D2.3
Specification of the technology solutions and their impact
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Abstract	The deliverable will describe the most impactful technologies to accelerate supply chain resilience and will cluster them in terms of ecosystems and impact on the different indicators.

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RISE-SME: Resilient Industry Supply Chain Enhancement for SMEs

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Executive summary

This deliverable presents a comprehensive analysis of the most impactful digital technologies for enhancing supply chain resilience across four representative European industrial ecosystems: electric vehicles, wine production, footwear manufacturing, and Mobility-as-a-Service (MaaS). It is part of the RISE-SME project's broader objective to support the digital and green transition of SMEs by equipping them with tools and knowledge to withstand and adapt to increasingly complex and disruptive environments.

The report introduces a structured methodology that combines scenario-based modelling, a multi-dimensional KPI framework, and system dynamics simulations to evaluate how specific technologies can mitigate the effects of disruptions. Four disruption scenarios were defined (energy instability, cyber threats, geopolitical volatility, and social (human-centric) risks), each mapped to the ecosystem where its impact is most critical. For each scenario, a digital technology was selected based on its potential to enhance resilience and operational performance:

- Edge Computing for energy resilience in electric vehicle production
- Data Spaces for cyber resilience in MaaS platforms
- Artificial Intelligence for geopolitical resilience in wine supply chains
- Blockchain for social resilience in footwear manufacturing

Each technology was assessed through quantitative simulations using a set of resilience KPIs, including adaptability, recovery rate, visibility, and the Supply Chain Resilience Index (SCRI). The results demonstrate that these technologies can significantly improve supply chain performance under stress, enabling faster recovery, better decision-making, and more robust operations.

The deliverable also aligns the technological assessment with key EU policy objectives, including the European Green Deal, the Digital Europe Programme, and the New European Prosperity Plan. It shows how digital innovation can support climate neutrality, industrial competitiveness, and social inclusion, particularly by empowering SMEs to adopt scalable and sustainable solutions.

Key contributions of this deliverable include:

- A replicable framework for evaluating the impact of digital technologies on supply chain resilience
- A detailed mapping of technologies to ecosystem-specific disruptions and resilience KPIs
- Quantitative evidence of the mitigation effects of digital solutions across diverse industrial contexts
- Strategic alignment with EU policy goals to ensure relevance and scalability

The insights generated here provide a foundation for future work in WP3, where the focus will shift to identifying technological gaps, assessing sustainability KPIs in greater depth, and refining the models with real-world data. This work supports the development of a decision-support system that enables SMEs and policymakers to prioritize investments in technologies that deliver both operational resilience and long-term sustainability.

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List of Abbreviations and Acronyms	
AI	Artificial Intelligence
Ad	Adaptability
Ag	Agility
C&KS	Cooperation & Knowledge sharing
D	Density

DCR	Demand Change Response
EC	European Commission
ENPV	Expected Net Present Value
ESC	Expected Customer service level
EU	Europe
FC	Flow complexity
G	Geographical risk
KPI	Key parameter indicator
MaaS	Mobility as a Service
ND	Node complexity
OTIF	OTIF
RR	Recovery Rate
SCRI	Supply Chain Resilience Index
SLHRP	Stock level of high-risk parts
SRR	Supplier Replacement Rate
SS	Single sourcing with single plant
TI	Technological innovation
TCTL	Team Cross-Training Level
V	Visibility
VF	Volume flexibility supplier

1 Introduction

This deliverable, *Specification of the Technology Solutions and Their Impact*, presents the technological solutions with the highest potential to enhance supply chain resilience across four selected industrial ecosystems. The study is conducted within the context of EU strategic objectives, focusing particularly on resilience and operational performance as key dimensions.

The work addresses current and emerging disruptions affecting European supply chains, such as energy instability, cybersecurity threats, geopolitical turbulence, and social factors[1], and evaluates how specific technologies can mitigate these impacts. It also links these effects to wider EU objectives, including climate neutrality, digital transformation, and social sustainability.

1.1 Purpose and scope

The purpose of this deliverable is to identify and analyse the most impactful technologies that can improve supply chain resilience across selected European industrial ecosystems. This analysis is carried out in alignment with current EU strategic objectives, particularly those targeting climate neutrality, digital leadership, and social and economic cohesion.

The scope of this deliverable includes:

- The selection and classification of disruptive scenarios affecting supply chains across different sectors.
- The identification of technologies capable of mitigating those disruptions.
- The clustering of technologies by ecosystem relevance and measurable impact.
- The definition and application of a KPI system focusing on resilience and operational performance to quantify technology-driven improvements.
- An initial assessment of how these improvements contribute to overarching EU policy objectives.

While this deliverable focuses primarily on resilience and operational KPIs, the sustainability dimension (including environmental, social, and economic performance KPIs) is acknowledged and will be further developed in subsequent work (WP3).

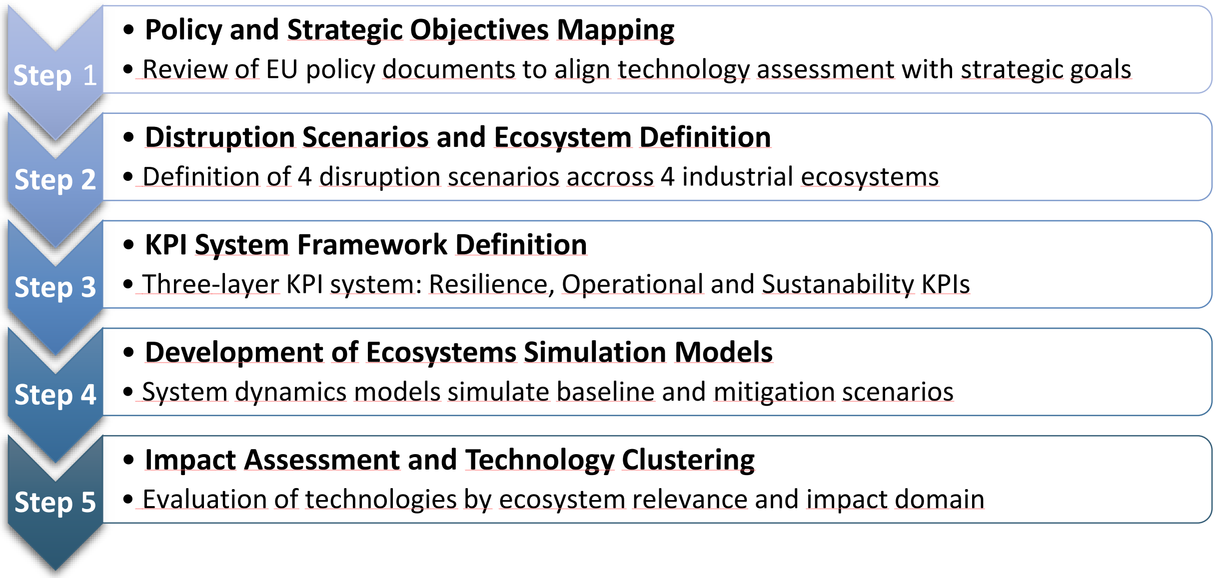
This report provides actionable insights for policymakers, industry stakeholders, and researchers, facilitating a better understanding of how technologies can strengthen supply chains in the face of growing uncertainty.

[1] Resilience of global supply chains - European Parliament

1.2 Methodology

The methodology followed in this task is structured in the following steps:

Figure 1: D2.3 methodological approach.



Step 1: Policy and Strategic Objectives Mapping

A comprehensive review of EU policy documents was conducted to align the technological impact assessment with the strategic goals of the Union. The documents analysed include:

- The European Green Deal
- A Europe Fit for the Digital Age
- Promoting Our European Way of Life
- An Economy That Works for People
- The European Industrial Strategy
- The New European Prosperity Plan
- The European Commission Competitiveness Compass

From this analysis, the key objectives relevant to supply chain resilience, sustainability, innovation, and industrial autonomy were identified.

Step 2: Disruption Scenarios and Ecosystem Definition

Four disruption scenarios aligned with the most pressing risks affecting supply chains were developed:

- **Energy Resilience**
- **Cybersecurity Resilience**
- **Geopolitical Instability**
- **Social & Human-Centric Resilience**

These scenarios were tailored to reflect disruptions relevant to four representative ecosystems identified in D2.1, and incorporate realistic disruptions such as supply shortages, cyberattacks, labour market instability, and geopolitical constraints.

Step 3: KPI System Definition

To evaluate the impact of the disruptions and the mitigating role of technologies, a three-layer KPI system was established:

- **Resilience KPIs:** Measure responsiveness, recovery, flexibility, and stability of supply chains.
- **Operational KPIs:** Focus on performance metrics such as delivery reliability, lead time, and inventory responsiveness.
- **Sustainability KPIs (Environmental, Social, Economic):** These will be more deeply analysed in WP3.

The selected KPIs enable us to quantify disruption impacts and assess the effectiveness of each technology.

Step 4: Development of Ecosystem Simulation Models

Using the supply chain configurations from D2.1, a quantitative model was developed for each ecosystem. These are quantitative and system dynamics-based models that simulate operations, interactions, and timing within each ecosystem.

Each model reflects:

- Normal (baseline) operations
- The impact of specific disruptions
- The mitigation effect of introducing targeted technologies

This approach enables direct measurement of KPI variations across scenarios—with and without technology intervention—and facilitates the evaluation of resilience improvements.

Step 5: Impact Assessment and Technology Clustering

Technologies were evaluated based on their capacity to mitigate disruption impacts, improve KPIs, and support EU policy targets. Technologies were clustered by:

- Their **ecosystem relevance** (e.g., manufacturing, digital, mobility)
- Their **impact domain** (resilience, operational efficiency, environmental benefits)

This clustering provides a clear mapping of where and how each technology contributes to supply chain transformation.

1.3 Structure of the deliverable

This deliverable is organized into the following sections:

- **Section 1: Introduction**
  Presents the context, purpose, and structure of the deliverable.
- **Section 2: EU Policy Framework and Climate Objectives**
  Summarizes relevant EU strategies and documents that define the long-term goals for resilience, sustainability, and competitiveness.
- **Section 3: Scenario Development and Supply Chain Disruptions**
  Describes the disruption scenarios formulated per ecosystem, including their relevance to current geopolitical, environmental, and technological challenges.
- **Section 4: KPI System and Categorization**

Details the multi-criteria KPI system developed to measure the impact of disruptions and the effectiveness of technological interventions.

- **Section 5: Modelling Framework per Ecosystem**
  Explains the system dynamics models used to simulate supply chain behaviour, disruption impacts, and technology responses.
- **Section 6: Technology Solutions Clustering**
  Classifies the scouted technologies by ecosystem and by their effect on resilience and performance indicators.
- **Section 7: Impact Assessment of Technology Solutions**
  Compares disruption impact scenarios with and without technological mitigation, highlighting improvements in resilience and alignment with EU goals.
- **Section 8: Conclusions**
  Summarizes key findings and proposes recommendations for future adoption and policy design.
- **Section 10: References**
  Lists all sources, policy documents, and scientific references used throughout the report.

2 EU Policy Framework and Climate Objectives

To ensure that the selection and assessment of technology solutions align with the broader goals of the European Union, this section maps the strategic policy framework guiding Europe's transformation toward a more resilient, sustainable, and competitive economy. The technologies analysed in this deliverable—particularly their impact on resilience and operational performance—are assessed in the context of key EU objectives.

This analysis builds upon a thorough review of seven cornerstone strategies and policy packages issued by the European Commission, which articulate the vision and priorities for the EU across climate, digital, industrial, and social domains. The policies analysed include:

Table 1: European policies analysed, key objectives and themes.

Policy	Key Objectives	Themes
European Green Deal (2019)	Climate neutrality by 2050; clean energy; circular economy; pollution reduction; sustainable cities	Climate, Industry, Biodiversity, Social Inclusion
Europe Fit for the Digital Age (2020)	Digital sovereignty; AI; cybersecurity; digital infrastructure and services; skills development	Digital Transformation, Infrastructure, Cybersecurity
Promoting Our European Way of Life (2020)	Rule of law; cultural diversity; equality; fundamental rights; crime prevention	Social Values, Justice, Wellbeing
An Economy That Works for People (2020)	Inclusive growth; job creation; sustainable development; trade; poverty reduction	Social Fairness, Employment, Finance
European Industrial Strategy (2020, updated 2021)	Climate-neutral industry; competitiveness; strategic autonomy; SME support; innovation	Industry, Innovation, Resilience
New European Prosperity Plan (2024)	Clean industrial deal; circular economy; digital productivity; labour and skills upgrade; turbo-charged investment	Competitiveness, Investment, Green Transition
European Commission Compass (2024)	Innovation; decarbonization as growth driver; supply chain diversification; resilience	Security, Innovation, Energy, Resilience

As some of these policies are long-standing while others have been recently introduced or updated (e.g., Prosperity Plan 2024–2029), this section also explores how priorities have evolved, deepened, or become more urgent over time—especially in response to global crises such as COVID-19, geopolitical tensions, and energy security disruptions.

Over the past decade, the EU's strategic objectives have evolved from high-level sustainability and digitalization goals toward more integrated and operational agendas:

- *2019–2020: Baseline Framework for Green and Digital Transitions*
  The **European Green Deal** established the foundation for climate neutrality, circular economy, and clean energy.
  Simultaneously, **Europe Fit for the Digital Age** laid the groundwork for digital sovereignty, rights, and infrastructure.
  Promoting Our European Way of Life emphasized equity, democracy, and protection of social rights.

- *2020–2021: Post-COVID Recovery and Inclusive Growth*
  An Economy That Works for People and the **European Industrial Strategy** responded to the COVID crisis by linking recovery plans with sustainability and digital transition, while also addressing job creation and SME support.

Resilience emerged as a key theme in ensuring continuity of critical economic activities.

- *2023–2024: Strengthening Competitiveness and Resilience Amid Global Challenges*
  The **New European Prosperity Plan** and **Competitiveness Compass** were introduced in response to energy crises, war-related disruptions, and supply chain fragility.

These policies explicitly link technological innovation, energy independence, and security to economic competitiveness and resilience, emphasizing the urgency to close innovation gaps and reduce dependencies in strategic sectors.

The relevance of these policy objectives for this deliverable can be summarized as follows:

- **Resilience as a Horizontal Priority**: Featured across all recent policy updates (Industrial Strategy, Compass, Prosperity Plan), resilience is central to European efforts to secure critical infrastructure, diversify supply chains, and withstand shocks.
- **Technological Innovation**: Innovation is not only a goal but a strategic enabler of decarbonization, autonomy, and productivity. The technologies analysed in this report are key to achieving EU leadership in AI, energy, and circular economy models.
- **Decarbonization and Clean Industry**: The integration of technologies that reduce emissions, improve resource efficiency, or enable circularity directly supports the climate and competitiveness pillars of the EU's twin transitions.
- **Social Equity and Inclusion**: Particularly highlighted in *An Economy That Works for People* and *Our European Way of Life*, social and human-centric resilience (including fair working conditions and digital inclusion) must be reflected in the scenarios and KPI framework developed in this task.

2.1 RISE-SME alignment with the EU policy objectives

To ensure the technological solutions proposed in this project are not only impactful for supply chain resilience but also aligned with European policy goals, a mapping exercise was conducted comparing the objectives of key EU policy frameworks with the scenarios, KPIs, and activities addressed in this task.

The table below presents a detailed synthesis of how the project contributes to and supports the strategic priorities of the European Commission, drawing on flagship policies such as the European Green Deal, the Digital and Industrial Strategies, and the New European Prosperity Plan. It highlights for each policy:

- The key objectives as articulated in the EU strategy documents,
- A description of each objective's meaning in context,
- How the project reflects, incorporates, or responds to that objective through its scenarios, KPIs, and ecosystem-level modelling.

This analysis validates the project's relevance and supports its strategic positioning within the EU's long-term transition goals for climate neutrality, competitiveness, digital transformation, and social cohesion.

Table 2: RISE-SME alignment with EU policy objectives.

