Ref. Ares(2025)9323413 - 30/10/2025

SARIL

Sustainability And Resilience for Infrastructure and Logistics networks

D3.4 General solutions for the resilience of logistic networks

Deliverable Number	D4.2
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Due/delivered Date	31.10.2025
Reviewed by	Miltiadis Kontogeorgos, Jan Tore Pedersen, Benjamin Lickert
Dissemination Level	PU
Version of template	1.2

Start Date Project: 2023-06-01 Duration: 36 months Project ID: 101103978

This project has received funding from the Horizon Europe program of the European Union under grant agreement ID 101103978.

Disclaimer:

The presented work was performed in context of the Horizon Europe project SARIL which is funded by the European Union under grant agreement ID 101103978. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them. More information on the project can be found under https://saril-project.eu.

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Document revisions

Revision	Date	Comment	Author
V0	10.10.2025	First complete version	Paula López Arévalo
V1	10.10.2025	Version with revision comments	Miltiadis Kontogeorgos, Jan Tore Pedersen
V2	27.10.2025	Reviewed version	Paula López Arévalo
V2	28.10.2025	Security and Quality Review	Benjamin Lickert
V3	30.10.2025	Final version	Paula López Arévalo

Executive Summary

Logistics networks face more frequent and intensive disruptions due to miscellaneous hazards (e.g. floodings, fire) due to climate change. Therefore, measures to improve the logistics sector's resilience and ecological footprint must consider the effect of these disruptions. The SARIL project (Sustainability and Resilience for Infrastructure and Logistics networks) aims for an encompassing resilience understanding of logistical operations incorporating green aspects. It is part of the European Union’s Horizon Europe research and innovation programme under grant agreement No 101103978, included in the call "HORIZON-CL5-2022-D6-02-07[1] - New concepts and approaches for resilient and green freight transport and logistics networks against disruptive events (including pandemics)".

This document is based on D3.3 “Green Resilience Assessment Results” (GRA) and uses the final results from the project tools simulations and their GRA analysis to obtain common patterns, shared KPIs and measures, so that general and specific solutions and measures regarding green resilience can be identified. The GRA methodology is previously defined in D2.1 “Survey of methodologies for resilience management” (SARIL project D2.1, 2024), D2.2 “Integrated Assessment Framework for the SARIL Case Scenario” (SARIL project D2.2, 2024) and D3.1 “Enhanced models and tools” (SARIL project D3.3, 2025).

Additionally, this document translates the scenario-specific results developed in earlier stages into a coherent, generalizable framework. Building on scenario-based analyses at regional, national, and European scales, the deliverable demonstrates that resilience can be quantified, compared, and generalized through standardized indicators of cost, time, and CO_2 emissions. D3.4 translates complex simulation data into transferable, data-driven solutions that balance operational robustness with environmental performance. The results confirm strong interdependencies between resilience and sustainability—showing that adaptive, well-designed mitigation strategies can simultaneously reduce disruptions and lower emissions, but also, that when this alignment is not achieved, having access to clear, data-driven insights becomes crucial, enabling managers to make informed decisions that balance operational, economic, and environmental factors. Moreover, the integration of business intelligence dashboards ensures that these analytical insights are directly usable for decision support, enabling stakeholders to test, visualize, and prioritize interventions across diverse contexts.

The results of this report will enter the work of Task 5.1 (that considers recommendations to be derived from the project work) as well as the work of Task 5.2 (that considers business models).

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[1] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d6-02-07

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List of Acronyms

Acronym	Definition
BI	Business Intelligence
D#	Deliverable #
DII	Disruption Information Interface
EDA	Exploratory Data Analysis
EIA	Environmental Impact Assessment
GIS	Geospatial Information Systems
GRA	Green Resilience Assessment
KPI	Key Performance Indicator
LCA	Life-Cycle-Analysis
SDGs	sustainable development goals
T#	Task #
WP#	Work Package #

1 Introduction

This deliverable examines and compares resilience patterns across the various scenarios explored within the SARIL project. Building on the simulation-based resilience assessment presented in D3.3 (SARIL project D3.3, 2025), it applies business intelligence (BI) tools to systematically analyze the results. The goal is to identify common patterns, shared key performance indicators (KPIs), and effective measures that shape the resilience of logistics networks under diverse disruptive conditions.

