the ISL data processing infrastructure, which then processes it alongside inputs from external data sources like IMF PortWatch, USGS, and INFORM Risk, covering societal and natural risks. The multimodal transport model analyses event and route data, identifies vulnerable route sections using a routing model and risk APIs, and generates alerts via an alert generator. The GWP model further enriches the analysis by evaluating the environmental impact of the routes, ensuring sustainability considerations are integrated. Alerts, such as warning about vessel traffic halting on the Suez Canal, are then delivered back to users through the ResC4EU platform, empowering them to take action, such as contacting forwarders, to address disruptions.

Finally, feature 6) and 7) (See Figure 14) access validated supplier data across multiple tiers of SMEs' supply chain, down to the raw material level. By leveraging autonomous mapping and supplier-validated data, this approach eliminates blind spots, giving businesses a competitive edge in resilience and ensuring a comprehensive understanding of supply chain dynamics.

---

[19] This process is, however, based on initial discussions on deploying the methodology as an extended toolset within the RESC4EU B2B platform. This is however subject to change as the project moves into the next phase in Work Package 6.

[20] https://en.wikipedia.org/wiki/REST

[21] This process is, however, based on initial discussions on deploying the methodology as an extended toolset within the RESC4EU B2B platform. This is however subject to change as the project moves into the next phase in Work Package 6.

Funded by the European Union

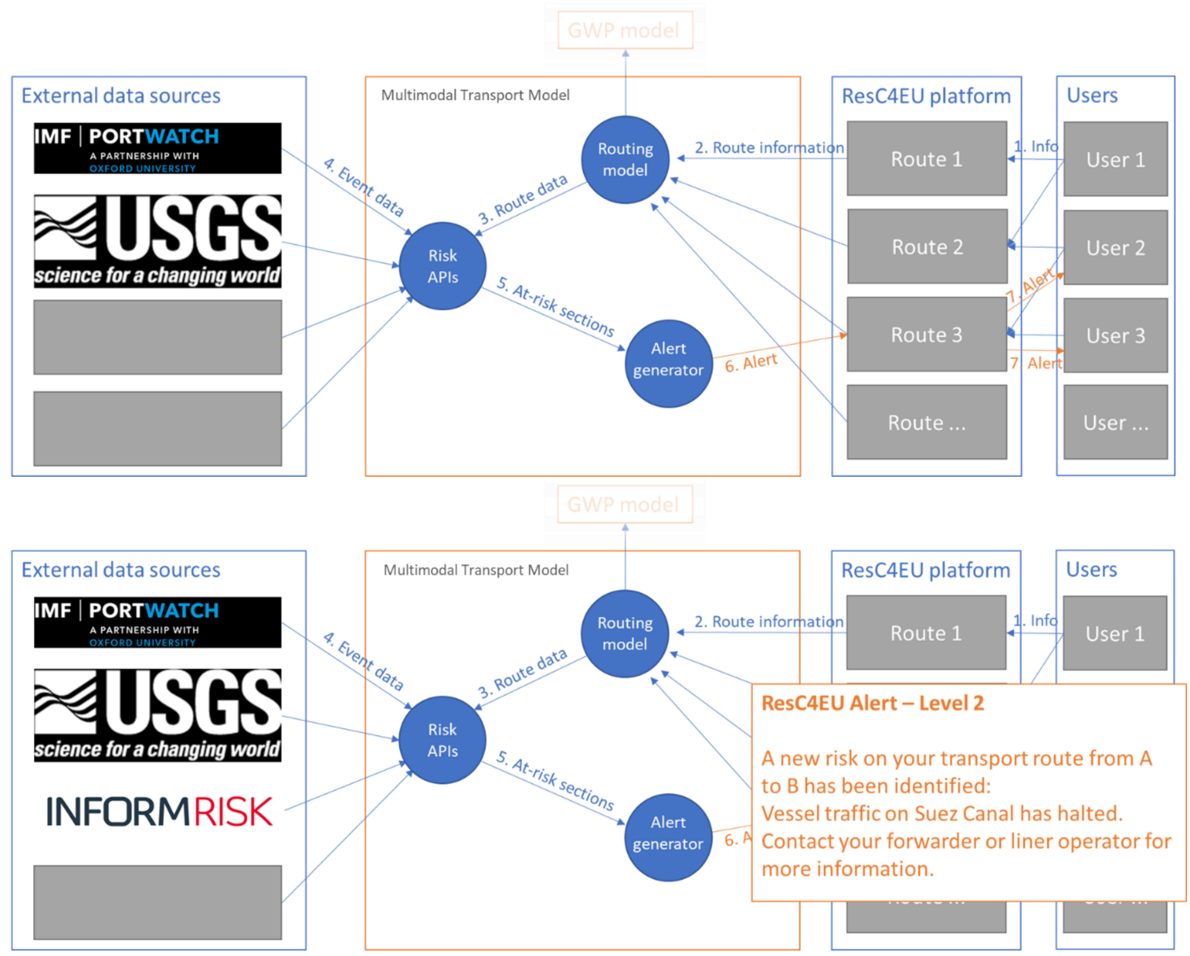



*Figure 13: Risk Alert*

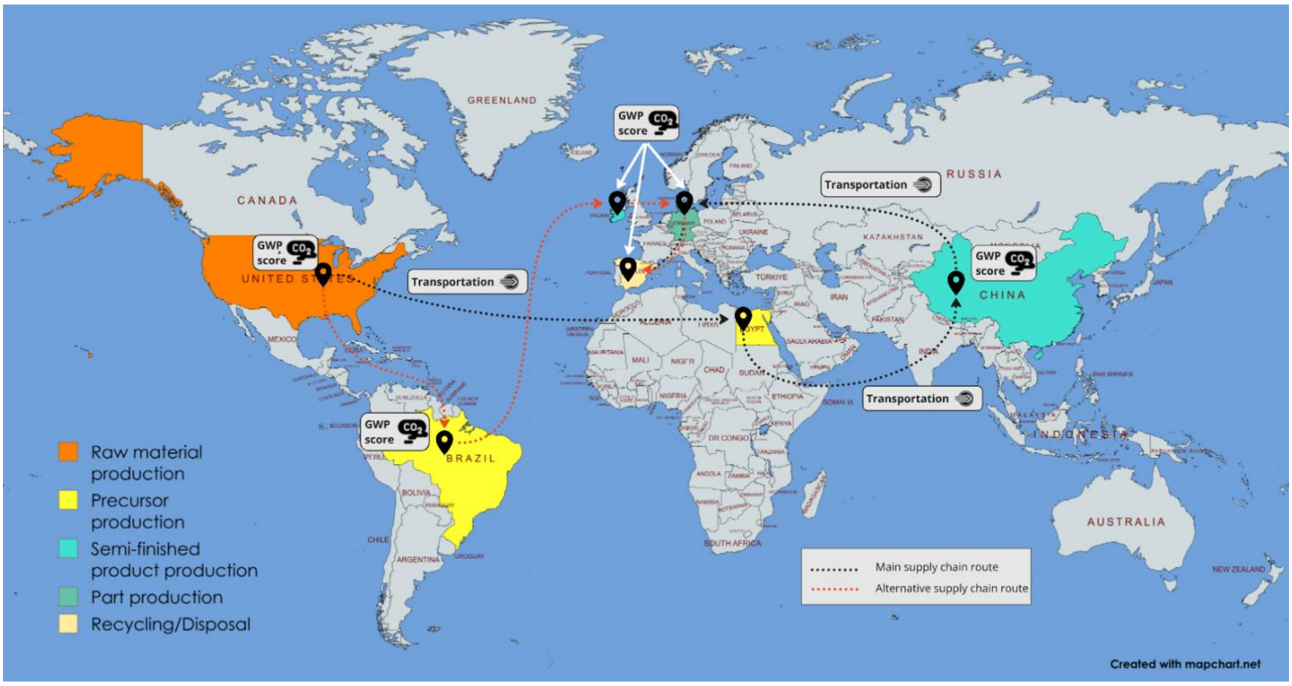
Features 6 and 7 provide a service to calculate the GWP within the supply chain. Using real data, SMEs gain insights into the environmental impact of their products. GWP is assessed at both a country-specific and process-specific level, utilizing Life Cycle Inventory (LCI) data that accounts for various process variants and regional technology mixes. Country-specific energy mixes are combined for each selected location to determine the resulting GWP. If a supplier's specific GWP is known, it can be entered directly into the platform, allowing businesses to choose between average database values or precise supplier-specific data. The final GWP score aggregates all process emissions across the supply chain, enabling informed sustainability decisions.