EU POLICY	KEY OBJECTIVES	DESCRIPTION	CONSIDERATIONS FOR D2.3	RISE-SME FIT
The European Green Deal	Achieve Climate Neutrality by 2050	Transform the EU into a modern, resource-efficient economy with zero net greenhouse gas emissions by 2050	Integrate technologies that reduce carbon emissions and enhance energy efficiency within supply chains	Project objectives & specific KPIs
	Decouple Economic Growth from Resource Use	Promote economic growth independent of resource consumption, emphasizing sustainability.	Implement circular economy practices to minimize resource use and waste	Specific KPIs
	Ensure No Person and No Place is Left Behind	Foster a just transition that is inclusive and beneficial for all regions and citizens	Assess the social impact of supply chain transformations to ensure equitable benefits	Specific Scenario: human-centric
A Europe Fit for the Digital Age	Strengthen Digital Sovereignty	Enhance Europe's capacity to set standards and develop key digital technologies	Incorporate advanced digital tools such as IoT, AI, and blockchain to improve supply chain visibility and efficiency ensuring robust cybersecurity measures to protect digital infrastructure.	Specific KPIs & scenario: cybersecurity & project objectives
	Promote Digital Transformation	Facilitate the adoption of digital technologies across all sectors to boost competitiveness and innovation	Evaluate the impact of digitalization on workforce skills and employment	Project objectives & specific KPIs

EU POLICY	KEY OBJECTIVES	DESCRIPTION	CONSIDERATIONS FOR D2.3	RISE-SME FIT
Promoting Our European Way of Life	Ensure Security and Safety	Develop tools to keep Europe safe, including addressing cyber threats	Develop strategies to mitigate risks associated with geopolitical instability and cyber threats	Specific scenarios
	Foster Social Inclusion and Fairness	Promote policies that uphold human rights and provide equal opportunities	Ensure that supply chain practices uphold labour rights and promote social inclusion	Specific Scenario: human-centric
EU POLICY	**KEY OBJECTIVES**	**DESCRIPTION**	**CONSIDERATIONS FOR D2.3**	**RISE-SME FIT**
An Economy That Works for People	Support SMEs and Entrepreneurship	Strengthen small and medium-sized enterprises as they are central to the EU's economy	Ensure that supply chain innovations are accessible to SMEs and support their growth	Project objectives
	Reduce Poverty and Inequality	Promote economic policies that lead to fair distribution of wealth	Evaluate the economic impact of supply chain resilience strategies on different socioeconomic groups	General economic KPIs & social scenario: human-centric
EU POLICY	**KEY OBJECTIVES**	**DESCRIPTION**	**CONSIDERATIONS FOR D2.3**	**RISE-SME FIT**
European Industrial Strategy	Strengthening the Single Market's Resilience	Enhance the robustness of the Single Market, particularly during crises, by ensuring the availability and free movement of goods and services, and guaranteeing transparency and coordination	Analyse how supply chain models can maintain operations and adapt during disruptions using digital technologies, ensuring continuity in the movement of goods and services	Project objectives & scenarios
	Addressing Strategic Dependencies	Identify and mitigate dependencies in key strategic areas to reduce vulnerabilities in supply chains	Evaluate the reliance on critical suppliers and materials, and explore the role of digital technologies to minimize risks associated with these dependencies	Project objectives & scenarios
	Accelerating the Green and Digital Transitions	Promote the adoption of sustainable practices and digital technologies to modernize industry and enhance competitiveness	Assess the implementation of green technologies and digital tools within supply chains to improve efficiency and sustainability	Project objectives & scenarios
	Supporting Small and Medium-sized Enterprises (SMEs)	Provide targeted measures to assist SMEs in adapting to new market conditions and embracing the twin transitions	Investigate how SMEs within supply chains can be supported to enhance their resilience and capacity to adopt new technologies	Project objectives & Scenarios
	Enhancing Supply Chain Resilience	Develop strategies to monitor and address supply chain disruptions, ensuring a steady flow of essential goods and services	Knowledge development and tools boost digital adoption to improve SC resilience	Project objectives & scenarios
New European Prosperity Plan	Make business easier and faster	Reducing bureaucratic obstacles to facilitate easier and more efficient business activities across the EU	Identify technology suppliers and evaluate new technologies implementation	Project objectives

EU POLICY	KEY OBJECTIVES	DESCRIPTION	CONSIDERATIONS FOR D2.3	RISE-SME FIT
			available for the European ecosystem through the tool	
	Build a new Clean Industrial Deal	Promoting the development and adoption of clean technologies to support the EU's climate neutrality goals and drive industrial growth	Support the implementation of sustainable digital technological solutions in Europe	Project objectives
	Work towards a more circular and resilient economy	Diversity supply chains and reducing dependencies to shift to a more sustainable pattern of production and consumption, retaining the value of resources in our economy for longer	Investigate how to improve the resilience and sustainability of the supply chains in Europe	Project objectives & scenarios
	Boost productivity with digital tech diffusion	Increasing investment and boosting access to digital technologies	Increasing awareness and opportunities of SMEs in Europe to implement digital technologies through knowledge and tools development	Project objectives & scenarios
	Put research and innovation at the heart of our economy	Prioritizing strategic research and innovation, expanding key R&D institutions, accelerating biotech commercialization, and fostering collaboration between universities and industry	Research, innovation and knowledge sharing through collaboration with industry	Project definition
	Turbo charge investment	De-risking private capital, revising investment rules, leveraging savings for innovation and transitions, and supporting strategic sectors through a European competitiveness fund	Knowledge development and tools to de-risk SME's investment in digital technologies	Project objectives
	Tackle the skills and labour gaps	Establishing a "Union of Skills" to promote lifelong learning and align education systems with labour market needs	Knowledge generation on new digital technologies available for European SME's contribute to crease awareness and readiness on skills and training needs	Project objectives

EU POLICY	KEY OBJECTIVES	DESCRIPTION	CONSIDERATIONS FOR D2.3	RISE-SME FIT
European Comision Compass	Closing the Innovation Gap	Boosting innovation within the EU by creating a favourable environment for start-ups and scale-ups, promoting the adoption of new technologies like AI, and simplifying rules for businesses	Identify technology suppliers and evaluate the implementation of new technologies to improve the resilience of supply chains, focussing on tech-savvy SMEs and start-ups	Project objectives & scenarios

EU POLICY	KEY OBJECTIVES	DESCRIPTION	CONSIDERATIONS FOR D2.3	RISE-SME FIT
	Linking Decarbonization and Competitiveness	Integrating decarbonization policies with industrial, competition, economic, and trade policies to make the EU an attractive location for manufacturing, especially in energy-intensive sectors, while also promoting clean technologies and circular business models	Investigate how to improve competitiveness in Europe for SMEs through new technologies implementation to improve resilience. Focus on manufacturing sectors: textile, agrifood, automotive	Project objectives; Specific scenario: energy
	Reducing Dependencies and Increasing Security	Lessen the EU's reliance on external sources for critical goods and services, such as defence industrial capabilities, critical raw materials, and clean technologies, while enhancing security and resilience across key sectors.	RISE-SME supports resilience and security of European supply chains and lessen dependence of non-EU technology providers	Project objectives & scenarios: geopolitical

3 Scenario Development and Supply Chain Disruptions

To evaluate the impact of digital technologies on the resilience of the specific supply chains identified within the project ecosystems, four scenarios were developed based on current global trends and pressing concerns. These scenarios reflect the primary sources of disruptions currently affecting supply chains worldwide and provide a structured basis for analyzing vulnerabilities and potential mitigation strategies through technological solutions.

The starting point to develop the proposed scenarios were the Top 5 supply chain risks identified for 2025 by DHL together with Everstream analytics[2]. They issued a report that identified as biggest concerns:

1. Climate change
2. Geopolitical instability
3. Increase in cybercrime
4. Lockdown on rare materials and minerals
5. Crackdown on forced labour

All these risks can have a potential impact on the 4 ecosystems at the core of RISE-SME project; they were turned, in the framework of the present deliverable, into potential resilience scenarios.

Each scenario represents a distinct dimension of disruption that is increasingly relevant in today's global context. Climate change and lockdown on rare materials and minerals were grouped into an energy resilience scenario; while the other risks are mapped one to one to translate them into resilience scenarios as follows:

- **Energy Resilience**: This scenario examines a supply chain's ability to maintain stable and efficient operations amid energy-related disruptions. These may include volatility in energy prices, regulatory shifts, or physical shortages—particularly in sectors heavily reliant on energy inputs or battery components. The scenario assesses how well supply chains can secure alternative energy sources, adopt renewable technologies, and improve energy efficiency to reduce dependence on fossil fuels.
- **Cyber Resilience**: As digitalization advances, cyber threats pose growing risks to supply chain continuity. This scenario explores a supply chain's capacity to prevent, resist, and recover from cyberattacks, system failures, and data breaches, with minimal disruption to operations. It emphasizes the robustness of digital infrastructure, data protection practices, and recovery protocols.

[2] Top 5 supply chain risks in 2025 - Delivered - Global

- **Geopolitical Instability Resilience**: This scenario focuses on the disruptions caused by political and regulatory shifts such as trade restrictions, international conflicts, or sanctions. It evaluates a supply chain's adaptability to changes in sourcing and logistics due to unstable geopolitical conditions, especially in regions critical to material or component supply.
- **Social (Human-Centric) Resilience**: This scenario addresses the social dimension of resilience, analysing how supply chains support workforce well-being and continuity in times of socio-economic disruption. Key aspects include fair labour practices, adaptability through training and upskilling, and maintaining employee engagement during crises.

Each scenario has been evaluated across the four ecosystems to determine the degree of impact and relevance for their associated supply chains. Based on this analysis, one ecosystem per scenario—representing the most affected or illustrative case—was selected for further modelling and simulation. These models will be used to quantify the contribution of digital technologies in enhancing supply chain resilience within the defined disruption scenarios.

3.1 Energy Resilience

The Energy Resilience scenario addresses the ability of a supply chain to maintain stable and efficient operations despite energy supply disruptions, fluctuations in energy prices, or changes in energy regulations (particularly in industries dependent on high-energy inputs or battery components). This scenario tests how well a supply chain can secure reliable energy sources, adapt to renewable energy transitions, and optimize energy efficiency to reduce dependency on fossil fuels. Key metrics may include the percentage of energy sourced from renewables, energy storage capacity, backup power system availability, and energy cost volatility mitigation strategies.

The Energy Resilience scenario evaluation for the different ecosystems is shown below.

Table 3: Relevance of the Energy Resilience scenario per ecosystem.

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
Electric Vehicles (EV)	One of the most energy-dependent sectors due to battery production, assembly lines, and material extraction (e.g., lithium mining). Securing stable, sustainable energy sources is critical to long-term viability and cost control. Crucial to avoid production disruptions due to supply shortages, geopolitical risks, or resource depletion. Battery supply chain disruptions (e.g., lithium, cobalt, nickel shortages) could significantly slow production and increase costs. Renewable energy	Very high

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
	integration in manufacturing must ensure stability during fluctuations.	
Wine production	While not as energy-intensive as manufacturing, energy is crucial for refrigeration, processing, and logistics. Climate change increases the risk of power outages affecting irrigation and fermentation processes. Transitioning to solar or wind energy can enhance resilience.	Medium
Shoe production	Footwear production requires stable energy for machinery, supply chain logistics, and material processing. Energy efficiency measures and alternative energy sources can help mitigate disruptions and cost fluctuations.	Medium
Mobility as a Service (MaaS)	Highly reliant on energy stability, especially as electric fleets expand. Charging infrastructure, grid reliability, and renewable energy integration directly impact operational resilience and service reliability. Important for charging infrastructure stability as a key factor in ensuring continuous operations	High

According to the evaluation shown above, the Electric Vehicles (EV) ecosystem is the most affected by the Energy Resilience scenario and therefore the EV supply chain model will be studied for this scenario.

3.2 Cyber Resilience scenario

The Cyber Resilience scenario addresses the ability of a digital supply chain to anticipate, withstand, recover from, and adapt to cyber threats, data breaches, and system failures without significant service disruption, ensuring minimal disruption to operations. It includes the robustness of digital infrastructure, data security measures, incident response capabilities, and business continuity strategies in the face of cyberattacks, data breaches, or system failures. Key metrics may include cybersecurity maturity levels, frequency of cyber incidents, recovery time from cyber disruptions, and compliance with cybersecurity regulations.

The Cyber Resilience scenario evaluation for the different ecosystems is shown below.

Table 4: Relevance of the Cyber Resilience scenario per ecosystem.

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
Electric Vehicles (EV)	Highly digitalized, with complex global supply chains relying on interconnected IT systems, automation, and supplier networks. Cyber threats can compromise	High

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
	manufacturing, software-integrated components (e.g., battery management systems), and intellectual property security. Crucial to avoid production disruption, especially in JIT environments where precise coordination with suppliers is required. EVs themselves are vulnerable to cyber risks (e.g., hacking of vehicle software, data breaches in connected car networks)	
Wine production	While traditionally less digitalized, modern wineries use IoT sensors for climate control, automated production, and supply chain tracking, making them vulnerable to cyber risks. However, the overall impact of a cyberattack is lower than in other industries.	Low
Shoe production	Less relevant, the overall impact of cyber threats is less severe. Increasing automation and digital tracking systems (e.g., RFID for inventory management, smart factories) introduce cyber risks. ERP systems and supply chain software could be disrupted by cyberattacks, but physical production would largely continue. Supply chain disruptions due to ransomware or data breaches could impact production and logistics.	Low
Mobility as a Service (MaaS)	Digital security is mission-critical for MaaS platforms that rely on cloud-based data, real-time user transactions, AI-driven route optimization, and connected vehicle systems. A cyberattack could disrupt services, compromise user data, and cause reputational damage. Crucial to ensure data integrity and security. Very important to keep real-time transportation data, payment processing, and overall service availability in the case of cyber threats	Very high

According to the evaluation, the Mobility as a Service (MaaS) ecosystem is the most affected by the Cyber Resilience scenario and therefore the MaaS supply chain model will be studied for this scenario.

3.3 Geopolitical Instability Resilience

The Geopolitical Instability Resilience addresses the ability of a supply chain to anticipate, absorb, and adapt to disruptions caused by geopolitical events such as trade restrictions, tariffs, sanctions, conflicts, or sudden regulatory changes in key sourcing or distribution regions. This can be measured through factors like the percentage of critical materials sourced from geopolitically unstable regions, lead time increases due to geopolitical disruptions, or financial impact (e.g., additional costs incurred from rerouting logistics)

The Geopolitical Instability Resilience scenario evaluation for the different ecosystems is shown below.

Table 5: Relevance of the Geopolitical Instability Resilience scenario per ecosystem.

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
Electric Vehicles (EV)	Electric vehicle supply chains depend on critical minerals (e.g., lithium, cobalt, nickel) sourced from geopolitically sensitive regions. Political instability, export restrictions, or resource nationalization can directly impact production capacity.	High
Wine production	Wine supply chains depend on agricultural imports (e.g., bottles, corks, specialized machinery) and export markets. Trade restrictions, tariffs, or political instability in key export regions can disrupt sales and profitability	Very High
Shoe production	Footwear manufacturing often relies on raw materials (leather, textiles) and production facilities in geopolitically sensitive areas (e.g., Asia). Trade tensions or labour regulations can severely impact supply continuity.	High
Mobility as a Service (MaaS)	While digital services are less impacted by physical trade restrictions, geopolitical instability can affect regulatory environments (e.g., data privacy laws, government policies on ride-sharing) or disrupt partnerships in key operating regions.	Low

According to the evaluation, the Wine Production ecosystem is the most affected by the Geopolitical Instability Resilience scenario and therefore the Wine supply chain model will be studied for this scenario.

3.4 Social (human-centric) Resilience scenario

The Social (human-centric) Resilience scenario addresses the ability of a supply chain to sustain operations and workforce well-being during disruptions by ensuring fair labour conditions, worker adaptability, and maintaining workforce engagement. This scenario tests how well a supply chain can protect its employees and stakeholders while adapting to social and economic shifts. Key metrics may include workforce retention rates during crises, investments in employee upskilling, workplace safety compliance, and employee satisfaction during disruptions.

Table 6: Relevance of the Social (human-centric) Resilience scenario per ecosystem.

Ecosystem	Relevance of the scenario in the ecosystem	Evaluation
Electric Vehicles (EV)	Advanced manufacturing requires a skilled workforce. Retention of trained employees and investment in reskilling programs (for automation and digitalization) are critical to maintaining productivity.	High
Wine production	Labor-intensive sector relying on seasonal and skilled workers. Climate change, economic shifts, and labour shortages make workforce resilience crucial. Adaptation strategies include training programs, fair wages, and safe working conditions.	Medium
Shoe production	Often reliant on global supply chains with large labour forces in developing regions. Ethical labour practices, worker retention, and fair wages significantly impact operational stability and brand reputation.	Very High
Mobility as a Service (MaaS)	While digital services are less physically labour-intensive, driver/operator engagement (for ride-sharing) and tech employee retention impact service continuity. Regulatory changes affecting gig workers also influence resilience.	Medium

According to the evaluation, the Shoe Production ecosystem is the most affected by the Social (human-centric) Resilience scenario and therefore the Show supply chain model will be studied for this scenario.

4 KPI Framework System

To assess the impact of digital technology implementation on supply chain performance, a comprehensive KPI framework has been developed. This framework adopts a multi-criteria approach, encompassing indicators that measure resilience, operational efficiency, and sustainability—the three pillars critical to evaluating the transformation of supply chains in line with European policy ambitions.

The selected KPIs were carefully identified and structured based on a detailed review of EU policy objectives, as outlined in Section 2. This ensures that the framework is not only aligned with strategic priorities—such as those of the European Green Deal, the Digital Europe Programme, and the New European Prosperity Plan—but also provides a practical tool for measuring how supply chain models contribute to climate neutrality, digital readiness, social responsibility, and industrial competitiveness.

By integrating performance metrics from these three dimensions, the KPI system allows for a robust assessment of how digital technologies enhance the resilience of supply chains under disruptive scenarios. It also supports the evaluation of broader impacts, such as improved adaptability, reduced environmental footprint, strengthened human capital, and better risk mitigation across interconnected supply networks.

This framework will serve as the basis for comparing the performance of modelled supply chains under baseline conditions and after the integration of selected digital technologies, enabling a data-driven understanding of their effectiveness across different ecosystems. In the first approach of the supply chain models developed in this deliverable, only some of the resilience KPIs and basic operational parameters have been considered. Next section (4.1) compiles the Resilience KPIs as key for this work, while the Operational and Sustainability KPIs are included in the annexes of this document. The analysis performed to understand the relevance of each KPI in each ecosystem is also attached in the form of annexes at the end of this document.

4.1 Resilience KPIs

The set of resilience KPIs initially identified in Deliverable D2.1 was further refined to ensure their applicability across all supply chains represented in the different ecosystems. The objective of this revision was to make the KPIs more inclusive, generic, and adaptable, allowing for consistent measurement of resilience regardless of the sectoral context (e.g., manufacturing, agriculture, digital services).

The table below presents the final list of KPIs, including their updated definitions and the proposed methods for quantifying them within the supply chain models.