By integrating and synthesizing findings across the regional, national, and European scenarios, D3.4 aims to move beyond scenario-specific insights. Its purpose is to define a set of general solutions and strategies that enhance the green resilience of transport and logistics networks at all levels. These overarching solutions are designed to complement—rather than replace—context-specific measures, enabling stakeholders to address both systemic vulnerabilities and localized challenges.

Through this comparative and integrative approach, D3.4 advances SARIL's broader mission of providing evidence-based guidance for shaping logistics networks that are resilient, adaptive, and environmentally sustainable.

The document presents the following parts:

- Section 2, SARIL project Overview. This section's goal is to provide all the necessary background about SARIL project to understand the development presented. It first presents SARIL tools in section 2.1, then in section 2.2 how these tools are connected within different scenarios and finally the work developed in previous deliverables about the Green Resilience Assessment.
- Section 3, State of the art. It presents a State-of-the-art review of the two areas of the study: the GRA (section 3.1) and the Business Intelligence tools (Section 3.2).
- Section 4, Resilience Patterns Generalization. This section presents the methodology and results applied and obtained. The Methodology section and Results section are both divided into GRA developments and the Resilience platform, as results of the BI techniques application.
- Section 5, Final Remarks and Conclusions. It discusses the results presented in section 4.2 and provides a series of conclusions.

2 SARIL Project Overview

The SARIL Project is an EU-funded initiative that redefines how Europe's transport and logistics systems prepare for and respond to disruptions. Moving beyond traditional approaches that focus only on recovery irrespective of environmental costs, SARIL integrates resilience with environmental sustainability—promoting a vision of "green resilience" that safeguards both critical infrastructure and the environment.

This section provides a brief overview of the tools developed within the SARIL project and the scenarios considered in their application. It summarises the key functionalities of each tool, as well as the main disruption scenarios analysed to demonstrate their use in assessing the resilience and sustainability of European transport and logistics networks.

2.1 SARIL tools

To fulfil SARIL's objectives, the project integrates a suite of advanced tools, which detailed information can be found in D3.1 (SARIL project D3.1, 2024), to assess and enhance the resilience of Europe's transport networks under various disruptive conditions. These include:

- **ASTROIT Tool:** ASTROIT (Agent-based SimulaTion for Resilience Of Intermodal Transportation) is an agent-based simulation tool that models each cargo unit as an individual agent capable of determining its optimal route from origin to destination. Route selection is based on predefined cost preferences, which may include operational costs per kilometre, CO_2 emissions, and travel duration.
- **Vulnerability and Traffic Tool:** This tool integrates advanced traffic modelling with comprehensive vulnerability and risk analyses. Due to the complexity of these features, it requires substantial computational resources and extensive data. It enables infrastructure managers and public authorities to make data-driven decisions, supporting the optimisation of risk management strategies and budget allocation.
- **Scour Monitoring for Decision Support Tool:** Designed to enhance the resilience of bridge networks, this tool assesses the structural reliability of bridges by utilising Structural Health Monitoring data. It combines this information with analyses of both direct and indirect costs. By applying a risk-based methodology, the tool supports infrastructure managers in making informed decisions during flood events—using real-time data on structural conditions and bridge capacity to withstand flooding.
- **Natural Hazard Maps Tool:** This tool identifies and locates vulnerable areas surrounding road and railway infrastructure, aiding in vegetation and risk management by integrating geospatial and remote sensing data with climatic and historical hazard information. In SARIL, forest fire risk maps are simulated for potential fire spread, supporting proactive hazard mitigation. The tool can consider other natural hazards as well.
- **Traffic Simulation Tool:** The Traffic Simulation Tool analyses the impacts of extreme events on transport networks. Initially developed to model flood disruptions, it was later adapted under the SARIL project to address fire-related events. Built on the open-source platform SUMO (Simulation of Urban Mobility), the tool simulates traffic flows at an aggregate level, focusing on interactions between groups of vehicles rather than individual movements.
- **Route Attributes – Energy Module:** This module estimates energy or fuel consumption, and emissions (CO_2 and NO_x) based on the transport network, road characteristics, and vehicle type. Its user-friendly interface allows users to select origin and destination points on a map,