## 4.1 Functionality

**Supply chain resilience assessment methodology**

Figure 15 illustrates the risk and alerts framework emphasizing relations among key constructs of supply chain resilience identified in Table 2. It underscores the critical links between supply chain capabilities and vulnerabilities, showing how they influences resilience and ultimately drives performance outcomes.

In addition, the framework highlights that dynamic resilience is achieved through a combination of proactive capabilities, such as collaboration and visibility, and reactive capabilities, like adaptability and recovery mechanisms. For instance:




Black arrows mark the main supply chain route and the orange arrows the alternative supply chain route

*Figure 14: Visualization of the GWP Assessment Model for production and transportation*

- Visibility and collaboration within companies and across supply networks help mitigate the impact of turbulence caused by currency fluctuations, price volatility, geopolitical disruptions, or natural disasters. By enhancing real-time visibility of information flows, products, equipment, and workforce, and fostering trust-based partnerships, organizations can improve decision-making and increase their ability to manage risks effectively.
- Adaptability serves as a critical capability in addressing external pressures, such as competitive innovation and price fluctuations. It enables supply chains to pivot quickly in response to disruptions by reducing lead times, optimizing supplier networks, and incorporating strategic gaming and simulation techniques to assess and refine response strategies.

This supports a multidimensional evaluation of resilience by linking operational, social, and ecological performance metrics to strategic supply chain capabilities and identified risks.

At the core of the model shown in Figure 15 is an equation for calculating the Supply Chain Resilience (R) Self-Assessment Score:

$$R = \sum W \cdot C - \sum W \cdot VR$$

Where:

- C: Represents capabilities (e.g., adaptability, flexibility, collaboration) - All items and constructs as per Table 2.
- V: Represents vulnerabilities (e.g., turbulence, resource constraints). All items and constructs as per Table 2.

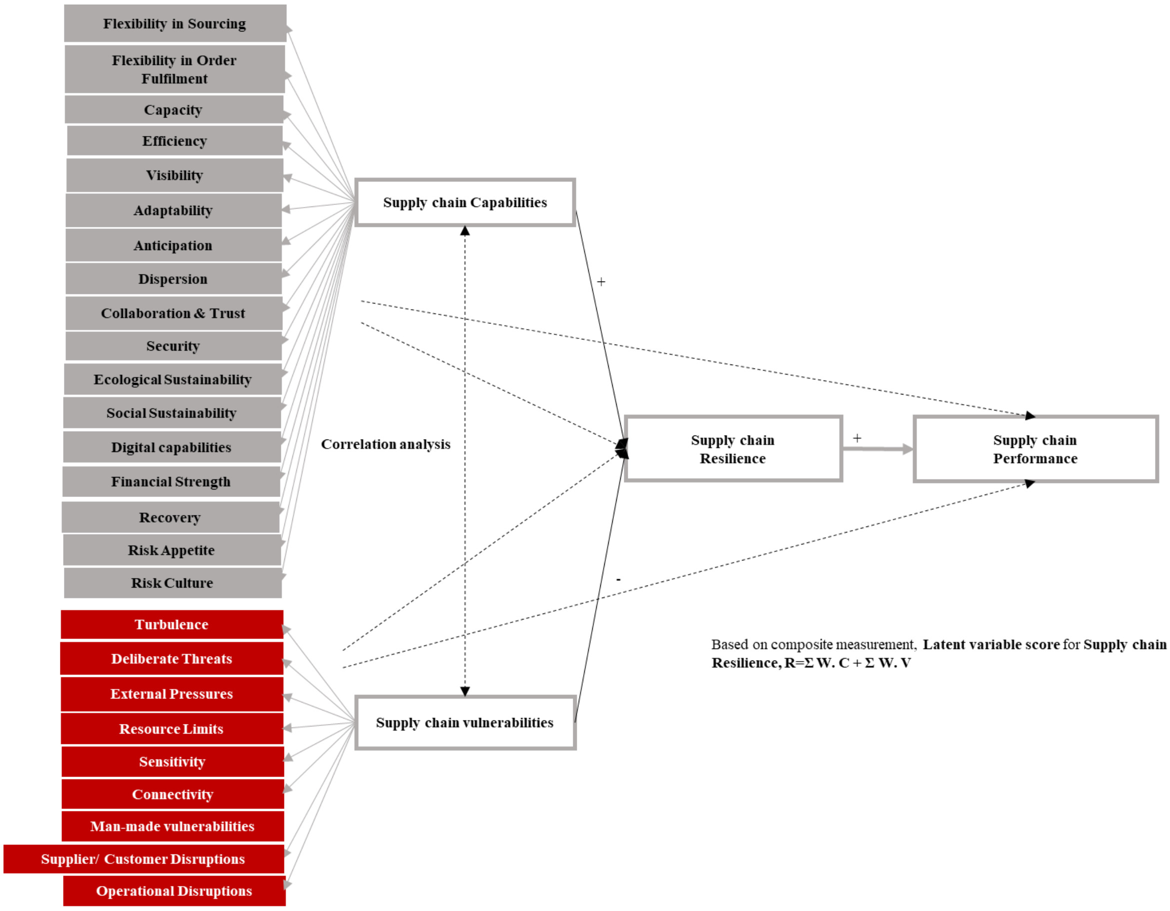



*Figure 15: Supply chain resilience self-assessment framework*

- W: Refers to weights assigned to each capability or vulnerability items and constructs based on their relative significance. This weightage is based on approximation and are assigned and updated using regression-based approaches (refer to the subsections 4.2.2 and 4.2.3).

This equation adopts a composite measurement approach, where positive contributions from capabilities (W·C) offset the negative impacts of vulnerabilities (W·V).