Table 7: Resilience KPIs

	Indicator	Description	Measurement
1	Adaptability (Ad)	Measures how quickly and effectively a supply chain can adjust operations, processes, or resource allocation in response to disruptions, new market demands, or changing external conditions	Time taken to adjust operations post-disruption; measured in days
2	Supplier Replacement Rate (SRR)	Assesses the time required to identify, qualify, and integrate alternative suppliers for critical components, key materials or services, ensuring continuity in case of supplier failures or disruptions	Average time to onboard alternative suppliers; measured in weeks
3	Demand Change Response (DCR)	Evaluates the ability to meet unexpected fluctuations in demand, either through stock availability, production flexibility, or alternative sourcing strategies	Percentage of demand fluctuations met without stockouts
4	Technological innovation (TI)	Tracks investment in new technologies, process improvements, or digital transformation initiatives aimed at increasing efficiency, resilience, and competitive advantage	Investment in new technologies as a percentage of total operational budget
5	Expected Customer service level (ESC)	Measures the proportion of customer demand that can be fulfilled within expected service times, ensuring reliability in product or service delivery	Percentage of orders fulfilled within the promised timeframe
6	OTIF (On Time in Full)	Percentage of total deliveries that are received on time and in full according to customer requirements, reflecting supply chain efficiency and reliability	Percentage of deliveries made on time and in full
7	Cooperation & Knowledge sharing (C&KS)	Assesses the stability and strength of collaborative relationships between supply chain members, including suppliers, manufacturers, and logistics providers, to improve coordination and risk management. Measures the frequency and effectiveness of information exchange between supply chain actors, supporting coordination, transparency, and adaptive decision-making	Frequency of collaborative meetings and shared initiatives per quarter
8	Density (D)	Represents the level of interconnectedness in a supply chain network by measuring the ratio of actual supply chain relationships to potential	Ratio of actual to potential supply chain connections

	Indicator	Description	Measurement
		relationships, influencing resilience and risk dispersion	
9	Node complexity (ND)	Quantifies the total number of entities (suppliers, manufacturers, warehouses, distributors, etc.) within a supply chain, affecting operational complexity and risk exposure	Total number of entities involved in the supply chain
10	Visibility (V)	Evaluates the ability to monitor, track, and receive feedback on supply chain activities, ensuring real-time data availability for decision-making and risk mitigation	Percentage of supply chain processes monitored in real-time
11	Team Cross-Training Level (TCTL)	Measures the proportion of employees trained to perform multiple roles, enhancing operational flexibility and workforce adaptability during disruptions	Percentage of employees trained in multiple roles
12	Flow complexity (FC)	Counts the total number of material and information flows within the supply chain, including forward (from suppliers to customers) and reverse (returns, recycling, remanufacturing), impacting system resilience	Number of distinct material and information flows
13	Stock level of high-risk parts (SLHRP)	Assesses the availability of critical inventory by measuring how long existing stock would last under normal or disrupted conditions, ensuring continuity of operations	Days of inventory available for critical components
14	Geographical risk (G)	Calculates the percentage of key materials, components, or services sourced from geopolitically or environmentally high-risk regions, affecting supply chain vulnerability	Percentage of suppliers located in high-risk regions
15	Volume flexibility supplier (VF)	Measures the flexibility negotiated in supplier contracts to accommodate demand fluctuations, ensuring responsiveness to market changes or unexpected supply shortages	Percentage change in order volume accommodated without penalties
16	Expected Net Present Value (ENPV)	Assesses the financial resilience of the supply chain by calculating the probability-weighted NPV of different operational and disruption scenarios	Projected financial value considering risk-adjusted returns

	Indicator	Description	Measurement
17	Agility (Ag)	Evaluates the ability to reduce lead times and quickly respond to market or operational changes, enhancing competitiveness and supply chain responsiveness	Average lead time reduction achieved post-disruption
18	Single sourcing with single plant (SS)	Measures the dependency on single suppliers with single production locations for critical components, identifying potential risks to supply chain continuity	Percentage of critical components sourced from single suppliers
19	Recovery Rate (RR)	Quantifies the speed and effectiveness of post-disruption recovery by measuring the time needed to restore operations and the level of performance achieved after recovery	Time taken to restore operations to pre-disruption levels; measured in days
20	Supply Chain Resilience Index (SCRI)	Quantifies the resilience of supply chains by measuring the ability of a supply chain to respond to and recover quickly from disruptions which can be calculated as a single indicator.	Model-based KPI as an index of service level and cost delta. For more information see (Sardesai & Klingebiel 2023)

Future work to be developed in WP3 will take into account other Resilience KPIs as well as the Operational and Sustainability KPIs to measure the whole impact of digital technologies on the supply chains resilience.

5 Modelling Framework per Ecosystem

5.1 Description of the Four Ecosystem Models

The mobility ecosystem is a complex system with many different Suppliers and Production locations. The main aspect of the mobility ecosystem is the relevance of value creation in various EU member states, the strategic importance of the process of electrification of drive technologies for the green transition and the susceptibility to disruption due to complex, global and closely timed supplier relationships. The ecosystem can be classified as a producer-driven supply Chain, which are characterized by high capital intensity and a structure controlled by central companies. One important aspect is the global distribution of the supply Chain, in Asia and in the Eu. The connection between these regions are created through see routes or air shipments. These shipments are critical for the supply chain and disruptions can have long lasting effects.

Another driver of complexity in the automotive supply chain is that the value-adding activities cover a broad spectrum (Turner et al. 2005; Remane et al. 2016; Serdasaran et al. 2013) In the automotive supply chain, the production steps are carried out from raw material extraction to the final product and include many intermediate steps and components (Turner et al. 2005).

The Node Complexity is 49 and the Flow Complexity 2.73. The Supply Chain Index is 0,16 this indicates a Complex Supply Chain (minimum value is 0,01 for very complex SC; max is 1 for a non-complex SC).

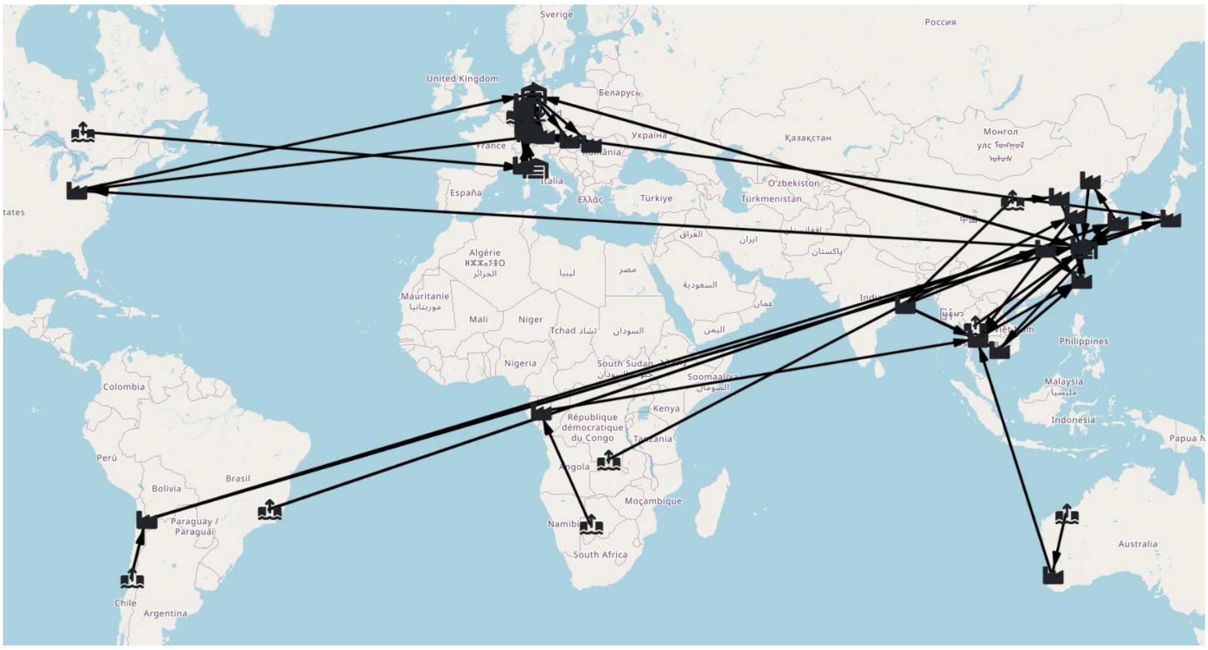


Figure 2: Geographical overview of the Automotive Supply Chain in OTD-NETWORD

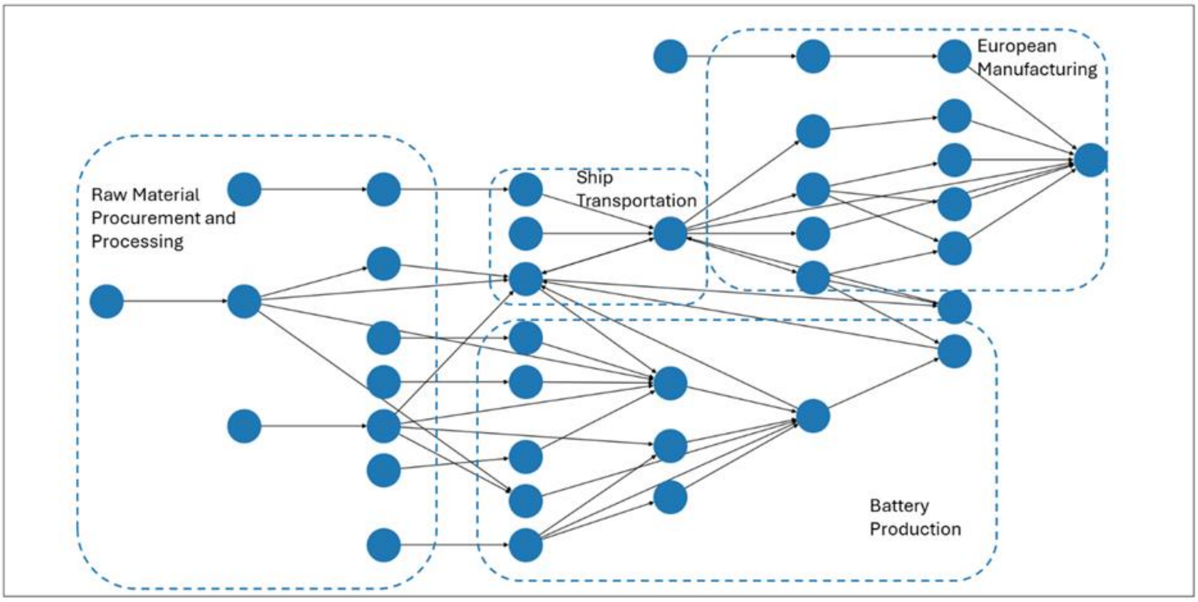


Figure 3: Node Overview and Clustering of the modelled automotive supply chain

The agri-food ecosystem comprises all actors and activities in the food supply chain, including farmers, food producers, retailers as well as suppliers and other service providers in the food supply chain. The selected supply chain produces wine and is separated in four phases production (harvest and aging), filling, packaging and dispatching. Important materials beside the grapes are the cork and products which are not produced nationally. For example, bottles and filtration pads.

One unique factor of the wine SC is the are the staggered work phases, where many workers are needed for the harvest and later only a small number of workers are needed to produce the finished product. One further aspect is that the demand is constant over the simulation period, but the production is focused on a small timeframe.

The next chapter will address these special features and illustrate the corresponding disturbances.

The Node Complexity is 22 and the Flow Complexity 1.9. The SCI is 0,26 it is still moderate Complex. This value comes from many the different Suppliers of materials which a shown in the Network Map.

Figure 4: Geographical overview of the agri-food supply chain

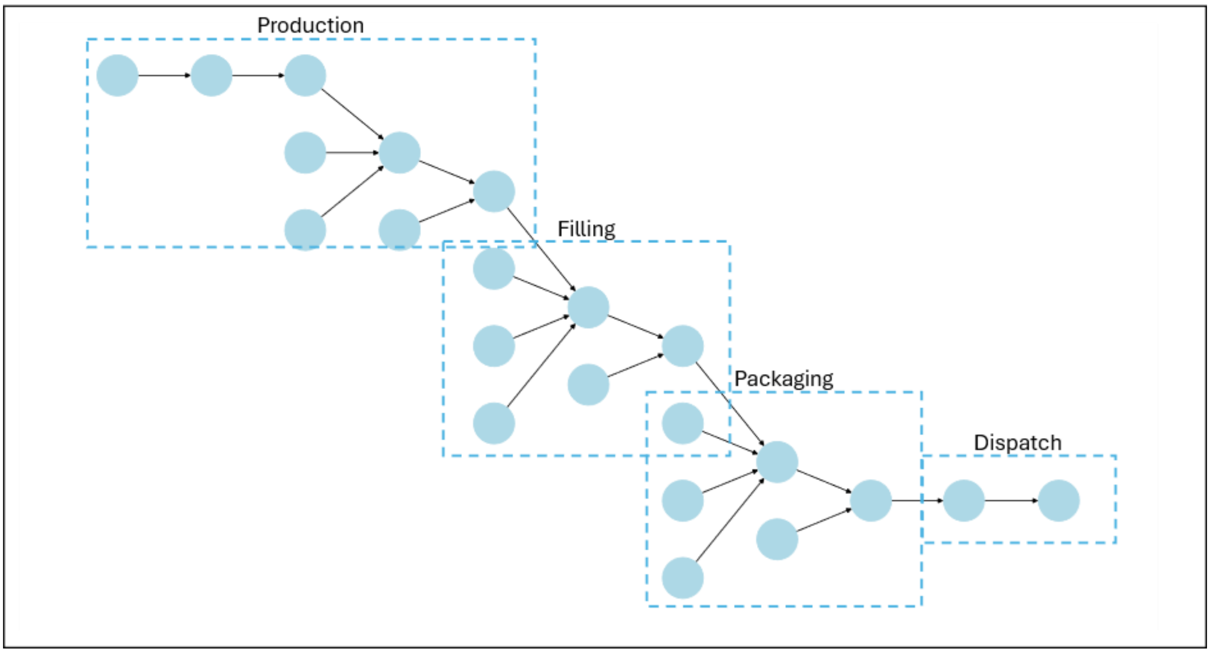


Figure 5: Node Overview and Clustering of the modelled agri-food supply chain

The textile ecosystem is very complex due to the large number of SMEs and global competition. It has a strong link between major brands and suppliers. The textile ecosystem includes the processing of natural (e.g. cotton, flax, wool), man-made and synthetic (synthetic polyester and viscose fibres) fibres into yarns and fabrics, the production of yarns, home textiles, industrial filters, technical textiles, carpets and apparel. The ecosystem also includes the production of shoes and leather, the manufacture of intermediate products and fashion items and the distribution of these products. The fashion industry is the most important market for textile products. Critical factors are that a lot of the production is done by people and that individual production steps or the entire process is outsourced to other companies, which are located in Asia.

The Node Complexity is 20 and the Flow Complexity 2.2. The SCI is 0,23.