define vehicle characteristics, and specify driving styles, enabling accurate and flexible emission and energy assessments.
- **Disruption Information Interface (DII):** The DII sits at the core of the SARIL tool architecture (D3.2 (SARIL project D3.2, 2025)), serving as the project's central data hub. It collects and processes inputs from diverse data-generation tools, generates disruption-related outputs, and delivers them to downstream processing and analysis modules—ensuring efficient data exchange and seamless integration across the entire system.

Two of the SARIL tools (Vulnerability and Traffic tool and Traffic simulation tool) do traffic simulations through different types of software (SUMO and TransCAD) ensuring the flexibility of the approaches, not only to different locations or scenarios, but also to their interconnection with other tools outside of the project scope.

2.2 SARIL scenarios

At its core, SARIL develops a holistic modelling framework for the European transportation network, linking three interconnected scenarios across different geographical scales. These scenarios were defined in D1.1 "Scenario cases definition" (SARIL projetct D1.1, 2023):

- **Regional**: examining regional challenges in Italy driven by floods and cyber-attacks;
- **National**: analyzing national-level risks in Spain and Portugal shaped by climate-related hazards;
- **European**: addressing cross-border disruptions including regional conflicts and prolonged global events that reshape freight flows between Asia and Europe.

This integrated approach enables a consistent assessment of risks and responses across diverse locations and types of crises.

Regional Scenario

Within the regional scenario, the **Vulnerability and Traffic Tool** and the **Scour Monitoring for Decision Support Tool** are employed to evaluate network performance during flood events.

This regional analysis focuses on the transport network surrounding the Mincio River near Mantua, Italy, with particular emphasis on highways and state roads. It examines three main aspects:

- **Bridge vulnerability**: evaluating the risk of structural damage and functional disruption under varying flood intensities;
- **Road segment susceptibility**: analysing the likelihood of road closures and their impacts on regional connectivity caused by riverine flooding; and
- **Bridge scour effects:** examining how sediment erosion around bridge foundations during floods can compromise their structural integrity.

The **Vulnerability and Traffic Tool** supports strategic planning by evaluating bridge and road vulnerabilities, traffic disruptions, and the associated indirect economic losses. Meanwhile, the **Scour Monitoring for Decision Support Tool** provides real-time information during flood events, guiding operational decisions such as the need for bridge closures. Together, these tools deliver a comprehensive understanding of both long-term vulnerabilities and immediate flood impacts.

The analysis of the regional scenario starts of the study of the base-case scenario: the normal behaviour of the area of study without any disruption. Then the disrupted scenario is analyzed, in this scenario, the disrupted case refers to the traditional response to flooding events: closure of all bridges affected. Finally, different mitigation cases are studied, this mitigation cases respond to different closure and opening configurations of the bridges of study.

The analysis of the three mitigation cases using the Vulnerability and Traffic Tool reveals a clear correlation between the extent of asset damage, traffic congestion levels, and indirect economic losses, highlighting the critical importance of targeted mitigation and resilience-building interventions. Furthermore, when the Scour Monitoring for Decision Support Tool is applied to bridges prone to local scour, the results show that traditional blanket closure strategies across the network are often suboptimal. Instead, targeted, data-driven management approaches can significantly reduce both infrastructure damage and associated economic losses.