The resulting self- assessment score R gives a first indication of the overall resilience of the supply chain for an SME. The scoring is based on latent variable score, derived using Partial Least Squares Structural Equation Modeling (PLS-SEM). The main features of these scoring are:

- Quantification of Construct Relationships: PLS-SEM measures the direct and indirect relationships among capabilities, vulnerabilities, and performance outcomes, offering an understanding of resilience dynamics.
- Significance of Weights: Weights (WW) are derived from empirical data, ensuring that the scoring system reflects real-world significance and industry-specific factors.
- Dynamic Framework: The methodology's reliance on PLS-SEM facilitates the continuous refinement of constructs and weights as new data is integrated, maintaining its relevance across diverse contexts

The methodology offers several practical benefits for SMEs:

- Actionable Insights: By identifying strengths and weaknesses through the scoring system (weighted score of each observation for each parameter), SMEs can prioritize resources and capabilities effectively (refer to 4.2.2- EXAMPLE 2: Identifying critical capabilities and vulnerabilities).
- Holistic Evaluation: The integration of operational, social, and ecological performance metrics ensures that resilience capabilities align with broader business and sustainability goals (refer to the different constructs and items in Table 2- Capabilities parameters such as social sustainability, ecological sustainability and performance parameters such as ecological performance and social performance)
- Dynamic Adaptability: Scores are adapted based on regression and learning: industry-specific requirements and evolving supply chain conditions by recalibrating the weights of the different parameters (refer to 4.2.2- EXAMPLE 1: Calculating supply chain resilience scores first para).

To determine the most critical resilience factors/parameters, outer weights are extracted from the SmartPLS algorithm and are used to calculate the weighted score for each factor and item for each observation (specific user- participants/companies). Outer weights represent the relative contribution of each construct's indicators (items) to the overall resilience construct in the PLS-SEM framework.

These weights are obtained from the SmartPLS 4 software and are characterized as follows

- Estimated at the model level rather than for individual observations.
- Reflect the contribution of each item to its respective construct.
- Enable computation of observation-specific critical factors by weighting each observation's rating with its corresponding outer weight.

The formula for an individual observation-level weighted score is:

$$\textbf{Weighted Score}_{ij} = \textbf{Outer Weight}_{j} \times \textbf{Rating}_{ij}$$

Where:

- **Outer Weight** $_j$= Weight assigned to item j by SmartPLS 4 at the model level.
- **Rating** $_{ij}$ = Score given to item j for observation i.

In resilience assessment, an organization must match its capabilities with identified vulnerabilities. This process involves determining which capabilities effectively mitigate specific vulnerabilities through correlation analysis within the SmartPLS 4 software. SmartPLS 4 quantifies the relationships between resilience factors. The latent variable correlation matrix and individual observation-level correlation analysis provide insights into which capabilities strongly counteract vulnerabilities. Furthermore, the analysis is complemented by an extensive scientific and practice-oriented literature base, which provides established matched pairs of vulnerabilities and capabilities.

**Multimodal Transport Model**

Users will receive risk alerts whenever a new hazard geographically intersects with their transport routes, including supplier or customer locations. To ensure data privacy, the ResC4EU platform owner, GTW, will receive these alerts via API calls and then distribute them to the relevant SME representatives through the platform, thus maintaining secure and targeted communication.

**GWP Assessment Model**

For a comprehensive calculation of the overall GWP of the supply chain, the following equations are applied, incorporating various parameters.

The GWP for a production process is calculated using the following equation 2:

$GWP_{Pro} = GWP_{PVe} + EC_{PV} * GWPF$ (2)

Where:

- GWPPro: Specific GWP of one process in the supply chain
- GWPPVe: Specific GWP of the process variant excluding the energy consumption
- ECPV: Total energy consumption of the process variant
- GWPF: Country specific global warming potential factor for energy mix

Based on the available data an aggregated country specific GWP value of the process might be used directly according to the following equation 3:

$GWP_{Pro} = GWP_{PVi}$(3)

- GWPPro : Specific GWP of one process in the supply chain
- GWPPVi : Specific GWP of the process variant including the GWP of energy consumption

Considering equations 2 and 3, the total GWP of the supply chain can be calculated using equation 4:

$GWP_{SC} = \sum GWP_{Pro}$ (4)

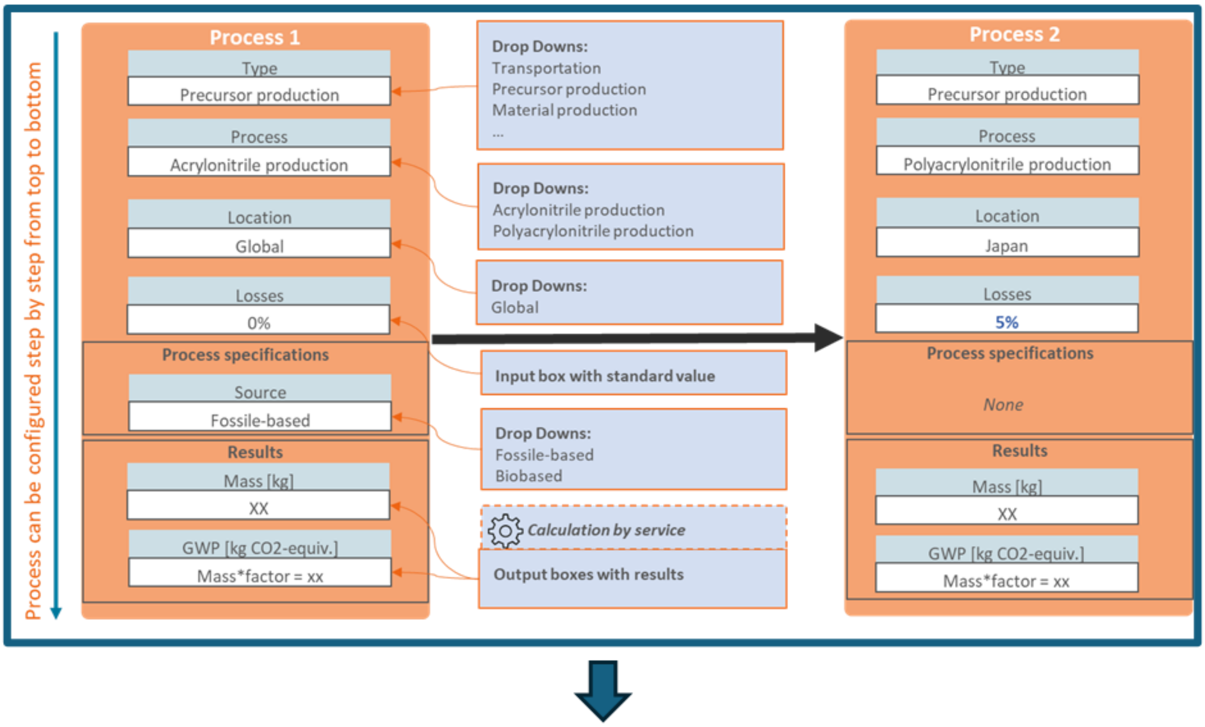
Where:

- GWPSC: Total GWP of the supply chain.

The GWP is calculated for each process in the supply chain, including production and transport processes. All values are subsequently summed up to give an overall GWP score for the entire supply chain (equation 4). A visual representation is shown in Figure 14, which presents a map demonstrating that each process yields a distinct GWP value. The locations of each process within the supply chain are illustrated, starting with material production and ending with the end-of-life of the product as well as the transportation route between the respective processes. The black arrows indicate the route of the main supply chain that was entered by the user and the orange arrows indicate an alternative route, using different suppliers or transportation modes. The alternative route is not calculated automatically but instead depends on the established supply chain network within the B2B platform.