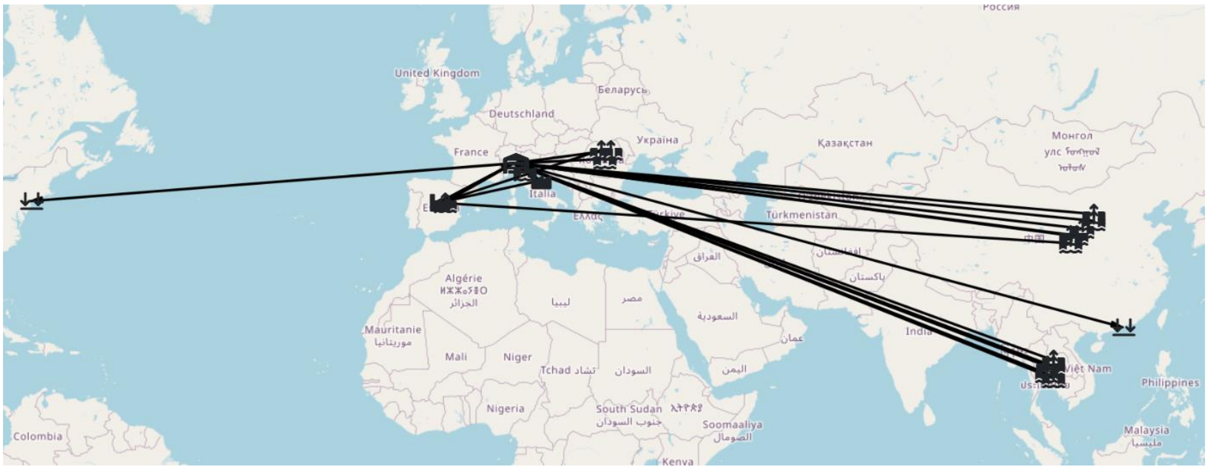


Figure 6: Geographical overview of the textile supply chain

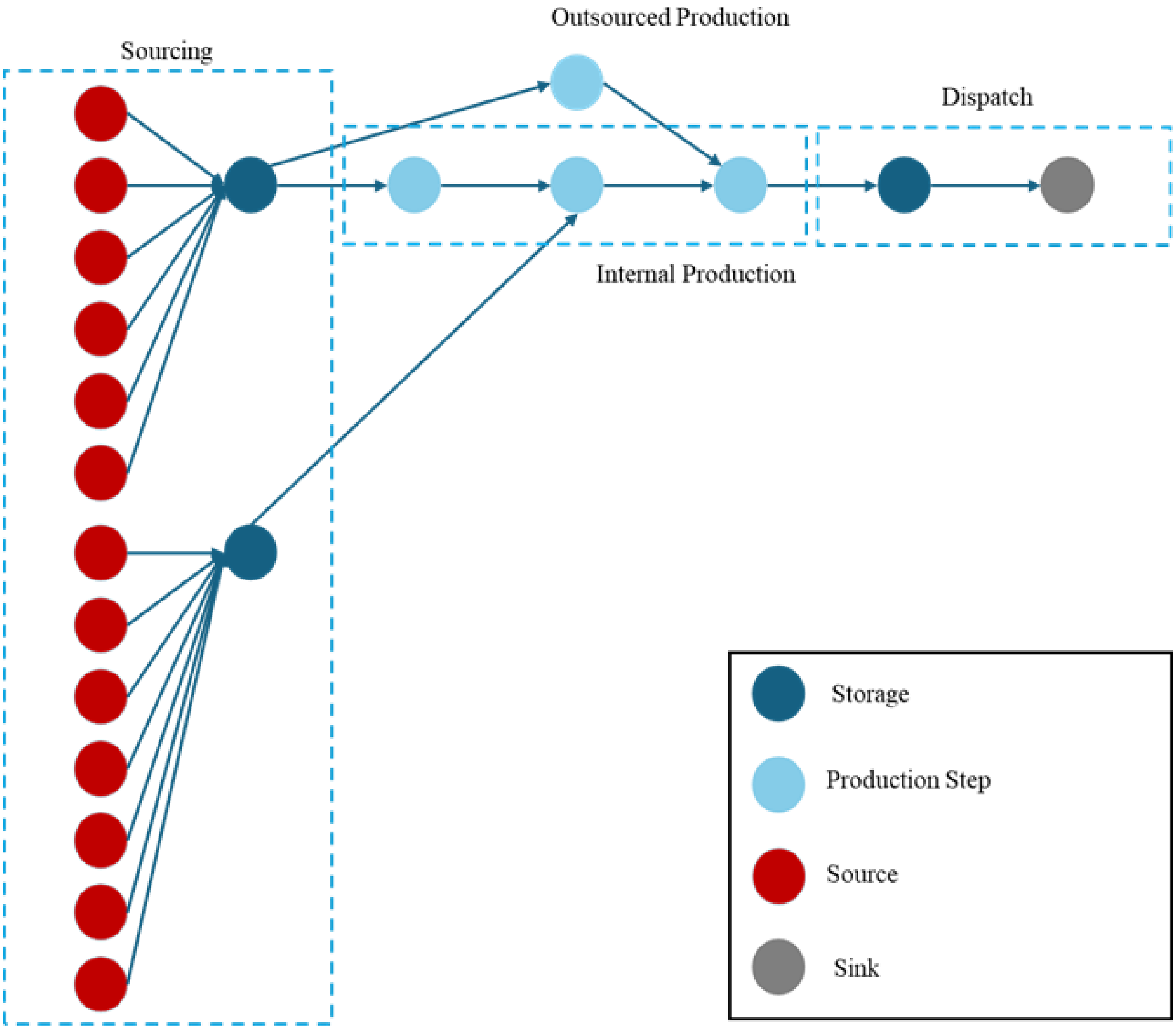


Figure 7: Node Overview and Clustering of the modelled textile supply chain

The ecosystem Model of Mobility as a Service (MaaS) encompasses users, physical fleets, infrastructure providers and other influencing factors, which are divided into the supply and demand sides. Demand is shaped by factors such as environmental consciousness, weather conditions, travel duration and user income, which influence choices of transport mode. The supply side is influenced by the number of available vehicles, which is adjusted based on demand and population to ensure an optimal balance between vehicle acquisition and retirement. Technological performance of the MaaS application, as determined by payment integration, user experience and app performance, is crucial for success as failures in these areas can create significant bottlenecks.

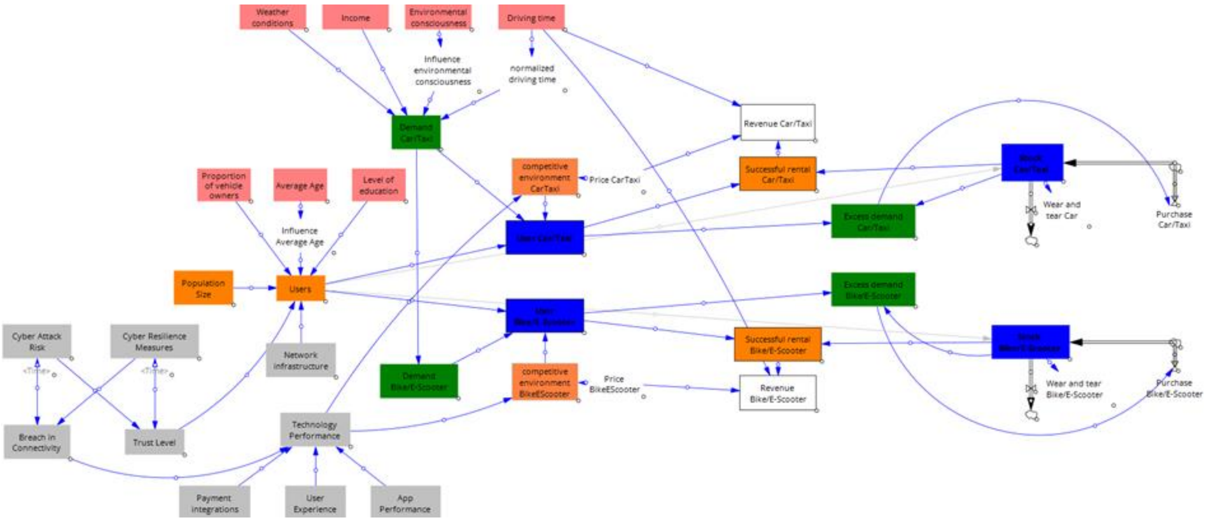


Figure 8: Overview of the digital MaaS System Dynamics Model

5.2 Simulation of Disruptions and Technology Responses

Two different disruption scenarios were designed for each ecosystem, tailored to the specific characteristics of the selected supply chains. Table 8 shows the scenarios that have been developed. The table contains information on the critical factors, their impact on the supply chain, and which locations will be explicitly affected. In addition, a preselection of resilience KPIs from Table 7 has been made, which are now used to measure the resilience of the supply chain.

The two EV supply chain scenarios focus on energy supply, as the production steps involved in manufacturing a car require very high energy consumption. The first scenario envisages a widespread power outage in which production cannot take place throughout Germany for a short period of time. Affected areas include final assembly, but also the production of steel and aluminum parts, which are transported throughout Europe to manufacture components such as brakes and suspension systems.
The second scenario envisages a restriction in availability throughout the entire simulation period, which could arise from the integration of renewable energies. The focus here should be on electricity price fluctuations, as electricity prices could fluctuate in the future depending on weather conditions and available resources.

The two scenarios of the wine supply chain focus on geopolitical characteristics, with the first scenario focusing on the customs process, which plays an important role when products are distributed worldwide. The wine supply chain is particularly affected by this difficulty, as it is not possible to relocate wine production. In the simulation, this disruption is represented by a longer transport process, which ensures that deliveries do not arrive at the customer on time and also results in significant additional costs for supply chain participants.

The second scenario focuses on the reshoring of certain production steps that were outsourced in the past. In the simulation, this is represented by multiple production sites that can be accessed at will, whereby the procurement process does not run smoothly at first but is subject to certain fluctuations and disruptions until the reshoring is complete and a normal process is restored.

The textile scenarios focus on the social conditions of the supply chain, with an ever-decreasing availability of workers reflected in reduced production capacities throughout the simulation period. On the other hand, outsourcing is considered and the problems that outsourcing processes entails. Particular emphasis is placed on the reduction in quality and the associated decline in customer satisfaction. There is also a decline in punctuality due to the need for additional long-distance transport.

In the context of digital ecosystems, the two disruption scenarios relate to cybersecurity and highlight potential risks for companies in the Mobility as a Service (MaaS) sector. The possibility of a cyberattack and the occurrence of a security incident can both have a significant impact on the functionality and acceptance of such services. The first scenario describes a decline in user trust resulting from the risk of a security incident, which can negatively affect usage and customer loyalty. The second scenario focuses on connectivity disruption caused by a cyberattack, which can result in the service being unavailable or only partially available.

Table 8: Overview of the implemented scenarios in the simulation models

Simulation	Ecosystem	SCENARIOS	Supply Chain	Critical Factors	Impact for the supply chain	Impacted Nodes	Relevant KPIs
Power outage	Mobility	Energy Resil-ience	Electric vehicles (EV)	Energy shortage Fluctuation in the amount of resources available Increase cost of raw materials Difficulties in integrating renewable energies	Several production sites in one region affected - production stoppages lasting a few days	Nodes: All production sites in Germany; Duration: 12-72h; Frequency: Once	Service level; SCRI; Flow Complexity
Restricted availability of Energy	Mobility	Energy Resil-ience	Electric vehicles (EV)	Electricity as a new source with limited availability	Highly energy-intensive processes are affected, such as steel and aluminium	Nodes: High-energy production (blast furnace process) Is discharged as material via electricity; Duration: The whole Simulation Time; Frequency: in this scenario it is permanent	Service level; SCRI; Flow Complexity
Extensive customs process	Agrifood	Geo-political	Wine	Increase in lead times for overseas customers	The customs process in the USA increases the time for transportation to the customer	Concerns the sea route to the USA and leads to higher lead times	Service level; SCRI; Flow Complexity
Rising costs for suppliers (Reshoring)	Agrifood	Geo-political	Wine	•Increase in costs of supply from certain countries •Decrease of sales towards certain countries •Need to quickly reconfigure supply chain	Rising material costs have an impact on resilience; rising transportation costs lead to the reshoring of materials	Node: Suppliers of easily substitutable products such as capsules, corks and labels; Duration: Whole Simulation Time	Service level; SCRI; Flow Complexity

Simulation	Ecosystem	SCENARIOS	Supply Chain	Critical Factors	Impact for the supply chain	Impacted Nodes	Relevant KPIs
Worker Shortage (Aging Population and Lack of skilled Workers)	Texti	Social (human centric) resilience	Shoe	•Lack of visibility on workers conditions in suppliers in global networks. •Difficulties for interactions and collection of appropriate information. •Difficulties to collaborate with suppliers to improve workers conditions.	Consider rising transportation costs of overseas sources; alternatively consider national production with higher material but lower transportation costs	Nodes Selection of different suppliers.	Service level; SCRI; Flow Complexity
Out-sourcing	Textil	Social (human centric) resil-ience	Shoe	•Lack of visibility on workers conditions in suppliers in global networks. •Difficulties for interactions and collection of appropriate information. •Difficulties to collaborate with suppliers to improve workers conditions.	Moving Production Aboard - Effects on the supply chain and implied working conditions; person loss and working hours by moving production to China, India, Vietnam etc.	Nodes: Production Units (Italy to Overseas)	Service level; SCRI; Flow Complexity
Cyber-attack	Digital	Cyber resil-ience	MaaS	Cyber-attacks breach in the connection difficulties to provide service	Availability of the service	Various parameters in the SD model	Number of trips, availability

6 Technology Solutions Clustering

6.1 Selection by Ecosystem

To analyse the potential of digital technologies to enhance supply chain resilience across different ecosystems, four specific technologies have been selected and assigned to the most relevant disruption scenario per sector. This selection is based on their capability to address specific vulnerabilities and enhance resilience KPIs through operational, structural, or collaborative improvements, as discussed in a previous project deliverable (notably D2.2). Each technology has been matched to the ecosystem where its impact would be most significant based on the sector's characteristics, current challenges, and alignment with EU resilience and digitalization priorities.

6.1.1 Edge Computing for Electric Vehicle Production under the Energy Resilience Scenario

Edge Computing is one of the most appropriate digital technologies for improving resilience in energy-intensive supply chains, such as electric vehicle (EV) production. It is particularly effective in addressing disruptions related to energy supply instability—a growing concern due to the volatility of energy prices, grid dependency, and the ongoing transition toward renewable sources.

1. **Local Real-Time Processing:** During energy disruptions, access to cloud-based services can be impaired. Edge Computing enables critical systems—such as IoT sensors and robotics—to operate autonomously with local backup power, maintaining production continuity (as described in D2.2: "resilient operation in network-constrained environments").
2. **Latency Reduction for Critical Operations:** Automated assembly lines in EV plants require millisecond-level decision-making. Edge devices process control and monitoring tasks locally, minimizing downtime and improving OTIF (On Time In Full) and agility KPIs.
3. **Support for Robotics and Predictive Maintenance:** Edge infrastructure can run predictive maintenance algorithms even during partial outages, enhancing recovery rate and reducing operational risks tied to power failure.
4. **Data Filtering and Prioritization:** Edge systems prioritize mission-critical data, reducing the load on communication networks and ensuring operational adaptability.
5. **Operational Resilience:** By decentralizing computing, Edge Computing enhances both redundancy and adaptability, allowing production lines to reconfigure dynamically in response to disruptions.

For example, a battery assembly line using Edge devices can continue production during main-grid failure, optimize resource allocation in real time, and execute fallback logistics protocols.

Edge Computing directly supports KPIs such as agility, adaptability, and operational visibility, making it the most suitable digital solution for EV manufacturing in an energy resilience scenario.

6.1.2 Data Spaces for MaaS under the Cyber Resilience Scenario

Data Spaces are particularly well-suited to strengthening cyber resilience in the Mobility-as-a-Service (MaaS) ecosystem, which is highly data-driven and exposed to threats from cyberattacks, system failures, and data breaches.

1. **Federated Governance and Access Control:** Data Spaces empower each actor (e.g., public authorities, ride-sharing providers, and payment platforms) to manage its own data securely, preventing centralized vulnerabilities.
2. **Interoperability with Embedded Security:** Using standards such as IDS-Connectors and iShare, Data Spaces provide secure-by-design data exchange mechanisms, ensuring traceability and authentication.
3. **Compartmentalization of Cyber Risk:** In case of a breach, only the affected node is exposed, minimizing the impact on the overall service network—a key benefit for maintaining KPIs such as recovery rate and visibility.
4. **Auditability and Incident Response:** Each data transaction is logged, enabling forensic audits and real-time revocation of access during a cyber event, contributing to transparency and reducing downtime.
5. **Compliance with EU Regulations:** Data Spaces align with GDPR, eIDAS, and the upcoming Data Act, supporting regulatory resilience and user trust.

For example, if a bike-sharing provider is compromised, the MaaS platform can revoke its access, isolate the issue, and maintain service continuity for other mobility options like buses or taxis.

By improving control, decentralization, and traceability, Data Spaces directly enhance cyber resilience and are the ideal digital technology for the MaaS ecosystem in this scenario.

6.1.3 Artificial Intelligence for Wine Supply Chains under the Geopolitical Instability Scenario

The wine sector is increasingly exposed to geopolitical risks, such as trade restrictions, tariffs, or border closures. Artificial Intelligence (AI) supports this ecosystem by enhancing strategic adaptability and operational foresight.

1. **Forecasting Market and Policy Shifts:** AI can anticipate market changes driven by political instability and propose proactive strategies, improving KPIs like ENPV, adaptability, and supplier replacement rate.
2. **Optimization of Local Resources:** By analysing soil, climate, and input data, AI supports localized production strategies that reduce dependence on imported inputs, thereby minimizing exposure to geopolitical shocks.
3. **Scenario Simulation and Logistics Planning:** AI simulates what-if scenarios (e.g., export bans) and optimizes route planning, inventory buffers, and supplier networks accordingly.
4. **Cost Reduction Through Efficiency:** AI-based automation lowers production costs, offsetting financial impacts caused by tariffs or supply chain rerouting.
5. **Strategic Flexibility:** AI enables real-time reconfiguration of operations, reinforcing resilience KPIs such as agility, recovery rate, and market strength.

For example, a vineyard using AI can shift its export strategy based on predicted trade policies, adjust input sourcing locally, and forecast demand fluctuations with higher accuracy.

AI's ability to model uncertainty, optimize resources, and guide decision-making under geopolitical volatility makes it the most effective technology for the wine sector in this scenario.

6.1.4 Blockchain for Shoe Manufacturing under the Social (Human-Centric) Resilience Scenario

In the footwear industry, social resilience—focused on fair labour practices and stakeholder well-being—is paramount. Blockchain enhances transparency, ethical sourcing, and compliance across fragmented and often globalized supply chains.

1. **End-to-End Traceability of Labor Conditions:** Blockchain registers every step of the production chain immutably, allowing verification of labour conditions and ethical sourcing (e.g., fair wages, no child labour).
2. **Certifiable Proof of Sustainability and Equity:** Smart contracts automate compliance with social standards and certifications (e.g., fair trade), reducing manual audits and building trust among stakeholders.

3. **Empowerment of Small Producers:** Blockchain enables micro-enterprises to showcase ethical practices without intermediaries, enhancing their participation and visibility in global markets.
4. **Consumer Trust and Regulatory Compliance:** Consumers can verify the social footprint of their purchases. Manufacturers also gain resilience through better auditability and compliance with EU social and due diligence directives.
5. **Continuity Across Global Supply Chains:** Even during supplier shifts due to relocation or crises, blockchain ensures that social standards are upheld consistently.

For example, a European shoe brand uses blockchain to trace leather sourcing, certify safe working conditions in partner factories, and automate payment to local producers via smart contracts.

Blockchain enables human-centric resilience by enhancing visibility, fairness, and empowerment. It is the most suitable digital solution for the shoe sector in the context of social and labour-driven disruptions.

6.2 Classification by Impact on KPIs

To evaluate how digital technologies improve resilience in the face of disruptive scenarios, this section defines a systematic mapping between the technologies selected for each ecosystem and the key resilience KPIs identified in the project. This approach supports the objective of simulating the quantitative effects of technology adoption across modelled supply chains.

The selected digital technologies were chosen based on their ability to address specific vulnerabilities and risks identified within each ecosystem. Each technology is applied within a relevant disruption scenario where it demonstrates the greatest potential to enhance supply chain resilience.

To ensure consistency and traceability in the models, each digital solution is analysed in terms of how it directly influences resilience capabilities, and how these capabilities can be translated into the project's KPI framework. The analysis draws from scientific literature, particularly the framework proposed by Marinagi et al. (2023), which categorizes the influence of Industry 4.0 technologies on supply chain resilience through structural and functional dimensions such as agility, visibility, flexibility, and robustness.

The following subsections detail the alignment between each digital technology and the measurable resilience KPIs from the project, providing a rationale for their selection and defining the specific metrics to be used in simulation. This enables a quantitative comparison between baseline and technology-enhanced scenarios, supporting evidence-based conclusions on the value of digital transformation for resilient supply chains.