National scenario

In the national scenario, the **Natural Hazard Maps Tool** and the **Traffic Simulation Tool,** used in conjunction with the **Route Attributes – Energy module** and **DII**, are employed to analyse how transport systems respond to climate-related disruptions. This scenario focuses on the cross-border transport corridor connecting northern Portugal and the Galician region of Spain, specifically examining the road logistics network between Porto and Vigo. The analysis considers natural hazards (like forest fires) affecting key segments of the road network as the primary disruptive events.

For this analysis critical roads were identified, so the roads which serve as key connectors are the main assets of the analysis. The Disruption Information Interface (DII) was used to exchange data between the Natural Hazard Maps and the Traffic simulation tool. Data of regions endangered by fire were generated in the Natural Hazard Maps tool and sent through the DII to the operator of the Traffic simulation tool. Hazard maps were used to pinpoint the most vulnerable segments. After this analysis two different locations were selected for in-depth analysis:

- The A-55 motorway, which connects Vigo (Galicia) with the Portuguese border.
- The AP-9, the main transportation axis of Galicia’s Atlantic corridor.

This scenario comprises a base case with the undisrupted behaviour of the area of study. This scenarios studies two different disrupted cases: forest fires in the two aforementioned locations. As mitigation cases fire breaks, forest mass management and early warning systems are used as mitigation and adaptation measures.

The evaluation of two fire disruption scenarios reveals a high vulnerability of the network to fire-induced closures along strategic corridors, which lead to significant operational disruptions. Additionally, the findings show that when multiple critical sections are simultaneously affected, the network exhibits limited rerouting capacity, resulting in heightened congestion and inefficiencies. The results emphasize the need to integrate preventive mitigation strategies with adaptive digital solutions.

European scenario

The European case scenario is used to assess how the inner European transport flow reacts to global events (e.g. war in the European neighbourhood), and other events with long-term impacts, that cause disruptions along the line of freight flows from Asia to Europe. This scenario applies **ASTROIT Tool** and the **Route Attributes – Energy Module**, in collaboration with the **Disruption Information Interface (DII).** This tool combination makes it possible to conduct a resilience assessment of complex disruptions, which considers both the overall resilience of the network, and the CO_2 emissions caused by the disruptions. The European scenario uses a freight transport network covering part of west, central and east Europe.

The base case scenario represents the normal behaviour of the project logistic providers: CSL and GW during September 2024. This normal behaviour already includes the effects of Ukraine war. The disrupted case adds to the analyses the disruption caused by a strike in Hamburg harbour, which stops any cargo approaching Europe by sea route to enter the discussed freight network through Hamburg harbour for a time span of two weeks. The disrupted case assumes (based on discussions with logistic providers) that this disruption would shift the cargo over Rotterdam and Bremerhaven. Different mitigation cases are analyzed:

- Introducing E-trucks in South Germany and Austria.
- Using trains to support freight transport from Istanbul.
- Higher percentage of deliveries which can shift to another mode.

The disruption case clearly demonstrated the cascading effects caused by a strike in Hamburg on the logistics network of the European network, leading to higher CO_2 emissions, operational costs, and delivery times. The introduction of e-trucks into the simulated logistics network in southern Germany and Austria reduced CO_2 emissions from transportation, although total operational costs increased due to the higher expenses associated with these vehicles. When only trains were used on routes from Istanbul to Europe, emissions decreased, but operational costs and delivery times rose slightly, as freight transport via trains is slower than via trucks. Since operational costs and delivery times are key priorities for logistics companies, reducing the cost of eco-friendly vehicles is essential to make them a viable alternative in the sector. Finally, increasing the percentage of time-critical deliveries that can be shifted to other transport modes resulted in slight reductions in both CO_2 emissions and operational costs, with only a minimal increase in delivery times. Although the differences were small, this was the only measure that simultaneously reduced emissions and costs without significantly affecting efficiency, highlighting the importance of a network with balanced cargo distribution and the potential of synchro-modal approaches.