**Data Schema**

To accurately determine the GWP of the supply chain, users can enter relevant data for each process in the supply chain. This is facilitated through a structured input system that captures essential parameters for each process. The information will be entered via series of dropdown menus, ensuring a standardized and consistent approach (see Figure 16). The key data to be entered through the platform' user interfaces include:




| Header | Type | Process | Location | Losses (configurable) | Process specification 1 | Process specification 2 | Process specification 3 |
|---|---|---|---|---|---|---|---|
| | | | | | | Transportation | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | ***Efficiency*** | | |
| | Transportation | Transport by Truck | | 0 | Euro 6 | | |
| | Transportation | Transport by Truck | | 0 | European Mix (Euro 1-6) | | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | | | |
| | Transportation | Transport by Ship | | | | | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | | | |
| | Transportation | Transport by Train | | | | | |
| | | **Transport by truck** | | | **Euro 6** | | |
| | | | | | | Processes | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | ***Source*** | | |
| | Precursor production | Acrylonitrile production | Global | | fossile-based | | |
| | Precursor production | Acrylonitrile production | Global | 0 | biobased | | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | | | |
| | Precursor production | Polyacrylonytrile production | Global | | | | |
| | Precursor production | Polyacrylonytrile production | Japan | 0.05 | | | |
| | Precursor production | Polyacrylonytrile production | USA | | | | |
| ***Header*** | ***Type*** | ***Process*** | ***Location*** | ***Losses*** | ***Efficiency*** | ***Process Energy*** | |
| | Material production | Carbon fiber production | Global | | minium efficiency | electrical energy dominated | |
| | Material production | Carbon fiber production | Global | | minium efficiency | thermal energy dominated | |
| | Material production | Carbon fiber production | Global | | medium efficiency | electrical energy dominated | |
| | Material production | Carbon fiber production | Global | | medium efficiency | thermal energy dominated | |

Black arrows mark the main supply chain route and the orange arrows the alternative supply chain route

*Figure 16: Representation of the input system enabling the user to fill in information about the process, which is connected to the backend, being an excel-based data scheme*

- Process type: Categorization of the process (e.g., transport, precursor production, etc.).
- Process specification: Definition of the product or material being processed, including its characteristics, properties, and any relevant processing requirements
- Location: The geographical information of the manufacturer, specifically country details (excluding the exact locations of manufacturers or suppliers), is critical for evaluating the regional electricity grid mix and transport routes.
- Losses: Default values will be provided here, but users may also input custom values if available.
- Process specification: Additional details can be entered depending on the process, e.g., material source.

This procedure is carried out for each step in the supply chain, calculating a corresponding GWP value, which ultimately determines the GWP for the whole supply chain. Nevertheless, if the user already knows the GWP value of a process, there is always the possibility of entering the value directly. In cases where specific data points are unavailable, providing a default setting is being considered. These defaults will be designed specifically for the composite industry but may incorporate generally valid datasets, such as electricity grid mixes and transportation emissions, which can also be utilized across different industrial sectors.

The backend of this service is designed to systematically process the entered supply chain data and derive the corresponding GWP values. These values are stored in an Excel-based data scheme shown in Figure 16 defining the Life Cycle Inventory (LCA) database. A lookup service, connected via an API, facilitates this data retrieval. The database is built on open-source data, incorporating scientific papers and open LCI/LCA datasets. This framework provides the initial framework for the other industries sectors/clusters and they can use this framework in order to establish their own LCA database for assessing the GWP score for their specific processes/supply chain.

## 4.2 Interpretation of outputs and examples

### 4.2.1 Outputs of the supply chain resilience self-assessment methodology

The supply chain resilience self- assessment scoring system evaluates the position of each observation (e.g., participant, company) on resilience constructs based on latent variable scores (e.g., O1, O2, O3,…, O60) (Figure 17). These scores are calculated by the PLS-SEM algorithm of SmartPLS 4, which integrates two key models:

- *Measurement model:* Analyses relationships between observed indicators (survey items- refer to Table 2) and their corresponding latent variables (constructs- parameters such as flexibility, adaptability, etc for capabilities and turbulence or resource limits- refer to Table 2).
- *Structural model:* Examines the interactions and causal relationships between the latent variables (parameters such as vulnerabilities, capabilities, resilience and performance) themselves.

The resulting resilience self- assessment scoring system provides a dynamic and data-driven framework for evaluating supply chain resilience, allowing SMEs to establish an initial benchmark of their resilience levels.

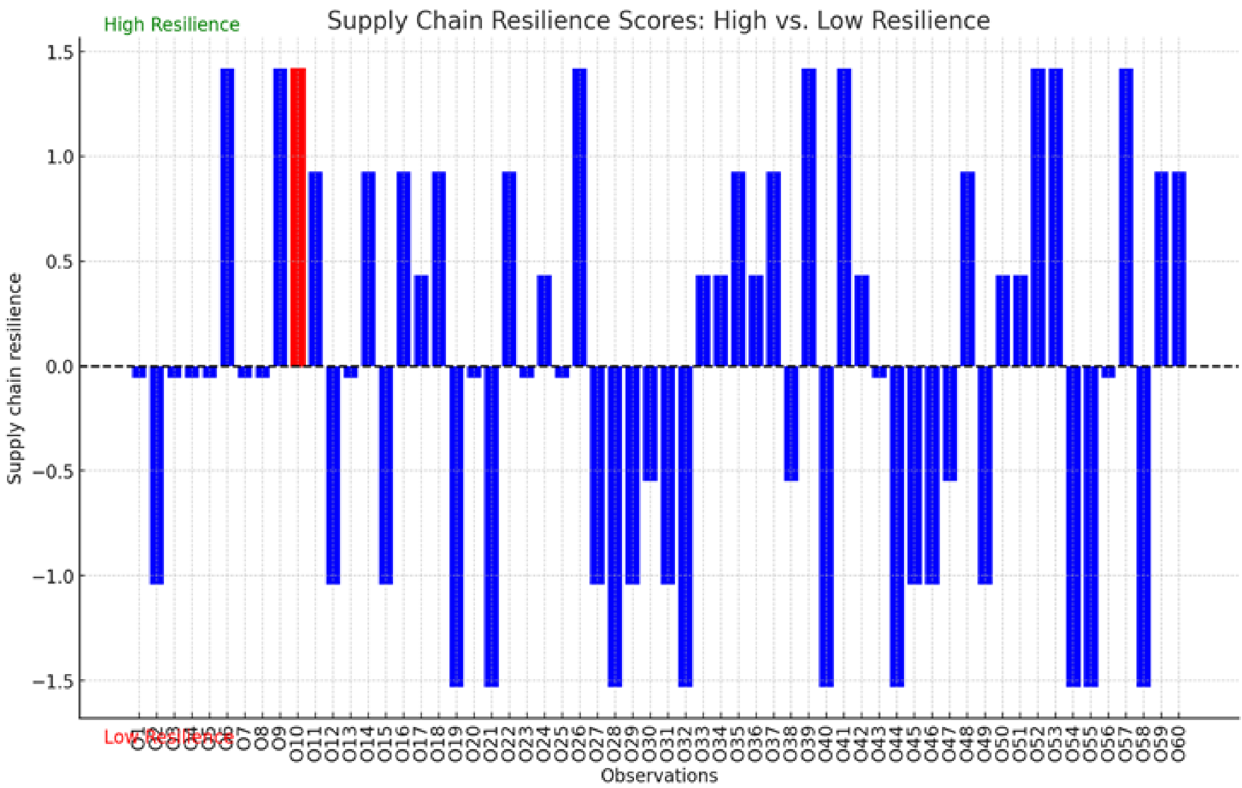



*Figure 17: Supply chain resilience self-assessment scoring based on latent variable scores- PLS-SEM*

**Interpretation**

The latent variable scores derived from PLS-SEM provide actionable insights by indicating an organization's performance on resilience constructs relative to the sample mean:

- Positive Scores (e.g., +0.456):
  - Indicate above-average performance
- Negative Scores (e.g., −1.351):
  - Reflect below-average performance.
- Zero Scores (0):
  - Represent the sample mean, indicating the company performs at the average level for the given construct.