The following table summarizes the results of this mapping exercise, detailing which KPIs are positively impacted by each technology and how these impacts contribute to strengthening the supply chain's ability to respond to disruptions. This mapping provides a crucial foundation for the next steps in modelling the quantitative benefits of digital technologies on resilience in the targeted ecosystems.

Table 9: Resilience KPIs impacted by digital technologies.

Digital Technology	Ecosystem / Scenario	Resilience Enablers (Marinagi et al., 2023)	Impacted KPIs in the Model
Edge Computing	EV production / Energy resilience	Visibility, Flexibility, Responsiveness, Operational Autonomy	- Visibility (↑ real-time monitoring) - Adaptability (↓ time to adjust post-disruption) - Agility (↓ lead time) - OTIF (↑ reliability in deliveries) - Recovery Rate (↓ recovery time) - Technological Innovation (% budget in edge-based tech) - Flow Complexity (↑ by decentralizing control)
Data Spaces	MaaS / Cyber resilience	Transparency, Security, Decentralized Governance, Interoperability	- Visibility (↑ monitoring of processes) - Cooperation & Knowledge Sharing (↑ secure data sharing) - Adaptability (↑ to cyber disruption) - Recovery Rate (↑ after cyberattacks) - Graph Energy (↑ system modularity) - Technological Innovation (↑ investments in secure data infra)
Artificial Intelligence (AI)	Wine production / Geopolitical instability resilience	Forecasting, Scenario Planning, Autonomous Decision-Making, Flexibility	- Adaptability (↑ responsiveness to market shifts) - Demand Change Response (↑ demand fulfilment) - ENPV (↑ risk-adjusted financial performance) - Supplier Replacement Rate (↓ onboarding time via AI sourcing tools) - Agility (↓ reaction time to geopolitical disruptions)

Digital Technology	Ecosystem / Scenario	Resilience Enablers (Marinagi et al., 2023)	Impacted KPIs in the Model
			- Technological Innovation (↑ AI investments) - Geographical Risk (↓ dependency via optimization)
Blockchain	Shoe production / Social-human resilience	Traceability, Transparency, Trust, Ethical Compliance	- Cooperation & Knowledge Sharing (↑ trust among actors) - Visibility (↑ traceability of sourcing and labour) - Node Complexity (↑ by decentralizing data) - Stock Level of High-Risk Parts (↑ forecasting accuracy) - Geographical Risk (↓ through verified local sourcing) - Recovery Rate (↑ by ensuring continuous ethical certification) - Technological Innovation (↑ investments in blockchain traceability)

Table 10: Mapping of the impacted Resilience KPIs

Technology	Ad	SRR	DCR	TI	ESC	OTIF	C&KS	D	ND	FC	SLHRP	G	ENPV	Ag	SS	RR	SCRI
Edge Computing	✓	✓	✓	✓	✓	✓	✓				✓		✓	✓	✓	✓	✓
Data Spaces	✓		✓		✓	✓	✓						✓	✓		✓	✓
Artificial Intelligence	✓	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓	✓	✓	✓	✓
Blockchain	✓			✓	✓	✓	✓	✓					✓			✓	✓

6.2.1 Data Spaces for MaaS – Cyber Resilience Scenario

Data spaces enable secure, decentralized, and governed data exchange, which enhances the cyber resilience of digital ecosystems like Mobility as a Service (MaaS). Based on the Marinagi et al. framework, the key resilience elements supported by data spaces include **visibility, collaboration, information sharing, and security**. These elements correspond to the following project KPIs:

- **Visibility**: Improved through real-time monitoring of digital services and secure interoperability.
    - *KPI Match*: **Visibility (percentage of supply chain processes monitored in real-time)**
- **Information Sharing**: Controlled, secure data access and usage via IDS/iShare protocols.
    - *KPI Match*: **Cooperation & Knowledge Sharing (frequency of collaborative meetings and shared initiatives per quarter)**
- **Security**: Reduced vulnerability due to decentralized governance and fine-grained access controls.
    - *KPI Match*: **Recovery Rate** (reduced recovery time from cyber incidents), **Cybersecurity Incident Rate** (could be proxied using **OTIF** during cyberattacks)
- **Collaboration**: Trust-building via traceable, permissioned exchanges.
    - *KPI Match*: **Density** (ratio of actual to potential data-sharing partnerships), **Node Complexity** (manageable growth of digital actor networks)

6.2.2 Artificial Intelligence for Wine Production – Geopolitical Instability Resilience Scenario

AI supports **forecasting**, **resource optimization**, and **scenario planning**, which are essential for supply chains facing geopolitical risks (e.g., tariffs, supply disruptions). AI improves the supply chain's **flexibility, adaptability, robustness, visibility**, and **situation awareness**. Mapped KPIs include:

- **Adaptability**: Rapid reconfiguration based on AI-generated demand and supply forecasts.
    - *KPI Match*: **Adaptability (time to adjust operations post-disruption)**
- **Demand Change Response**: Scenario-based AI planning enhances responsiveness to market shifts.
    - *KPI Match*: **Demand Change Response (% of demand met without stockouts)**
- **Geographical Risk**: AI supports reshoring and diversification strategies based on geopolitical forecasting.
    - *KPI Match*: **Geographical Risk (reliance on high-risk regions)**
- **Technological Innovation**: AI investment reflects digital maturity and innovation capability.
    - *KPI Match*: **Technological Innovation (% of budget allocated to digital solutions)**
- **Agility**: Automated decision-making reduces lead time under stress.
    - *KPI Match*: **Agility (lead time reduction post-disruption)**
- **Expected Net Present Value (ENPV)**: AI-based scenario modelling improves financial foresight.

- *KPI Match*: **ENPV (probability-weighted future value based on adaptive decisions)**

6.2.3 Blockchain for Shoe Production – Social (Human-Centric) Resilience Scenario

Blockchain provides **traceability, trust, and transparency**, supporting fair labor conditions and ethical sourcing—key components of **social resilience**. According to Marinagi et al., blockchain improves **collaboration, visibility, robustness, information sharing**, and **security**. This maps to:

- **Visibility**: End-to-end traceability of material origins and labor conditions.
  - *KPI Match*: **Visibility (monitoring of product provenance and working conditions)**
- **Cooperation & Knowledge Sharing**: Verified, shared ethical compliance data across actors.
  - *KPI Match*: **Cooperation & Knowledge Sharing**
- **Graph Energy**: Reduction in network opacity and fraud improves structural resilience.
  - *KPI Match*: **Graph Energy (simplified, trustworthy network structure)**
- **Single Sourcing with Single Plant (SS)**: Smart contracts and traceability encourage distributed sourcing.
  - *KPI Match*: **SS (% of critical components from single suppliers)**
- **Recovery Rate**: Faster auditing and verification post social compliance issues.
  - *KPI Match*: **Recovery Rate (time to restore reputation/compliance after disruption)**
- **Technological Innovation**: Blockchain enables automation of labour rights verification via smart contracts.
  - *KPI Match*: **Technological Innovation**

6.2.4 Edge Computing for Electric Vehicle Production – Energy Resilience Scenario

Edge computing facilitates **localized processing**, ensuring **autonomous decision-making**, particularly during energy outages. According to Marinagi et al., it supports **agility, flexibility, visibility**, and **robustness**. Relevant KPIs include:

- **Adaptability & Recovery Rate**: Localized reconfiguration of operations during grid failure.
  - *KPI Match*: **Adaptability**, **Recovery Rate (days to restore production)**
- **OTIF**: Reduced dependency on cloud connectivity ensures consistent delivery performance.
  - *KPI Match*: **OTIF (On Time In Full delivery rate)**

- **Technological Innovation**: Deployment of edge-enabled predictive maintenance systems.
    - *KPI Match*: **Technological Innovation**
- **Stock Level of High-Risk Parts**: Improved inventory control through local sensor data analytics.
    - *KPI Match*: **Stock Level of High-Risk Parts (days of buffer stock)**
- **Flow Complexity**: Optimized through local decision-making to reroute production.
    - *KPI Match*: **Flow Complexity**
- **Agility**: Millisecond-level response times for process optimization.
    - *KPI Match*: **Agility**

7 Impact Assessment of Technology Solutions

7.1 Quantitative Impact of Disruptions

All simulations of ecosystems proceed with certain fluctuations, as would be expected in reality. In the following analyses, the SCRI and the service level are used to make a statement about the performance of the supply chain and the severity of the disruptions. However, since the order volume is not constant, the order volume must be compared when considering the service level, as a high service level is generally expected when order numbers are low because the system load is lower.

Mobility Ecosystem:

The first fault scenario depicts a widespread but brief power outage that occurs halfway through the simulation period.

The service level is an apparent indicator to identify the disruption, which resulted in a 5% reduction for the whole month of July compared to a benchmark simulation. Figure 9 shows the service level and the corresponding order volume over the simulation period.

The calculation of the supply chain index according to Sardesai also shows that the supply chain is not resilient and that improvement measures should be taken. With a value of 0.15, the supply chain is in a non-resilient range.

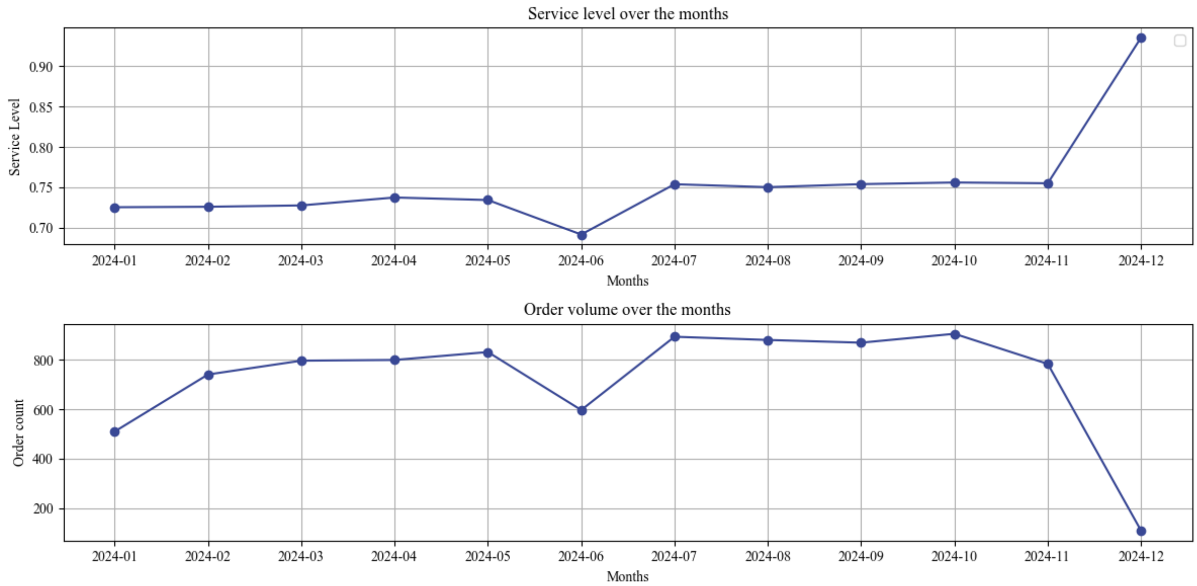


Figure 9: Service Level and Order Volume Graph for disruptive scenario in the automotive supply chain for scenario 1

The second scenario shows a restriction in energy availability throughout the entire simulation period for high-energy processes. Again, the service level can be used to quantify the effects of the disruptions. As a result, compared to the first scenario, the service level is only 60% and, in general, due to the sporadic availability of energy, the processes cannot run smoothly and fluctuated greatly in the first few months.

According to Sardesai, the SCRI for this scenario without countermeasures is lower than in the first scenario, with a value of -0.1.

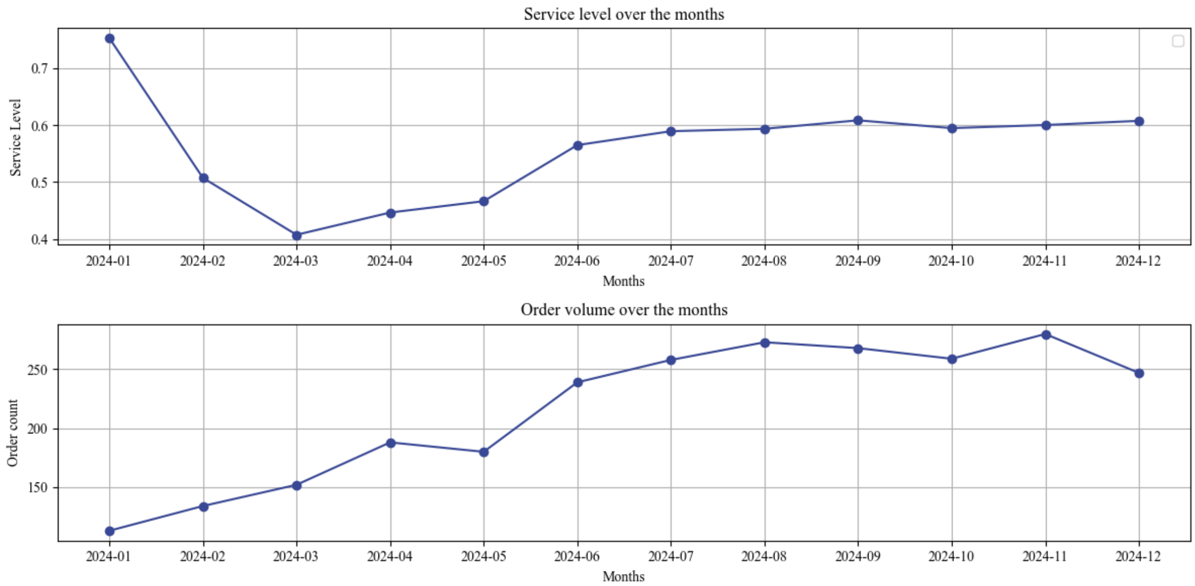


Figure 10: Service Level and Order Volume Graph for disruptive scenario in the automotive supply chain for scenario 2

Agri-Food Ecosystem

The wine supply chain is determined by the uneven production of wine. This makes it difficult to assess the service level, as there is no consistent order load. However, Figure 11 shows that irregular waiting times can cause the service level to fluctuate between 100% and 38%. The SCRI shows a similar picture, with a value of 0.95, which is quite high and just short of being resilient, as a value of one or higher would indicate a resilient supply chain. This high value is primarily due to the fact that a service level of one is frequently achieved.

The production intervals can also be seen in the order load in the lower part of Figure 11, which rises sharply every year after the harvest.

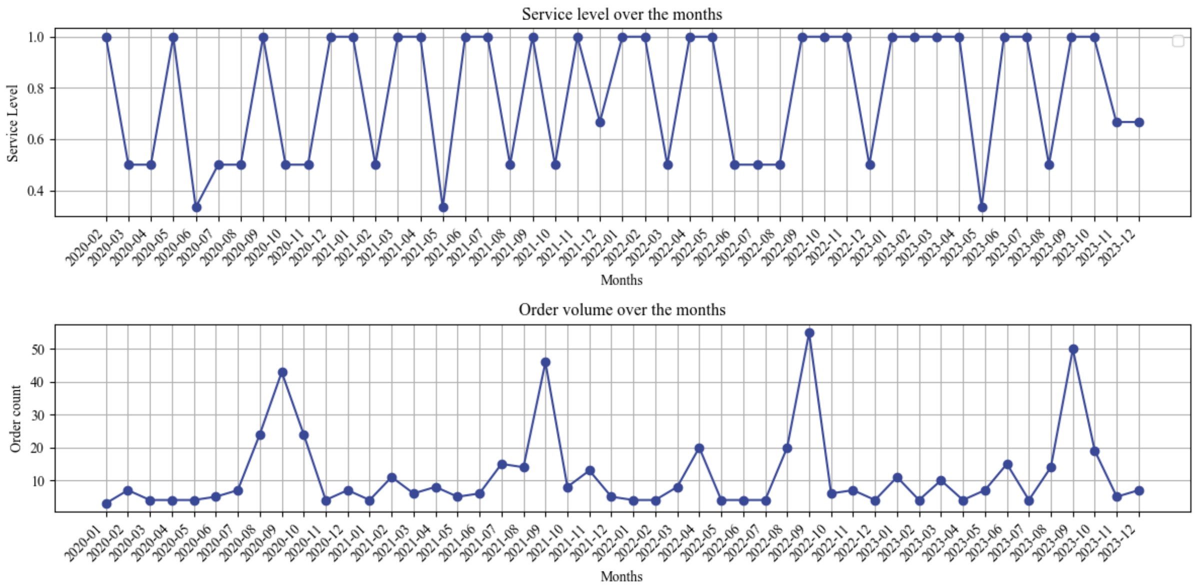


Figure 11: Service Level and Order Volume Graph for disruptive scenario in the agri-food supply chain for scenario 1

The second scenario considers the reshoring process of bottle production from Asia to Europe. The disruption was modelled in such a way that the demand for bottles for filling cannot be fully met within a period of three months. This is because the new production facility has yet to start up. This behaviour can also be observed in Figure 12, where the service level drops more sharply in the disruption period from August to November 2022 than in previous years.

The SCRI according to Sardesai shows a similar picture with a value of 0.06, which indicates a non-resilient supply chain.