Summary

Table 1 summarises some of the key points from the different SARIL scenarios:

- Geographical area covered by the scenario.
- The type of transport modes analysed.
- The analysed disruptions.
- The mitigation approaches applied.
- The output information received from T3.3 and used for this deliverable developments.
- How the GRA dimension is taken into account in the different scenarios.

Table 1: Summary of scenarios information.

	Regional Scenario	**National Scenario**	**European**
Area covered	Network surrounding the Mincio River in eastern Italy.	The National Scenario covers the cross-border transport corridor connecting the north of Portugal and the Galician region of Spain.	European Network.
Type of transport mode	Road transport.	Road transport.	Multimodal.
Disruptions	Flooding.	Closure of roads due to natural hazards: - Fire at A-55 - Fire at the Access Vigo (AP-9)	Disruptions: - War in Ukraine - Strike in Hamburg Port
Mitigation measures	Different combinations of bridges closure configurations.	- Firebreaks - Forest mass management - Early warning digital system	- Introducing E-trucks in South Germany and Austria - Trains from Istanbul - Higher percentage of deliveries which can shift to another mode
Output information	Regarding traffic simulations outputs, providing per each network arc information relative to: - Daily flows - Flow speed - Daily travel time - Volume-to-capacity (VOC) ratio. Regarding the bridges maintenance: - Bridges probability of failure - Risk analysis for the different cases - Costs related to the different cases	- Natural Hazard Maps with fire maps with information regarding fire risk and risk probability regarding wind and rain. - Fire propagation Maps with the calculated arrival time of fire. - GeoJson files with network information. - GeoJson files with simulation outputs: position and speed of vehicles with time.	Simulation outputs with network nodes and edges information per timestamp regarding: - Relation between vehicles, nodes and edges. - Vehicles position. - Nodes capacity and number of vehicles. - Edges capacity and number of vehicles.
Green Resilient Assessment	A better knowledge of the possible options to manage the response to the disruptions and the most optimized solution for the traffic management improves the resilience of the network decreases waits and longer rerouting which causes higher negative impact of the environment.	The Energy Module was applied on the European scenario obtaining relevant parameters relative to duration, costs and CO_2 emissions. Also, an optimal management of the networks and their traffic improves the resilience of the network and decreases waits and longer rerouting, reducing the negative impact on the environment.	The Energy Module was applied on the European scenario obtaining relevant parameters relative to duration, costs and CO_2 emissions

2.3 SARIL’s Green Resilience Assessment

As part of the SARIL project, several activities and documents have been developed to date, all with the common goal of creating tools and methods for assessing and strengthening the resilience and sustainability of transport and logistics networks in the face of disruptions. A key element of this work is the approach called “Green Resilience Assessment” (GRA). GRA is an integrated assessment that combines the analysis of a transport network's resilience to various types of disruptions with environmental and resource efficiency aspects. In practice, this means examining the extent to which a given transport system is able to maintain functionality, recover quickly, and at the same time minimize its negative impact on the environment.

The aim of the GRA is not only to identify weaknesses in transport networks, but also to lay the foundations for implementing adaptation strategies and designing measures to mitigate the effects of disruptions. This process provides stakeholders with knowledge to support investment and operational decisions in line with the principles of sustainable development. The result is a system that is not only more resilient to disruptions but also supports climate and environmental goals.

The GRA methodology in SARIL (Figure 1) described in Deliverable 2.1 (SARIL project D2.1, 2024) comprises several key stages. The first is vulnerability and risk assessment, which involves identifying threats, key resources, and their interdependencies. This stage takes into account both technical and organizational factors, analysing the vulnerability of transport infrastructure to floods, fires, cyber disruptions, and geopolitical events. The next step, described in Deliverables D3.1 (SARIL project D3.1, 2024) and D3.2 (SARIL project D3.2, 2025), is to model transport flows and analyse the effects of disruptions in various scenarios, which allows for the identification of critical points where disruptions generate a domino effect. This makes it possible to simulate the operation of the transport network in crisis conditions and to identify possible solutions to minimize negative effects.