This interpretative framework enables organizations to pinpoint specific strengths and weaknesses, forming the basis for tailored resilience strategies. Given the complexity and breadth of parameters incorporated into the assessment, a simplified example (Example 1: Calculating supply chain resilience scores) is provided to illustrate the calculation logic in the following sub section 4.2.2. By reducing the number of parameters, this example (EXAMPLE 2: Identifying critical capabilities and vulnerabilities) offers a clearer understanding of how critical capabilities (strengths) and vulnerabilities (weaknesses) are identified or matched based on the weighted score for each item and for each observation as a part of the next features, demonstrating the underlying methodology in a more accessible manner.

### 4.2.2 Examples

**EXAMPLE 1: Calculating supply chain resilience scores**

The following example includes a reduced number of parameters (constructs and items) to illustrate the computational logic involved in calculating the supply chain resilience self-assessment score. In reality, this scoring range will differ significantly (typically falling between +2 and -2 as shown above) as it will account for a much broader set of parameters. In this process, PLS-SEM employs an iterative approach where initial weights (w) (Refer to Table 3) are approximated to each parameter and subsequently refined using regression-based techniques within the SmartPLS 4 software. The rating (r) (Refer to Table 3) for observations or participants (O1, O2, O3, O4) represents the survey responses collected as part of the survey tool or platform (which will be implemented in future phases). Considering this is a generic benchmarking without the need for any context-specific differences, such as firm size or industry, for the participants, total scores will be benchmarked based on the average score of the other participants.

Table 3: Example 1: Supply chain resilience self-assessment scoring calculation

| Category | Construct | Measurement Item | Weight (w) | O1 (r) | O2 (r) | O3 (r) | O4 (r) | Weighted Score Formula |
|---|---|---|---|---|---|---|---|---|
| Capabilities (Positive Impact) | Flexibility in Sourcing | CFSO1: Modular product design | 0.57 | 5 | 6 | 4 | 7 | r×0.57 |
| | | CFSO2: Multiple uses | 0.57 | 6 | 5 | 7 | 8 | r×0.57 |
| | Flexibility in Order Fulfilm. | COF1: Alternate distribution channels | 0.76 | 4 | 3 | 5 | 6 | r×0.76 |
| | | COF2: Delayed commitment / Production postponement | 0.76 | 5 | 6 | 4 | 7 | r×0.76 |
| | Capacity | CC1: Reserve capacity | 0.35 | 7 | 6 | 8 | 5 | r×0.35 |
| | | CC2: Backup energy sources & communication | 0.35 | 6 | 7 | 5 | 8 | r×0.35 |
| | Efficiency | CE1: Labor productivity & product variability reduction | 0.40 | 6 | 5 | 6 | 7 | r×0.40 |
| | | CE2: Asset utilization & waste elimination | 0.40 | 5 | 7 | 6 | 8 | r×0.40 |
| Total Capability Score (Sum of capability scores) | | | - | 16.98 | 14.85 | 17.46 | 18.42 | |
| Vulnerabilities (Negative Impact) | Turbulence | VT1: Market fluctuations | -0.60 | 6 | 7 | 5 | 4 | r×−0.60 |
| | Deliberate Threats | VDT5: Cyber-attacks | -0.50 | 8 | 6 | 7 | 5 | r×−0.50 |
| | External Pressures | VEP2: Social/Environmental change | -0.40 | 5 | 4 | 6 | 7 | r×−0.40 |
| Total Vulnerability Score (Sum of vulnerability scores) | | | - | -10.60 | -9.10 | -8.50 | -7.80 | |
| Final Resilience Score (R) (Capabilities- Vulnerabilities) | | | - | 6.38 | 5.75 | 8.96 | 10.62 | |

Each observation (O1, O2, O3, etc.) represents a different SME involved in a supply chain:

- O4 has the highest resilience score (10.62), indicating strong capabilities and lower vulnerabilities.
- O2 has the lowest score (5.75), suggesting it may need to strengthen its resilience.
- Next step provides the critical weakness (vulnerabilities) and strengths (capabilities) base on demonstrating the weighted scores for each parameter and for each observation.

**EXAMPLE 2: Identifying critical capabilities and vulnerabilities**

Here is another example designed to demonstrate the logic for identifying critical capabilities and vulnerabilities. Since this is a context-specific scoring approach that accounts for factors such as industry and firm size, participants are clustered based on their respective industries and firm sizes. In this example, observations (O1, O2, O3, O4) represent two industries with different SME sizes: large, medium and small SMEs (Refer to Table 4, 5 and 6). The parameters included have also been deliberately limited to maintain simplicity.

*Table 4: Example 2: Industries based on the various observations (user participant-manager/company)*

| Observation | Industry | Company Size |
|---|---|---|
| O1 | Electronics | Large Company |
| O2 | Electronics | Medium Company |
| O3 | Mobility/Transport/Automotive | Large Company |
| O4 | Mobility/Transport/Automotive | Small Company |

*Table 5: Example- Critical capability calculation*

| Category | Construct | Measurement Item | Weight (w) | O1 (r) | O2 (r) | O3 (r) | O4 (r) | Weighted Score Formula |
|---|---|---|---|---|---|---|---|---|
| Capabilities (Positive Impact) | Flexibility in Sourcing | CFSO1: Modular product design | 0.30 | 5 | 6 | 4 | 7 | r×0.30 |
| | | CFSO2: Multiple uses | 0.28 | 6 | 5 | 7 | 8 | r×0.28 |
| | Flexibility in Order Fulfilment | COF1: Alternate distribution channels | 0.34 | 4 | 3 | 5 | 6 | r×0.34 |
| | Capacity | CC1: Reserve capacity | 0.26 | 7 | 6 | 8 | 5 | r×0.26 |
| | Efficiency | CE1: Labor productivity & product variability reduction | 0.29 | 6 | 5 | 6 | 7 | r×0.29 |
| Total Capability Score (Sum of capability scores) | | | - | **3.93** | **3.49** | **4.18** | **4.62** | |

*Table 6: Example- Critical vulnerability calculation*

| Category | Construct | Measurement Item | Weight (w) | O1 (r) | O2 (r) | O3 (r) | O4 (r) | Weighted Score Formula |
|---|---|---|---|---|---|---|---|---|
| Vulnerabilities (Negative Impact) | Turbulence | VT1: Market fluctuations | -0.32 | 6 | 7 | 5 | 4 | r×−0.32 |
| | Deliberate Threats | VDT5: Cyber-attacks | -0.27 | 8 | 6 | 7 | 5 | r×−0.27 |
| | External Pressures | VEP2: Social / Environmental change | -0.25 | 5 | 4 | 6 | 7 | r×−0.25 |
| Total Vulnerability Score (Sum of vulnerability scores) | | | - | **-4.61** | **-4.37** | **-3.78** | **-3.35** | |

- O4 (Mobility, Small Firm) is the most resilient= 4.62-3.35 = 1.27
- O1 and O2 (Electronics sector) have negative resilience scores, suggesting they are more vulnerable than capable.
- O3 (Mobility, Large Firm) shows moderate resilience= 4.18- 3.78= 0.4

1. Electronics Industry (O1 & O2)

Critical Capabilities and recommendations

1. **Modular Product Design (CFS1)** → Focus on product modularity to quickly adapt to component shortages and market changes: 5*0.3+6*0.3=3.3
2. **Alternate Distribution Channels (COF1)** → Develop several distribution pathways.