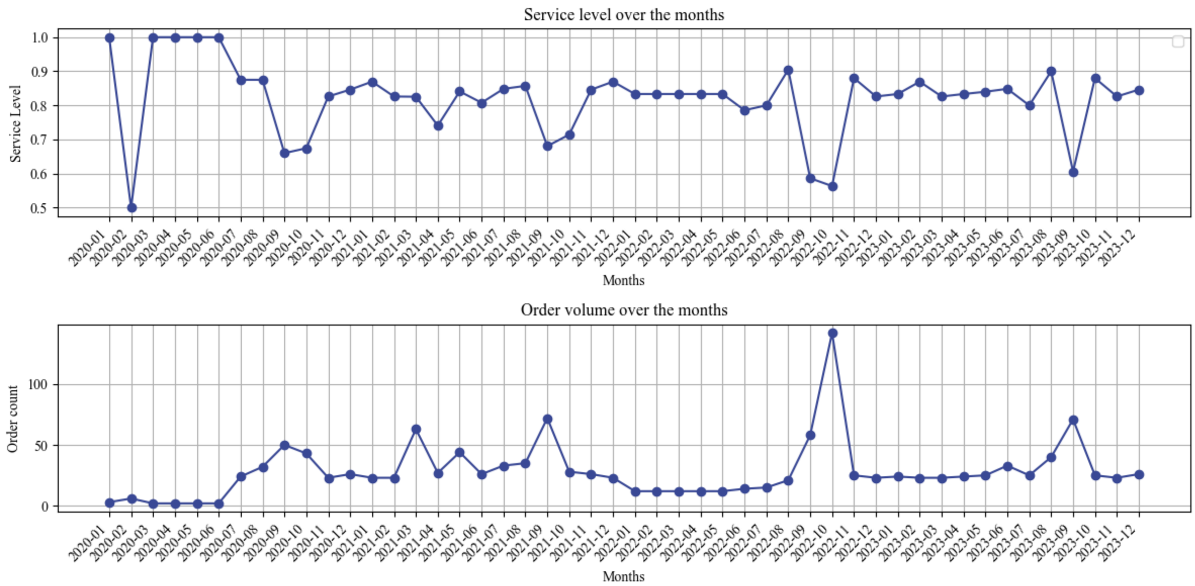


Figure 12: Service Level and Order Volume Graph for disruptive scenario in the agri-food supply chain for scenario 2

Textile Ecosystem

The first scenario in the textile supply chain depicts a lack of worker availability, with sporadic worker shortages throughout the simulation period and orders not being processed.

Two disruptions were planned for this scenario: first, a reduction in the workforce in the control room due to illness, and second, a prolonged period in the middle of the simulation during which there was insufficient capacity to ensure smooth production. This can also be seen in Figure 13, where the service level drops sharply in February but returns to a normal level in March. A steady decline in the service level can be observed in the period between June and October. The SCRI is also only 0.11, which would correspond to a non-resilient supply chain.

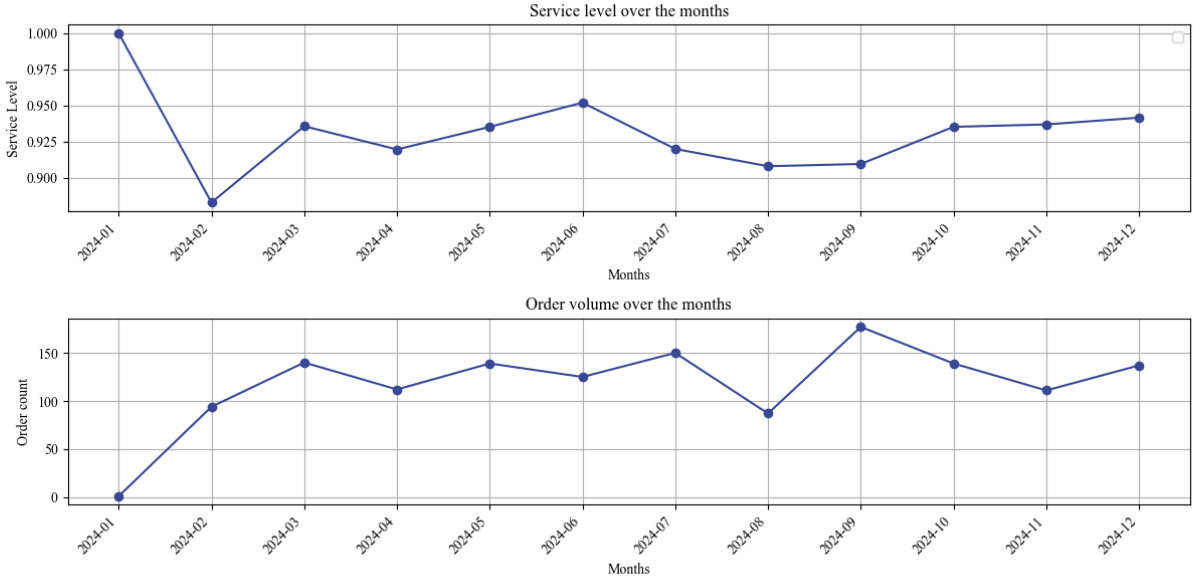


Figure 13: Service Level and Order Volume Graph for disruptive scenario in the textile supply chain for scenario 1

The second textile supply chain scenario deals with the outsourcing process for components and end products. The simulation depicts a new supplier who sends the products to an in-house quality control department, which checks the parts and decides whether they meet the quality standards. However, outsourcing can lead to various difficulties, such as goods being damaged during long transport journeys or the quality of the products not meeting requirements. This may be due to the use of inferior materials or manufacturing processes that have not been carried out properly, for example, the gluing of soles.

These problems lead to a reduction in service levels, as quality control can no longer function in line with demand. This behavior can also be seen in Figure 14, where the service level levels off at 65% once orders have reached a steady volume. This is also shown by the SCRI, which has a value of -0.16, classifying the supply chain as non-resilient.

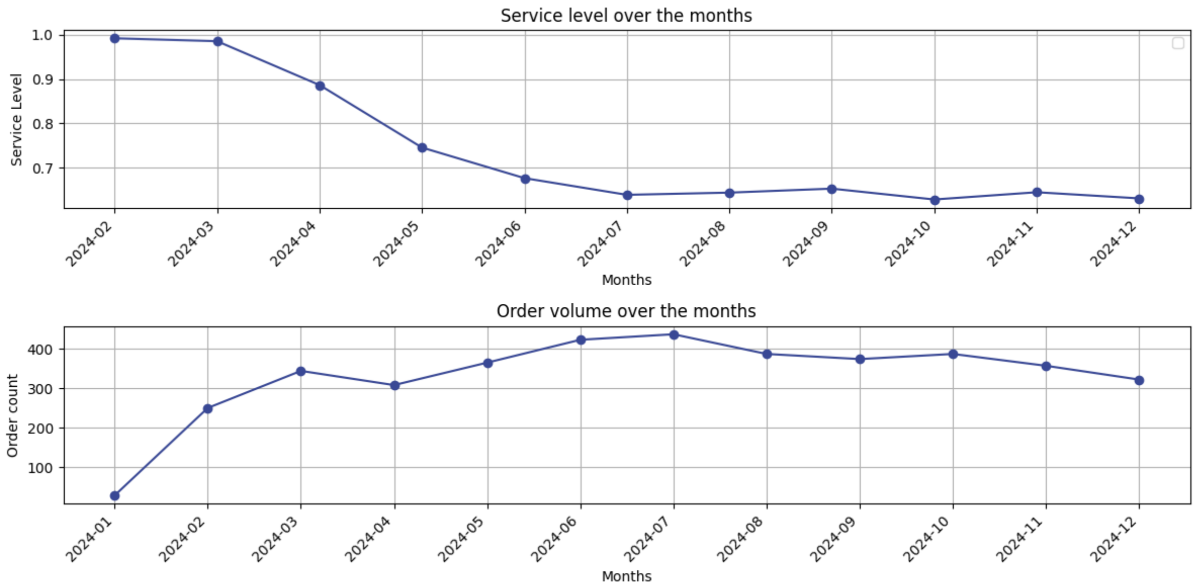


Figure 14: Service Level and Order Volume Graph for disruptive scenario in the textile supply chain for scenario 2

Digital Ecosystem:

In the digital ecosystem of Mobility-as-a-Service (MaaS), two key disruption scenarios can be identified that are primarily triggered by cybersecurity risks. These scenarios illustrate the quantitative impact of security incidents on system performance and user interaction. Figure 15 shows the modelling of the disruptive cyber security scenario as add on to the model.

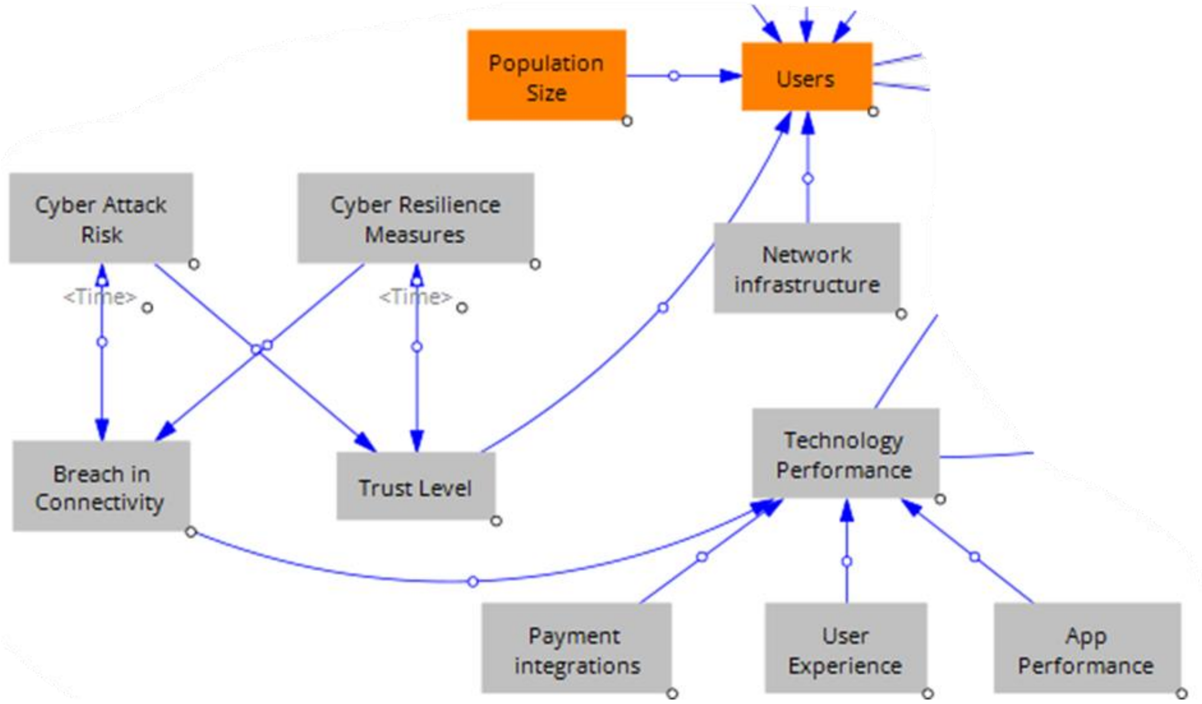


Figure 15: Modelling of disruption in MaaS scenario

The first disruption scenario describes a so-called breach in connectivity. This occurs when the risk of a cyberattack exceeds the tolerable level, interrupting the connectivity of the service. illustrates this relationship and shows that a disruption occurs at time t = 4 because the risk exceeds the critical threshold. In later time intervals, no further breach in connectivity is observed despite a renewed increase in risk (see Chapter 7.2)

Once triggered, such a disruption leads to a complete failure of technological performance. Even if other influencing factors remain constant, the performance of the digital system collapses abruptly (Figure 17)

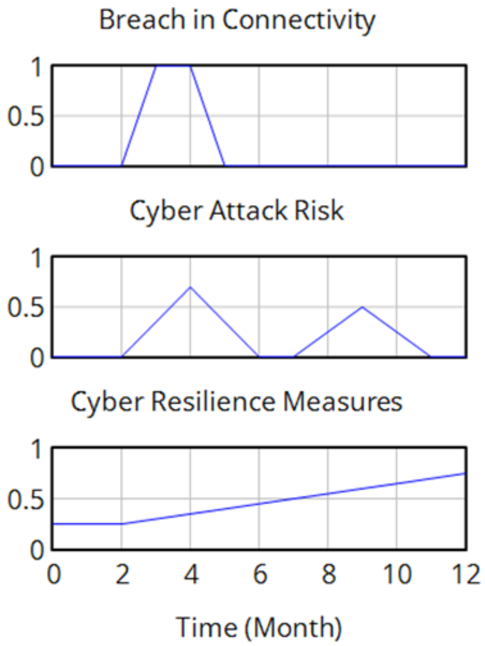


Figure 16: Cyber Attack Risks and resilience measures in disruptive scenario for MaaS Model

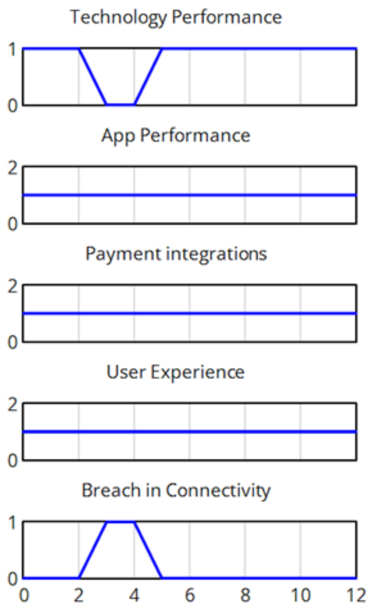


Figure 17: Performance during Breach in connectivity

The second scenario concerns user trust operationalized using the trust level indicator. This reflects users' confidence in the functionality and security of the platform. Trust is sensitive to discrepancies between risk and resilience measures.

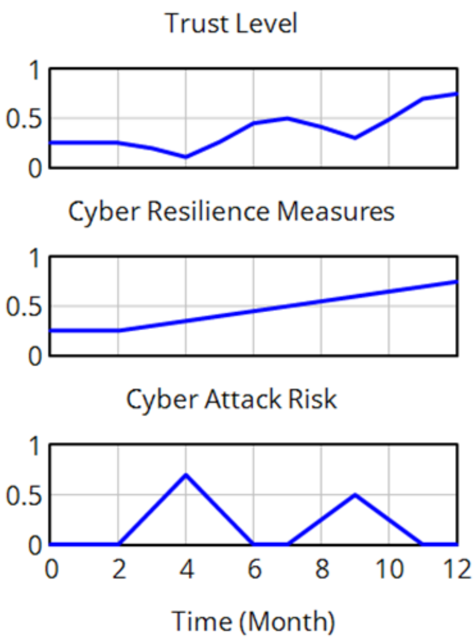


Figure 18: Trust Level over time in MaaS Model

Figure 17 shows the course of the trust level over time depending on the underlying variables. Especially in phases of increased risk, there is a temporary decline in trust, which can have a negative effect on the trust level. If the trust level falls below a certain level, this can lead to user churn.

These two scenarios—complete loss of service due to connectivity breaches and gradual loss of user trust—represent key quantitative consequences of disruption in the digital MaaS ecosystem. They highlight the potential vulnerability of data-driven services to cyber risks and emphasize the need to consider these risks when modelling and evaluating platform dynamics.

7.2 Technology Mitigation Effects

Mobility Ecosystem:
With the use of the technologies described in Chapter 6, the service level values have improved from 70% to 73%, and the SCRI now stands at 1.83, which is a range in which the supply chain can be considered resilient.

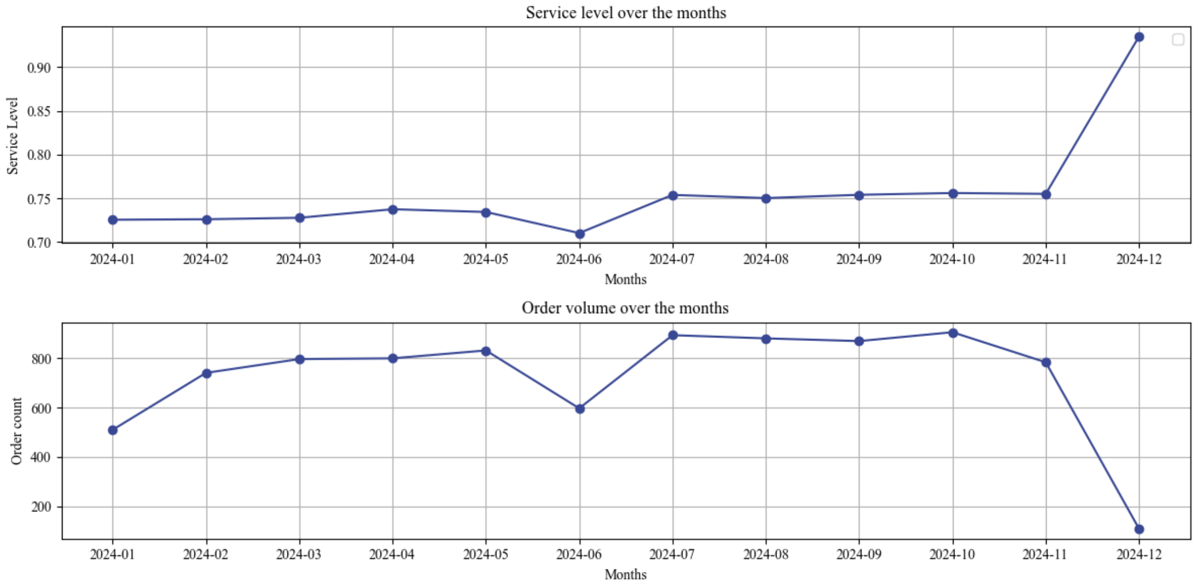


Figure 19: Service Level and Order Volume Graph for disruptive scenario in the automotive supply chain for scenario 1 after technology mitigation

Table 11: Mean Service Level and SCRI before and after technology mitigation in automotive supply chain scenario 1

Power outage	Before the technology was used	After the technology was used
Mean Service Level	70%	73%
SCRI	0,15	1,83

The trends shown in Figure 20 and Table 12 are still very similar, but it can be observed that in the first few months the service level only drops to 50%, compared to 40% in the previous process. However, the SCRI has hardly changed. With a value of 0.3, the supply chain is still not resilient, and further measures must be taken to prepare for fluctuations throughout the entire production period.