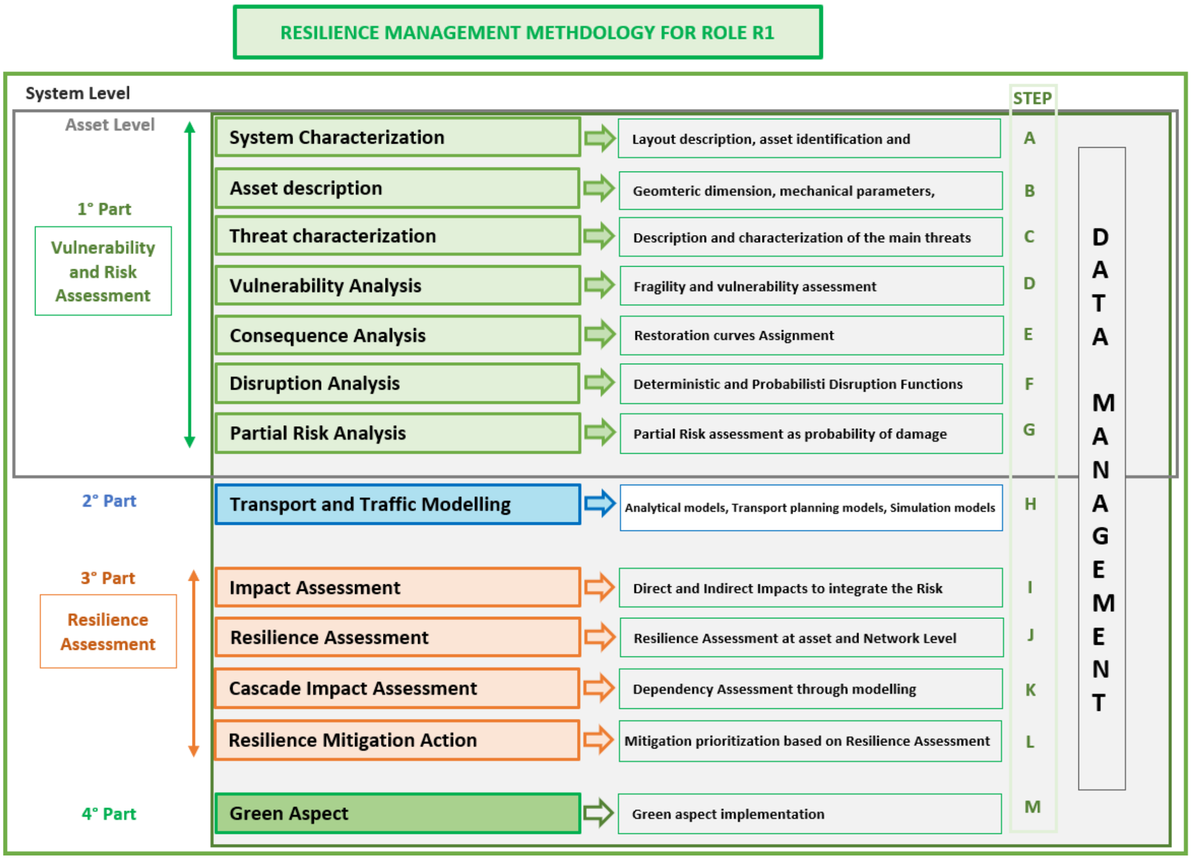


Figure 1: SARIL Green Resilience Assessment methodology.

Risk analysis and modelling are followed by a stage of assessing resilience and cascading effects, which involves evaluating the system's ability to absorb disruptions and return to normal functioning. This phase also analyzes how the system can learn from past events and implement preventive measures. The next stage is the integration of environmental aspects, which includes an assessment of practices related to energy use, emission reduction, and the implementation of green technologies in logistics processes. In this way, GRA combines the technical dimension with the ecological dimension, which is particularly important in the context of the European Green Deal policy.