Critical Vulnerabilities and recommendations

1. **Market Fluctuations (VT1)** → Prioritize demand forecasting, real-time market analytics, and scenario planning.
2. **Cyber-attacks (VDT5)** → Strengthen cybersecurity infrastructure, invest in data security audits, and implement incident response systems.

2. Mobility, Transport, and Automotive Industry (O3 & O4)

Critical Capabilities and recommendations

1. **Alternate Distribution Channels (COF1)** → Expand logistics networks: 5*0.3+6*0.3=3.74
2. **Labor Productivity & Product Variability Reduction (CE1)** → Invest in lean practices, automation, and predictive analytics.

Critical Vulnerabilities and recommendations

1. **Market Fluctuations (VT1)** → Develop adaptive pricing strategies and market risk hedging practices.
2. **Social/Environmental Changes (VEP2)** → Invest in sustainability programs, regulatory compliance tools, and stakeholder engagement initiatives.

The example is presented primarily from an industry sector perspective. However, as demonstrated in Table 5 and Table 6, critical capabilities and vulnerabilities can also be assessed and analysed at an individual company/user level.

**EXAMPLE 3: Matching supply chain vulnerabilities and capabilities**

This example is about matching vulnerabilities and capabilities of SMEs from the electronics and automotive industries. Suppose a correlation analysis is conducted to evaluate how effectively different capability constructs mitigate vulnerability constructs. The analysis might reveal strong negative correlations between specific resilience capabilities and external threats.

In the electronics industry, SMEs O1 and O2 could face external pressures (VEP) in the form of market volatility and regulatory shifts. The analysis might indicate that Flexibility in Sourcing (CFSO4 - Multiple Sources) has a negative correlation (-0.72) with external pressures, suggesting that companies with diversified supplier networks are less vulnerable to disruptions caused by supply constraints or geopolitical risks. Similarly, Alternate Distribution Channels (COF1) could show a negative correlation (-0.65) with market turbulence (VT), implying that companies with multiple delivery pathways are better positioned to manage fluctuations in demand.

On the other hand, SMEs in the automotive and mobility sector (O3 and O4) may experience a different set of vulnerabilities. Market fluctuations (VT) due to economic conditions and shifting consumer preferences could be identified as major challenges. In this case, correlation analysis might reveal that Reserve Capacity (CC1) is strongly negatively correlated (-0.68) with market turbulence, meaning that companies maintaining buffer capacity in production and warehousing are better able to handle sudden demand shifts.

Additionally, another critical insight could be the negative correlation (-0.70) between External Pressures (VEP) and Labor Productivity Optimization (CE1), indicating that efficiency improvements in workforce management help companies adapt to regulatory and competitive pressures.

These insights illustrate that the importance of specific resilience capabilities varies by industry and company size. For large electronics companies, investing in supplier diversification and alternative distribution mechanisms could significantly enhance resilience. Meanwhile, in the automotive industry, strategies such as maintaining reserve capacity and enhancing workforce efficiency may play a crucial role in addressing market uncertainties.

By systematically analysing these relationships using SmartPLS 4 latent variable correlations, SMEs can make data-driven decisions on resilience investments. While SmartPLS 4 does not directly compute observation-level correlations, exporting latent variable scores and conducting company-specific correlation analysis in tools like Excel or Python enables businesses to refine their resilience strategies based on their unique operational contexts.

**EXAMPLE 4: Multimodal Transport model**

Given the variety of sources that will be scanned for potential hazards and the requirement for a standardized alert template, all hazard data will be structured as follows:

| | |
|---|---|
| title: | M 7.0 - 13 km NNE of Néon Karlovásion, Greece |
| type: | earthquake [can be used for choice of icons or colour scheme of alerts] |
| route_id: | 824 |
| route: | Izmir – Hamburg (maritime)<br>[affected route of the user, with Izmir being the supplier location and Hamburg being the production site] |
| description: | Magnitude 7.0 earthquake 13 km NNE of Néon Karlovásion, Greece |
| advice: | Check cargo status and – if needed – alternative routing options with your shipping company or logistics operator. |
| aource: | U.S. Geological Survey |
| event_link: | https://earthquake.usgs.gov/earthquakes/eventpage/us7000c7y0/ ["More information…"] |

The advice text will be pre-defined based on a combination of hazard types and affected routes. For example, "shipping company" will be included only if maritime transport is affected.

**EXAMPLE 5: GWP assessment model**

The GWP modeling approach is designed around core classes that represent various processes, such as manufacturing, which are utilized to create concrete instances of specific processes. These instances are then used to calculate the corresponding GWP values for a given product (Figure 18)

As part of WP6, the model will be further integrated with the transport model provided by ISL and will allow a more comprehensive assessment of supply chain impacts, thereby providing more detailed calculations tailored for SMEs. The implementation will be demonstrated through a use case in the composites industry.

Additionally, initial discussions on deploying the model as a third-party backend service for the B2B platform have already taken place through a series of technical workshops focused on deployment and integration of the model with the platform in the form of API calls, ensuring data exchange and interoperability

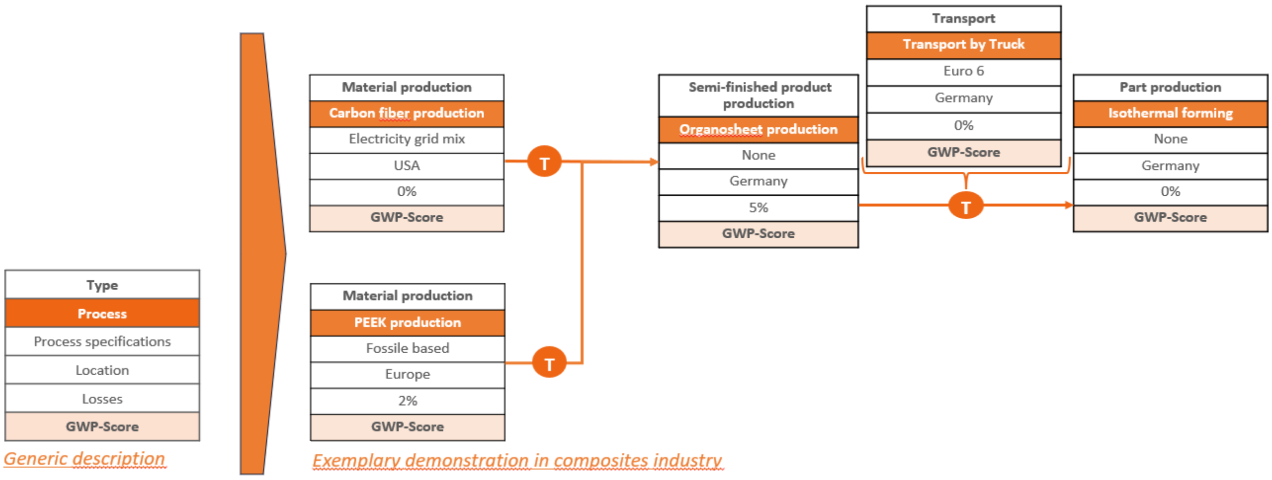



*Figure 18: Generic description and specific instances for exemplary supply chain (T: Transport)*