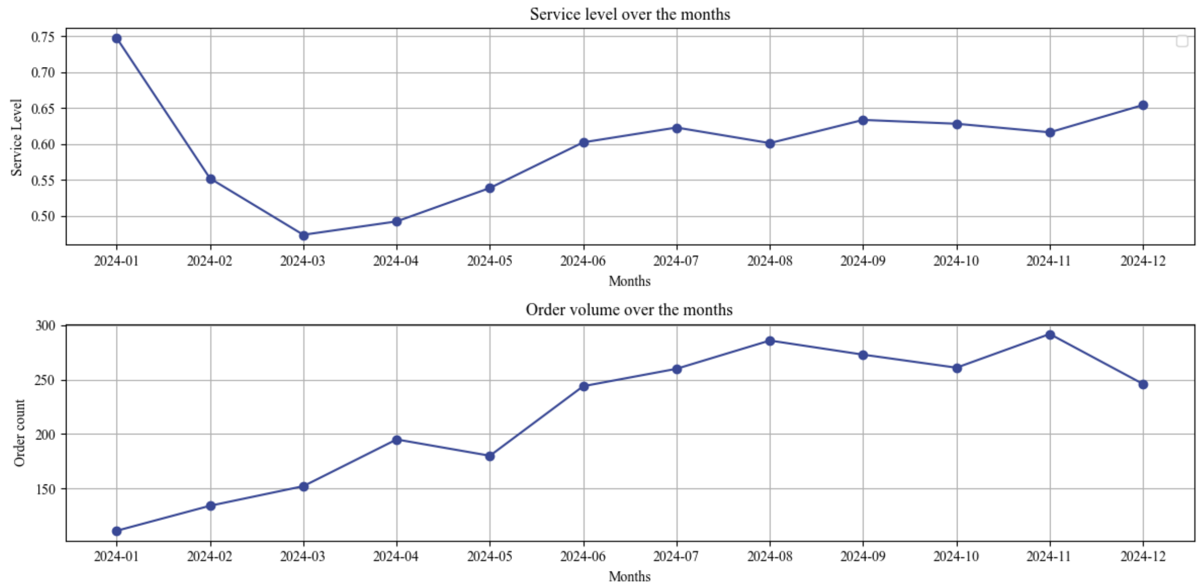


Figure 20: Service Level and Order Volume Graph for disruptive scenario in the automotive supply chain for scenario 2 after technology mitigation

Table 12: Mean Service Level and SCRI before and after technology mitigation in automotive supply chain scenario 2

Restricted availability of Energy	Before the technology was used	After the technology was used
Mean Service Level	56%	60%
SCRI	-0,1	0,3

Agri-Food Ecosystem:
After applying the technologies from Chapter 6, it became apparent that, at first glance, the service levels had hardly changed in the first scenario involving an extensive customs process. However, when looking at the SCRI, it can be observed that the value is now 1.1, which stands for a resilient supply chain. Although no significant improvements have been achieved, the supply chain has developed in the right direction and could be made even more resilient with further minor changes.

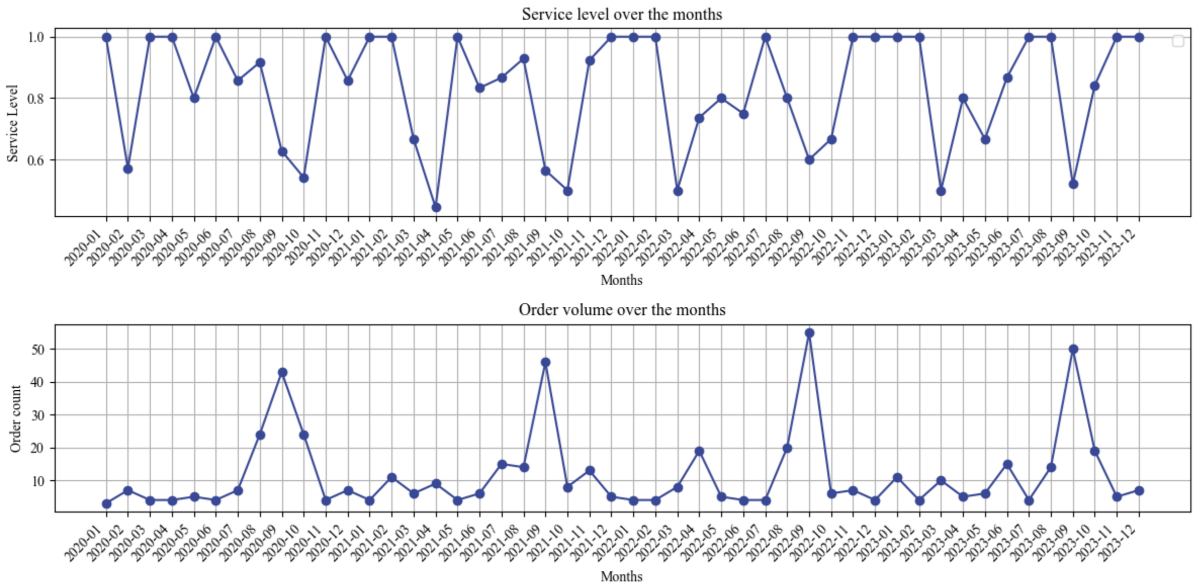


Figure 21: Service Level and Order Volume Graph for disruptive scenario in the agri-food supply chain for scenario 1 after technology mitigation

Table 13: Mean Service Level and SCRI before and after technology mitigation in the agri-food supply chain scenario 1

Extensive customs process	Before the technology was used	After the technology was used
Mean Service Level	75%	84%
SCRI	0,95	1,1

In the second scenario, which looked at reshoring, it can be seen that the selected techniques resulted in the service level only falling to 65% during the reshoring period, rather than to 60%. Although this is only a small change, it can be observed in the SCRI, which now has a value of 1.1 and classifies the supply chain as resilient, representing a significant improvement from the previous value of 0.06.

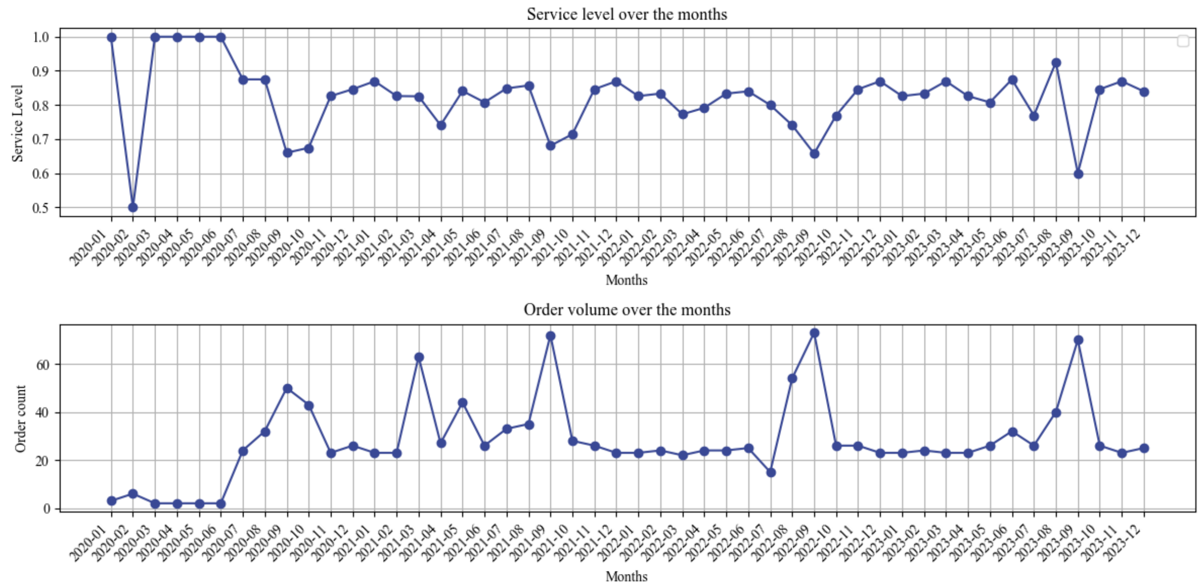


Figure 22: Service Level and Order Volume Graph for disruptive scenario in the agri-food supply chain for scenario 2 after technology mitigation

Table 14: Mean Service Level and SCRI before and after technology mitigation in the agri-food supply chain scenario 2

Rising costs for suppliers (Reshoring)	Before the technology was used	After the technology was used
Mean Service Level	82%	82%
SCRI	0,06	1,1

Textile Ecosystem:

In the scenario where the labour shortage was considered, the selected techniques enabled long-term capacity reduction from July to October. The service level improved, which is also reflected in the SCRI, which has a value of 3.7, indicating an extremely resilient supply chain.

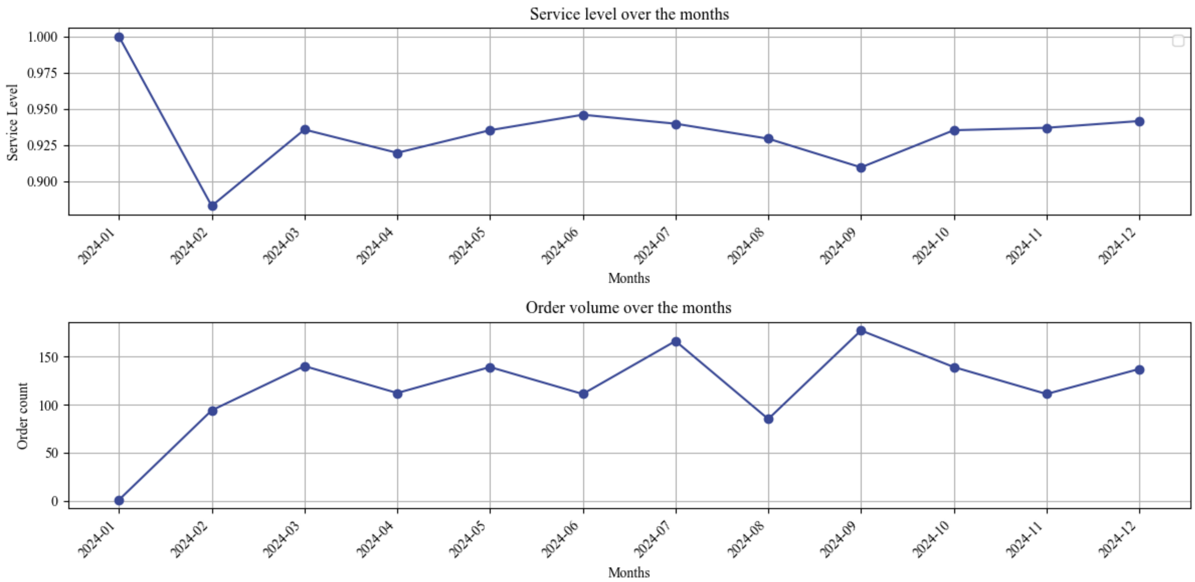


Figure 23: Service Level and Order Volume Graph for disruptive scenario in the textile supply chain for scenario 1 after technology mitigation

Table 15: Mean Service Level and SCRI before and after technology mitigation in the textile supply chain scenario 1

Worker Shortage	Before the technology was used	After the technology was used
Mean Service Level	92%	92%
SCRI	0,11	3,7

After applying the technologies described in Chapter 6, the service level could be increased from 65% to 80%, and the SCRI value could also be increased from -0.16 to 1.95, which corresponds to a resilient supply chain.

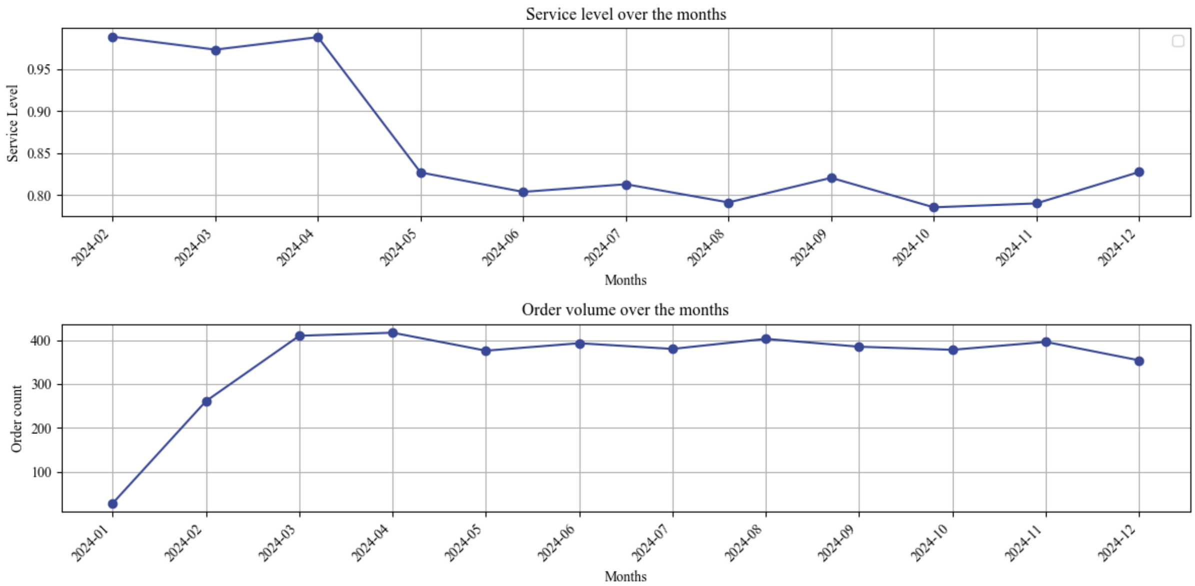


Figure 24: Service Level and Order Volume Graph for disruptive scenario in the textile supply chain for scenario 2 after technology mitigation

Table 16: Mean Service Level and SCRI before and after technology mitigation in the textile supply chain scenario 2

Outsourcing	Before the technology was used	After the technology was used
Mean Service Level	73%	86%
SCRI	-0,16	1,94

Digital Ecosystem:

In view of the disruption scenarios described in Chapter 7.1, the targeted use of technological measures to reduce risk is an essential component of systemic resilience in MaaS environments. So-called cyber resilience measures play a particularly important role here, as they directly influence both the probability of a disruption occurring and its effects. As can already be seen in Figure 15, an early and continuous increase in resilience measures (for example, from t = 2) can help to avoid critical events such as a breach in connectivity, even when the threat level is increasing (e.g., around t = 9). This allows the technological system performance to be stabilized in the long term. In addition, resilience measures also influence the trust level of users. A higher level of protection promotes trust. Figure 17 clearly shows that increasing resilience measures can raise the trust level, while only a limited increase is possible when the risk is high. Targeted measures can thus strengthen both technical robustness and user loyalty.

In summary, the development and maintenance of technological resilience strategies not only helps to prevent system failures but also serves as a means of securing trust within digital service models.

7.3 Contribution to EU Objectives

Our development of advanced simulation models for supply chain disruption mitigation and resilience enhancement represents a significant contribution to multiple key European Union policy objectives. The quantitative analysis of technology mitigation effects contributes substantially to the European Green Deal's climate neutrality objectives by enabling organizations to optimize their supply chains for reduced carbon emissions. Through predictive modelling of disruption scenarios, companies can implement more efficient logistics routes, reduce waste from supply chain failures, and transition to circular economy practices. Concerning "A Europe Fit for the Digital Age," the quantitative analysis strengthens European digital sovereignty by developing cutting-edge analytical capabilities that can set standards for supply chain management. The models incorporate advanced digital tools including artificial intelligence, Edge Computing, and blockchain technologies among others to enhance supply chain visibility and operational efficiency. This digital transformation facilitates competitiveness across sectors while addressing cybersecurity considerations through robust data protection measures embedded within the presented framework.

The models enable SMEs to compete more effectively with larger corporations by providing sophisticated planning tools previously available only to major organizations. This democratization of technology supports entrepreneurship while reducing economic inequality by strengthening the competitive position of smaller businesses within European supply chains. By identifying and analysing strategic dependencies, the models help organizations reduce vulnerabilities and minimize risks associated with critical suppliers and materials. The technology accelerates both green and digital transitions by demonstrating how sustainable practices and digital tools can improve operational efficiency. Most importantly, the models provide targeted support for SMEs in adapting to market conditions while embracing technological innovation. Finally, in alignment with the European Commission Compass objectives, the simulation models help close innovation gaps by providing start-ups and scale-ups with sophisticated analytical capabilities that promote technology adoption and business growth.

8 Conclusions and Outlook

This deliverable has demonstrated the value of a structured, scenario-based approach to assessing the impact of digital technologies on supply chain resilience across four key European industrial ecosystems (Wine production, Shoe production, Electric vehicles and Mobility as a Service). By combining scenario-based modelling, a multi-layered KPI framework, and system dynamics simulations, the work offers a robust and replicable methodology for evaluating how specific technologies can mitigate disruptions and enhance resilience under diverse stress conditions.

The main conclusion is that digital technologies, when strategically selected and contextually applied, can significantly improve the adaptive capacity, responsiveness, and robustness of supply chains. Each of the four technologies analysed in this report (edge computing, data spaces, artificial intelligence, and blockchain) demonstrated measurable improvements in resilience KPIs, including service level, recovery rate, adaptability, and visibility. These improvements were not only quantitative but also strategic, aligning with broader EU policy goals such as climate neutrality, digital sovereignty, and social inclusion.