# 5 Conclusion and Discussion

## 5.1 Supply Chain Resilience Self-assessment Methodology

This methodology provides SMEs with a structured approach to identifying critical vulnerabilities and aligns them with appropriate resilience capabilities. By leveraging weighted scoring and correlation-based insights, SMEs can take a proactive stance in strengthening supply chain resilience

Limitations:

- Biases in ratings: The methodology relies on SMEs' self-reported data, collected through online surveys, which may introduce biases.
- Dependency on Historical Data: The methodology is based on reactive subjective perceptual assessment from the users. In this line, past performance does not always predict future resilience in volatile environments.

Practical and Policy Implications:

- For Industry: SMEs can use the methodology as the future toolset for internal benchmarking and resilience enhancement initiatives.
- For Policymakers:
    1) Invest in open-source digital tools: SMEs often lack the funds and expertise for proprietary risk systems. Free, accessible tools help them identify risks, anticipate disruptions, and build resilience.
    2) Mandate resilience metrics in Regulations: Policymakers should require self-assessments in procurement, financing, and industry rules. Standardized metrics drive data-driven improvements and enhance supply chain stability.
    3) Incentivize digital transformation: Subsidies, tax breaks, and grants can help SMEs adopt modern risk assessment tools, reducing reliance on outdated, manual methods.
    4) Promote cross-sector collaboration: Public-private partnerships for benchmarking, knowledge-sharing, and stress testing ensure collective preparedness and resource optimization.
    5) Link resilience to sustainability goals: Regulatory incentives for low-carbon supply chains and GWP-based assessments encourage businesses to integrate sustainability into resilience planning.

## 5.2 Multimodal Transport Model

This model enhances supply chain resilience by integrating real-time risk alerts with decision-making processes. By leveraging external hazard data, companies can proactively reroute shipments and mitigate disruptions before they impact operations.

Limitations:

- Data accuracy: The effectiveness of risk alerts depends on the reliability of external data sources.

- Integration complexity: Implementing this model requires strong IT infrastructure and interoperability with existing supply chain management systems.
- Reaction time constraints: The model assumes that SMEs can react quickly to risk alerts, which may not always be feasible due to operational constraints.

Practical and Policy Implications:

- For Industry:
    1) Companies can integrate risk alert systems with logistics planning tools to enable dynamic rerouting.
    2) Enhanced visibility into potential supply chain disruptions enables companies to proactively manage risks rather than reactively addressing crises.
    3) Adoption of AI-driven predictive analytics can refine risk alert precision, helping companies distinguish between minor disruptions and critical threats.
- For Policymakers:
    1) Encouraging data-sharing initiatives among supply chain stakeholders can improve the overall effectiveness of risk-based routing models.
    2) Governments can support the development of standardized risk alert protocols to ensure compatibility across different logistics networks.
    3) Investing in open-access hazard databases will enhance the quality and accuracy of real-time risk assessment tools.

## 5.3 GWP Assessment Model

The GWP assessment model provides a robust methodology for evaluating the environmental impact of supply chain decisions. By quantifying $CO_2$ emissions across logistics networks, SMEs can make more sustainable choices while maintaining operational efficiency.

Limitations:

- Data availability: Comprehensive emissions tracking requires detailed supply chain visibility, which many companies lack.
- Industry-specific variations: The model needs adaptation for different industries with unique carbon footprint considerations.
- Regulatory changes: The evolving landscape of sustainability regulations may require frequent model updates.

Practical and Policy Implications:

For Industry:

1) Giving SMEs the ability to make data-driven decisions based on their GWP-score
2) Leading to transparency and awareness regarding ecological sustainability
3) Identify the potential of reducing GHG emissions by identifying alternatives regarding suppliers, transportation means or transportation routes

For Policymakers: Governments can integrate the GWP model into sustainability regulations, encouraging businesses to adopt eco-friendly supply chain practices in line with enhancing their supply chain resilience.

## 5.4 Discussion and future scope

The integration of the three models—supply chain resilience self-assessment methodology, multimodal transport model, and GWP assessment model—creates a comprehensive framework for strengthening supply chain resilience. The multimodal transport model serves as the backbone of the presented framework, generating risk alerts and feeding risk assessments into both the Supply Chain Resilience Self-Assessment Model (to enhance operational resilience) and the GWP assessment model (to ensure sustainability integration). The Resilience Self-Assessment Model helps SMEs determine their risk exposure, while the multimodal transport model provides real-time insights to improve decision-making. It also feeds into the GWP assessment model, ensuring that resilience strategies account for environmental impact. Together, they create a holistic approach that balances operational efficiency, risk mitigation, and sustainability. Such a modular approach empowers organizations to proactively manage risks, enhance supply chain resilience, and align logistics strategies with global sustainability objectives.

The next phase involves transcending models presented in this report into a full-fledged functioning tool and integrating into the ResC4EU B2B platform. This will require designing API calls to facilitate data exchange between the B2B platform and the models. The key components of this integration include:

- Resilience self-assessment tool (WP: T6.2): The scoring methodology will be developed into an interactive tool allowing SMEs to evaluate their resilience capabilities and receive data-driven insights.
- Risk alert tool (WP6: T6.2): The real-time risk alert system will be linked to global hazard databases, enabling automated notifications to inform SMEs of potential supply chain disruptions.
- GWP assessment tool (WP6: T6.1): The sustainability assessment will be expanded to include sector-specific $CO_2$ emissions calculations, supporting SMEs in making environmentally friendly supply chain decisions.

Finally, the integration of risk and alerts framework and its tools will enhance the functionality and impact of the ResC4EU B2B platform, empowering SMEs with actionable resilience, risk and sustainability insights.

# 6 ANNEX

## 6.1 Tested parameters for identifying threats and disruptions

These are different parameters considered initially in line with the supply chain resilience self-assessment methodology and the multimodal transport model

1. Main parameters for Supply chain vulnerabilities

Turbulence

1. Natural disasters
2. Exposure to geopolitical disruptions
3. Unpredictability of demand
4. Fluctuations in currencies & prices
5. Unforeseen technology failures
6. Pandemic

Deliberate Threats

7. Piracy & theft
8. Terrorism & sabotage
9. Labor disputes
10. Industrial espionage
11. Special interest groups
12. Product liability

External Pressures

13. Innovation (competition)
14. Social/Cultural changes
15. Political/Regulatory changes
16. Price pressures (competition)
17. Corporate responsibility
18. Environmental changes

Resource Limits

19. Supplier capacity
20. Production capacity
21. Distribution capacity
22. Raw material availability
23. Utilities availability
24. Human resources
25. Resources for data management, demand forecasting, and strategic procurement
26. Digital transformation adoption

Sensitivity

27. Complexity
28. Product purity
29. Restricted materials
30. Fragility
31. Reliability of equipment
32. Potential safety hazards
33. Visibility of disruption to stakeholders
34. Symbolic profile of brand
35. Concentration of capacity
36. Time-consuming production process

37. Cybersecurity threats to manufacturing systems

Connectivity

38. Scale/Extent of supply network
39. Reliance upon information flow
40. Degree of outsourcing
41. Import/Export channels
42. Reliance upon specialty sources
43. E-commerce and Omni channel distribution
44. Data analytics/management

Supplier/Customer Disruptions

45. Supplier trust, loyalty, relations, reliability
46. Customer disruptions
47. Concentrated customer dependence
48. Single Supplier dependence
49. Complex global supplier network
50. Ethical sourcing of raw materials and sustainability requirements

Other vulnerabilities

Demand side risks

51. Unanticipated or very volatile demand
52. Insufficient or distorted information from your customer about orders or demand quantities

Supply side risks

53. Poor logistics performance of suppliers
54. Supplier quality problems
55. Sudden demise of a supplier (e.g., due to bankruptcy)
56. Poor logistics performance of logistics service providers
57. Capacity fluctuations or shortages on the supply markets

Catastrophic risks

58. Political instability, war, civil unrest, or other socio-political crises
59. International terror attacks (e.g., 2005 London or 2004 Madrid terror attacks)
60. Diseases or epidemics (e.g., SARS, foot and mouth disease)
61. Natural disasters (e.g., earthquake, flooding, extreme climate, tsunami)

2. Main parameters for Supply chain Capabilities

Flexibility- Sourcing

62. Input commonality
63. Modularity and interchangeability
64. Multiple uses for supplies
65. Supplier contract flexibility
66. Multiple sources

Flexibility- Fulfillment

67. Alternate distribution channels
68. Risk pooling/sharing
69. Multi-sourcing (peak vs. base)
70. Delayed commitment, Production postponement
71. Inventory management
72. Fast re-routing of requirements

Capacity

73. Reserve capacity (materials, assets, labor, inventory)
74. Redundancy (assets, labor)
75. Backup empty sources/communications

Efficiency

76. Waste elimination
77. Labor productivity
78. Asset utilization
79. Product variability reduction
80. Failure prevention

Visibility

81. Business intelligence gathering
82. Information technology
83. Products, Assets, People visibility
84. Collaborative information exchange

Adaptability

85. Fast re-routing of requirements
86. Process Improvement, Lead time reduction
87. Strategic gaming & simulation
88. Seizing advantage from disruptions
89. Alternative technology development
90. Learning from experience
91. Reengineering

Anticipation

92. Monitoring early warning signals
93. Forecasting
94. Deviation, Near-miss analysis
95. Contingency planning, Preparedness (Training/Drill/Exercise plans)
96. Risk management, Business continuity planning
97. Recognition of opportunities

Recovery

98. Crisis management
99. Resource mobilization
100. Communications strategy
101. Consequence mitigation

Dispersion

102. Distributed decision-making
103. Distributed capacity & assets
104. Decentralization of key resources (including data)
105. Location-specific empowerment
106. Geographic dispersion of markets

Digital capabilities

107. System data analysis
108. Enterprise Resource Planning
109. Smart work procedures (real-time online storage, monitoring, tracking, control) and big data analysis
110. Additive manufacturing
111. Automated guided vehicles
112. Digitally enabled global shipping platform
113. Industry 4.0-based analytics techniques (machine learning/artificial intelligence)

114. Sophisticated digital solutions- Inventory level and performance

Organization

115. Learning, Benchmarking, Feedback
116. Responsibility, Accountability & Empowerment
117. Teamwork, Creative problem solving
118. Training, Cross-train workers
119. Substitute leadership capacity
120. Culture of caring for employees

Market position

121. Product differentiation
122. Customer loyalty/retention
123. Market share
124. Brand equity
125. Customer relationships
126. Customer communications

Security

127. Layered defenses
128. Access restriction
129. Employee involvement in security
130. Collaboration with governments
131. Cyber-security
132. Personnel security

Financial strength

133. Insurance
134. Portfolio diversification
135. Financial reserves & liquidity
136. Price margin

Risk Appetite and culture

137. High level of risk
138. Training and awareness

Social Sustainability

139. Health and safety
140. Human and labor rights

Ecological Sustainability

141. Pollution prevention
142. Recycling of materials
143. Waste reduction

Collaboration and Trust

144. Collaborative forecasting and
145. Communications- internal, external
146. Postponement of orders
147. Product life cycle management
148. Risk sharing with partners and postponement of orders
149. Relationship sincerity
150. Trust with information accuracy

## 3. Main parameters for Supply chain performance

Economic and operational performance

151. Quality

152. Lead time
153. Sales growth
154. Cost

Social performance

155. Incident and accident rates
156. Employee satisfaction and engagement

Ecological performance

157. Waste production levels and recycling rate
158. CO2 emissions

## 4. Main parameters for supply chain resilience

159. Alternative solutions
160. Risk Evaluation

## 5. Main transport-related parameters

Country-related risks

161. Epidemics risk
162. Current highly violent conflict intensity
163. Conflict risk
164. Governance risk
165. Disaster Risk Reduction score
166. Physical Infrastructure score

GIS-based regional risks

167. Earthquake risk
168. Tropical cyclone risk
169. Flood risk
170. Volcano eruption risk
171. Forest fire risk

Potentially disruptive events

172. Earthquakes (coordinates and magnitude)
173. Tropical cyclones (coordinates and intensity indicators)
174. Floods (coordinates)
175. Volcano eruptions (coordinates)
176. Forest fires (coordinates and affected area)
177. Airspace warnings

Maritime traffic disruptions at chokepoints

178. Bab al-Mandab Strait
179. Bohai Strait
180. Bosporus
181. Cape of Good Hope
182. Dover Strait
183. Korea Strait
184. Lombok Strait
185. Luzon Strait
186. Magellan Strait
187. Makassar Strait
188. Malacca Stait
189. Mona Passate

190. Ombai Strait
191. Oresund Strait
192. Panama Canal
193. Strait of Gibraltar
194. Strait of Hormuz
195. Suez Canal
196. Sunda Strait
197. Taiwan Strait
198. Torres Strait
199. Tsugaru Strait
200. Windward Passage
201. Yucatan Channel

**Maritime traffic disruptions at ports**

Maritime traffic will be monitored in all ports that are included in maritime transport chains indicated by users. This number is expected to quickly reach more than twenty.

## 6.2 stressors and disruptions, and their captured compounding effects

The following stressors and disruptions will be analysed with regard to their compounding effects on supply chains:

Russia's war against Ukraine and its impact:

1. Blockade of Ukraine's Black Sea ports
2. Blockade of Ukraine's air space
3. Attacks on port infrastructure and superstructure
4. Sanctions against Russian gas
5. Sanctions against Russian oil

Covid-19 pandemic:

6. Closure of Chinese ports
7. Covid-related production interruptions

Extreme weather events:

8. Drought: Low water on the Rhine due to draught
9. Drought: Low water on the Panama Canal

Natural disasters:

10. Hanshin-Awaji earthquake 1995
11. Eyjafjallajökull volcano eruption 2010
12. Indian Ocean tsunami 2004

Other stressors and disruptions will be analysed based on input from users of the ResC4EU platform.

Please visit our ResC4EU website & follow us on LinkedIn to be up to date on our activities:

www.resc4eu@com

LinkedIn #resc4eu

contact@resc4eu.com

Funded by
the European Union