The comparative analysis across ecosystems highlights that:

- **Edge computing** enables decentralized decision-making and operational continuity in energy-intensive manufacturing environments, such as electric vehicle production, even under conditions of energy scarcity or grid instability.
- **Data spaces** enhance cyber resilience in digital ecosystems like Mobility-as-a-Service (MaaS) by enabling secure, federated data exchange and minimizing systemic risk through decentralized governance.
- **Artificial intelligence** supports strategic foresight and operational agility in geopolitically sensitive supply chains, such as wine production, by optimizing sourcing, forecasting, and scenario planning.
- **Blockchain** reinforces transparency, traceability, and ethical compliance in socially complex supply chains, such as footwear manufacturing, thereby supporting human-centric resilience and regulatory alignment.

The use of the Supply Chain Resilience Index (SCRI) as a composite metric proved particularly valuable in quantifying the systemic impact of disruptions and the effectiveness of mitigation strategies. The SCRI enabled a consistent comparison across ecosystems and scenarios, offering a clear benchmark for resilience performance before and after technology deployment.

These findings validate the hypothesis that digital technologies, when contextually deployed, can serve as powerful enablers of resilience, not only improving operational performance but also aligning with broader EU policy goals related to sustainability, digital transformation, and industrial autonomy.

Beyond the technical findings, this deliverable also contributes methodologically by:

- Demonstrating the value of ecosystem-specific modelling to capture the unique dynamics and vulnerabilities of different industrial sectors.
- Providing a replicable framework for mapping technologies to resilience enablers and KPIs, which can be adapted for other sectors or future disruptions.
- Highlighting the importance of aligning technological innovation with EU strategic priorities, ensuring that resilience-building efforts also contribute to long-term sustainability, competitiveness, and social cohesion.

The methodology and insights developed in this deliverable lay the groundwork for future work in WP3, where the focus will shift toward identifying technological gaps, assessing sustainability KPIs in greater depth, and refining the models with real-world data. The approach also offers a decision-support foundation for SMEs and policymakers seeking to prioritize investments in resilience-enhancing technologies.

The work presented in the current document will be further developed in Deliverable 3.1 - Gaps analysis and opportunities recommendations. Indeed, D3.1 will provide a map of open technological gaps per ecosystem, their application, level of penetration and potential. For this, a cross-comparison of the identified technologies in D2.2 and the fields of application in the four selected ecosystems will be performed. This will showcase the degree of maturity and impact of applying the above technologies. The result will be a map identifying open gaps based on the examination of the technologies per ecosystem, their application, level of penetration and potential.

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10 Annexes

Annex 1. Relevance of the Resilience KPIs for the industrial ecosystems

The following table indicates the relevance of the resilience KPIs according to different colors as follows:

- Relevance Very High – Orange
- Relevance High – Yellow
- Relevance Medium – Green
- Relevance Low – Blue
- Relevance Very Low/No relevance - White

	Indicator	Wine production	Shoe production	Electric vehicles	Mobility as a Service
1	**Adaptability (Ad)**	Essential for adjusting operations to weather changes, harvest fluctuations, and shifts in demand	Important for responding to fashion trends, fast production cycles, and shifting consumer preferences	Critical due to technological advancements, regulatory changes, and supply chain disruptions (e.g., semiconductor shortages)	Required to adapt to demand fluctuations, regulatory changes, and technology updates
2	**Supplier Replacement Rate (SRR)**	Important for replacing suppliers of key raw materials (e.g., grapes, bottles, cork)	Essential due to frequent outsourcing; supplier disruptions can impact production timelines	Very critical since EV supply chains are highly dependent on specific suppliers for batteries, semiconductors, and rare minerals	Less relevant, as digital services rely more on software providers and cloud services rather than traditional suppliers
3	**Demand Change Response (DCR)**	Necessary to manage fluctuating seasonal demand and consumer preferences	Highly relevant for fast-changing fashion cycles and trend-driven production	Important due to increasing adoption rates and demand for different EV models	Essential to manage peak-hour demand, seasonal fluctuations, and changing mobility trends
4	**Technological innovation (TI)**	Somewhat relevant for vineyard automation	Critical for new materials and manufacturing processes	Very critical for battery and drivetrain advancements	Essential for platform development
5	**Expected Customer**	Important to ensure timely distribution,	Critical for meeting retailer deadlines and	Very important as delays can impact	Less relevant for software services, but important for fleet

	Indicator	Wine production	Shoe production	Electric vehicles	Mobility as a Service
	service level (ESC)	especially for export markets	avoiding stock shortages	entire vehicle production lines	availability in real-time operations
6	**OTIF (On Time in Full)**	Critical for ensuring deliveries to distributors and retailers occur as planned, especially for export markets and seasonal demand spikes.	Highly relevant for meeting retailer deadlines, particularly in fast fashion where missing a delivery window can lead to lost sales	Extremely critical, as delays in component deliveries (e.g., batteries, semiconductors) can halt vehicle production lines. Impacts overall supply chain efficiency due to just-in-time manufacturing practices.	Less relevant - adapted to measure service availability (e.g., ensuring vehicles or transport services are available on time for customers)
7	**Cooperation & Knowledge sharing (C&KS)**	Needed for partnerships with suppliers, distributors, and retailers	Important in managing design collaboration and supplier relationships	Crucial due to joint ventures and supplier collaborations (e.g., battery supply agreements)	Essential for coordinating with transport providers, government agencies, and software developers
8	**Density (D)**	Less relevant	Moderately relevant for supplier relationships	Very relevant due to intricate supplier networks	Highly relevant for platform-based service ecosystems
9	**Node complexity (ND)**	Moderately important, especially for export logistics	Relevant due to distributed manufacturing and retail networks	Highly relevant due to complex global supply chains	Important for managing digital service providers and transport partners
10	**Visibility (V)**	Necessary for monitoring grape supply, fermentation stages, and distribution logistics	Helps track suppliers, inventory levels, and order fulfilment	Essential for tracking components across a highly complex global supply chain	Important for real-time fleet tracking, route optimization, and demand forecasting
11	**Team Cross-Training Level (TCTL)**	Moderately relevant for operational flexibility	Important for adapting to seasonal workforce needs	Relevant for training workers in multiple production areas	Less relevant
12	**Flow complexity (FC)**	Important due to returnable bottle flows and recycling initiatives	Relevant for managing returns, recycling programs, and multiple	Highly complex due to forward and reverse logistics in battery recycling	Not relevant

	Indicator	Wine production	Shoe production	Electric vehicles	Mobility as a Service
			distribution channels		
13	**Stock level of high-risk parts (SLHRP)**	Important for packaging materials (e.g., bottles, corks), but not a major issue	Relevant for key materials like leather, rubber, or synthetic fibers	Extremely important for lithium batteries, semiconductors, and rare earth metals.	Not relevant
14	**Geographical risk (G)**	Important for sourcing raw materials, especially in regions affected by climate change	Relevant for managing risks from offshore suppliers in Asia and other key manufacturing hubs	Very critical due to dependence on minerals sourced from specific regions (e.g., lithium, cobalt)	Not very relevant since software operations are mostly cloud-based and decentralized
15	**Volume flexibility supplier (VF)**	Needed for dealing with seasonal harvest variability	Critical for adjusting production levels based on market demand	Important for dealing with supply constraints, particularly for batteries	Not relevant
16	**Expected Net Present Value (ENPV)**	Useful for assessing long-term financial viability in a volatile market	Important for evaluating profitability amid changing trends and consumer demand.	Very relevant due to high capital investments and long payback periods	Critical for measuring the financial sustainability of digital platforms and service expansions
17	**Agility (Ag)**	Less relevant since production is seasonal and cannot be easily accelerated	Important for quickly launching new collections in response to trends	Very important for rapidly adjusting production lines to new regulations or materials	Essential for adjusting to new urban mobility trends and regulations
18	**Single sourcing with single plant (SS)**	Less relevant since wine is mostly produced regionally	Important risk factor for brands relying on a single major manufacturer	Very critical due to reliance on single battery or semiconductor suppliers	Not relevant
19	**Recovery Rate (RR)**	Important for recovering from extreme weather events, disease outbreaks, or supply shortages	Necessary for dealing with supplier failures, factory disruptions, or shipment delays	Necessary for dealing with supplier failures, factory disruptions, or shipment delays	Important in case of cyberattacks, service outages, or regulatory shifts
20	**Supply Chain Resilience Index (SCRI)**	Moderately important due to seasonal dependencies and climate risks	Highly important given complex global sourcing, fast-changing fashion cycles,	Extremely critical due to strategic material dependencies, technological	Important for service continuity and platform reliability, though less supply chain dependent

Indicator	Wine production	Shoe production	Electric vehicles	Mobility as a Service
	affecting grape supply and distribution networks	and dependency on multiple supplier tiers across different geographical regions	complexity, and vulnerability to component shortages that can halt entire production lines	than physical manufacturing sectors

Annex 2. Operational KPIs and their relevance for the industrial ecosystems

The following table indicates the identified Operational KPIs and their relevance for the industrial ecosystems according to different colours as follows:

- Relevance Very High – Orange
- Relevance High – Yellow
- Relevance Medium – Green
- Relevance Low – Blue
- Relevance Very Low/No relevance - White

KPI	Description	Wine production	Shoe production	Electric vehicles	Mobility as a Service
Production Lead Time	Time taken from order to finished product delivery	Critical for managing fermentation and aging processes	Important for batch production efficiency	Essential for reducing time-to-market	Less relevant, unless considering vehicle deployment
Cycle Time	Time to complete one full process cycle in production	Key for bottling and packaging	Helps optimize assembly lines	Critical for manufacturing and component assembly	Important for service response time
Capacity Utilization (%)	Ratio of actual production to maximum capacity	Ensures efficient vineyard and production usage	Helps optimize factory operations	Critical for scaling production efficiently	Ensures fleet utilization and availability
First Pass Yield (FPY) (%)	Percentage of products manufactured correctly the first time, without rework	Important for reducing defective batches	Helps control quality in manufacturing	Essential for reducing scrap and defect costs	Not directly relevant
Order Fulfillment Rate (%) [Service Level]	Percentage of customer orders delivered on time and in full.	Critical for maintaining supply chain consistency	Key for retail and wholesale distribution	Helps manage large-scale production logistics	Ensures service reliability for users
Inventory Turnover Ratio	Number of times inventory is sold and replaced in a given period.	Lower turnover due to aging process.	High turnover required to keep up with fashion cycles	Moderate turnover depending on demand	Applies to spare parts inventory

KPI	Description	Wine production	Shoe production	Electric vehicles	Mobility as a Service
Stockout Rate (%	Percentage of items out of stock when demanded.	Critical for maintaining distribution reliability	Important to avoid lost sales	Crucial for supply chain stability	Applies to vehicle fleet availability
Supplier Lead Time	Average time taken by suppliers to deliver raw materials or components.	Relevant for bottle and packaging supply	Important for sourcing materials (leather, textiles)	Critical for semiconductor and battery components	Applies to infrastructure or software updates
Perfect Order Index (%)	Percentage of orders delivered on time, complete, and error-free.	Ensures consistency in distribution	Prevents disruptions in retail supply	Critical for automotive logistics	Important for customer satisfaction
Overall Equipment Effectiveness (OEE) (%)	Evaluates production efficiency by combining availability, performance, and quality.	Ensures efficient use of production equipment	Optimizes factory operations	Reduces downtime in automated production	Not relevant
Return Rate (%)	Percentage of products returned due to defects or dissatisfaction.	Relevant for quality issues in distribution	Important for e-commerce and retail returns	High importance due to warranty and safety concerns	Applies to refund rates in service issues
Backorder Rate (%)	Percentage of orders that cannot be fulfilled due to inventory shortages.	Important for maintaining supply consistency	Key for fast-moving products	Avoiding supply chain disruptions is crucial	Ensures service availability
Production Downtime (%)	Percentage of time production is halted due to machine breakdowns or shortages.	Impacts bottling and fermentation stages	Critical for meeting seasonal demand	High impact due to automation dependency	Not relevant
Customer Satisfaction Score (CSAT)	Measures customer perception of product/service quality.	Affects brand reputation	Crucial for fashion and retail	Drives customer loyalty	Key for service adoption

Annex 3. Sustainability KPIs and their relevance for the industrial ecosystems

The following tables indicate the identified Sustainable KPIs and their relevance for the industrial ecosystems according to different colours as follows:

- Relevance Very High – Orange
- Relevance High – Yellow
- Relevance Medium – Green
- Relevance Low – Blue
- Relevance Very Low/No relevance - White

Environmental KPIs	Description	Wine production	Shoe production	Electric vehicles	Mobility as a Service
CO2 emissions reduction in kt	Key for tracking decarbonization efforts	Indirect emissions via logistics and packaging	Footprint of synthetic materials and production	Critical for battery supply chain and lifecycle	Key metric for evaluating decarbonization of transport
Energy consumption in kWh	Tracks energy efficiency and helps identify opportunities for energy savings across operations	Processing and refrigeration	Production machinery	High energy use in battery and vehicle production	Energy-intensive data centres and fleet operations
Water usage in metric tons	Measures the environmental impact related to water consumption and supports water conservation strategies	Water-intensive agriculture	Tanning/dyeing stages may consume water	For production, cooling systems	Vehicle washing
Waste reduction in cubic meters	Assesses efficiency in waste management and contributes to circular economy goals	Waste from grape pressing, packaging	Production waste, off-cuts	Hazardous and e-waste from production	Digital/operational waste, batteries if e-scooters used
Plastic reduction in metric tons	Tracks efforts to minimize plastic usage and pollution, aligning with global sustainability targets	Bottling and packaging	Materials and packaging	Plastics in interiors, battery casings	Vehicle parts, user accessories
Material efficiency in material input per unit of service (MIPS)	Measures resource efficiency, essential for reducing material footprints	Glass, cork, energy inputs	High material intensity in production	Complex, high-value materials	Hardware, fleet components

Noise pollution in decibels	Monitors environmental noise levels, important for compliance and minimizing impact on surrounding communities	Limited impact	Factory level	Urban vehicle impact	Urban noise exposure from vehicles and hubs
Compliance with chemical safety requirements	Ensures safe handling, storage, and disposal of hazardous materials to protect workers and the environment	Use of agrochemicals in vineyards	Solvents, dyes, adhesives	Battery chemicals, paints	Maintenance of shared fleets
Compliance with environmental standards	Verifies adherence to national and international regulations (e.g., ISO 14001) to maintain environmental integrity	Agriculture and production	Often part of certifications	Essential for EV sustainability claims	For operations and emissions control
Number of suppliers audited against environmental standards	Indicates the extent of environmental due diligence applied throughout the supply chain	Packaging and logistics	Material sourcing	Battery minerals, electronics	Digital platform and hardware suppliers
Circularity index	Percentage of recycled/reused materials	Bottle reuse, organic waste valorization	Leather and textile reuse	Battery reuse and second-life applications	Shared mobility as circular model
Supply Chain Carbon Intensity	CO_2 emissions per unit of revenue or production	Localized supply chain	Textile sourcing impacts	Key to sustainability reporting	Emissions per trip/user must be optimized
Supply Chain Transparency	Traceability percentage (how much of the supply chain is transparent and monitored)	Local vs global sourcing	Tracing materials and labor	Essential for EV compliance and CSR	Tracks digital, fleet, and platform sourcing

Social KPIs	**Description**	**Wine production**	**Shoe production**	**Electric vehicles**	**Mobility as a Service**
Compliance with Code of Conduct (organizational, UN global conduct)	Ensures ethical business practices and sustainability commitments	Worker rights in agriculture	Labor rights and safety	Global ethical sourcing	Gig economy ethics, user data
Share of suppliers audited against CSR standards	tracking responsible sourcing and supply chain ethics	Packaging/logistics	Supply chain ethics	Responsible sourcing	Ensuring fair labor and data practices
Compliance with safety and security requirements	Manufacturing industries have strict safety regulations	Field safety	Factory standards	Battery and assembly risks	Vehicle/platform worker safety

Work-life balance, working hours	Reflects employee well-being, operational sustainability, and social responsibility efforts	Seasonal labour concerns	Repetitive work intensity	Factory labour management	Addresses gig economy concerns
People development, learning hours	Tracks investment in workforce skill development. Particularly important in industries transitioning to digitalization and automation	Traditional industry, evolving slowly	Upskilling in automation	Key for high-tech transition	For platform and fleet managers
Community engagement, volunteering hours	Contributes to social responsibility	Often community-linked vineyards	Local production support	Stakeholder buy-in essential	Public transport alternatives, community pilots
Share of diverse suppliers in the supply base	Supports supplier diversity, a key component of sustainable procurement	Niche producers	Sustainability-driven brands	Promoting tech diversity	DEI essential in inclusive platforms
Diversity, equity, and inclusion (DEI) percentage	Tracks workforce inclusivity, affecting corporate reputation and compliance.	Family-run businesses	Workforce diversity in global brands	Important for corporate image	Core to platform fairness
Consumer Behavior Impact	How shifts in customer preferences, sustainability awareness, and regulatory trends influence supply chain demand and adaptability	Strong influence on demand (organic, local)	Trends drive product demand	EV adoption shaped by public perception	Directly linked to MaaS growth and design
Customer Sustainability Perception	Percentage of customers perceiving a company as sustainable.	Influences brand loyalty	Key for market positioning	Shapes adoption and brand image	Impacts user retention and adoption rate

Business KPIs	Description	Wine production	Shoe production	Electric vehicles	Mobility as a Service
Working capital	Ensures financial stability and operational continuity	Seasonal cash flow	Inventory-driven	High investment intensity	Cash-heavy, asset-light model
Debt	More relevant for industries that require high capital investment	Varies by producer scale	Manufacturin	High CAPEX industry	Fleet leasing, infrastructure funding

			g loans common		
Turnover	Measures business growth and supply chain performance	Linked to seasonal exports	Volume-based model	Key to scaling EV production	User growth and platform expansion
Overall profitability	Assesses the financial success of sustainability strategies and supply chain operations	Influenced by climate and market	Cost-sensitive industry	Tied to subsidies, cost efficiency	Driven by fleet utilization and scale