The final stage is monitoring Key Performance Indicators (KPIs) and drawing conclusions (D2.4 (SARIL project D2.4, 2024)). At this stage, standardized measures are used to assess the effectiveness of the measures implemented and to compare different scenarios. These indicators include carbon emissions per unit of transport, operating costs, delivery time and delay levels, percentage of deliveries made on time, route flexibility and reliability, and the network's ability to recover after a disruption. The analysis of these indicators not only allows for the assessment of the current state of the system but also identifies areas requiring further improvement and investment. In this way, GRA is a dynamic tool that enables the continuous improvement of infrastructure and logistics processes.

KPIs are analyzed at various stages of the disruption cycle:

- Before – preparedness – the preparation stage, including preventive measures and planning;
- During – robustness – the stage during the disruption, in which the resilience and ability of the system to maintain its functions are assessed;
- After – recovery – the recovery stage, in which the ability to restore normal service levels is measured;

- Beyond – adaptive capacity – the stage beyond the disruption itself, in which the system's ability to adapt, learn, and implement improvements for the future is assessed.

Table 2 presents the main assessment categories along with examples of KPIs used in the SARIL project. This table shows which aspects of the transport system are analyzed and which specific measures allow for the assessment of the level of resilience and sustainability of logistics processes.

Table 2: Assessment categories with examples of KPIs used in the SARIL project

Assessment category	**Example KPIs**
Environmental aspect	CO_2 emissions per tkm, renewable energy consumption, share of low-emission vehicles
Operational aspect	Transport cost per tkm, delivery time, % of on-time deliveries, number of alternative routes
Resilience aspect	Functionality recovery time, route redundancy, availability of backup resources
Adaptive aspect	Route flexibility, ability to switch modes of transport, implementation of new technologies

The results of the work carried out so far, described in D3.3 (SARIL project D3.3, 2025), form the basis for the next stages of the SARIL project. In the next phases, the tools and procedures are developed and adapted to practical needs so that they can be used by entities responsible for planning, managing, and developing infrastructure and logistics networks in Europe. The SARIL project also envisages the wide dissemination of results and cooperation with stakeholders, which will enable the joint development of innovative solutions to strengthen the resilience and sustainable functioning of European transport networks. This will result in a set of proven and scalable methods that can be implemented both locally and internationally, creating added value for the entire European economy and environment.

3 State of the Art

This section presents the State of the Art review of the two main areas of study within D3.4 analysis: Green Resilience Assessment and Business Intelligence.

3.1 Green Resilience Assessment

Green Resilience Assessment refers to the systematic evaluation of an organization’s, community’s, or system’s capacity to maintain functionality and well-being in the face of environmental, social, and economic disruptions, while promoting ecological sustainability. It combines concepts of environmental resilience, sustainability assessment, and risk management to measure how well human and natural systems adapt to climate change, resource constraints, and socio-economic transitions. This interdisciplinary approach integrates ecological indicators with policy, infrastructure, and governance dimensions, making it a crucial framework for advancing Sustainable Development Goals (SDGs) (United Nations, 2015).

Over the past decade, the concept of resilience has evolved from a narrow focus on the ability to “bounce back” after disturbances toward a more comprehensive understanding that emphasizes adaptability, transformation, and long-term sustainability. Within this evolution, green resilience introduces an environmental perspective that aligns resilience assessment with the objectives of ecological balance, carbon neutrality, and circular economy principles. Current methodologies emphasize not only resistance to shocks (such as extreme weather or market volatility) but also the capacity of systems to evolve and improve under changing environmental conditions (Graveline & Germain, 2022) (Asadzadeh, Asad, et al., 2022).

Modern frameworks for GRA have emerged in response to the increasing complexity of global environmental challenges. Climate change, biodiversity loss, and resource scarcity have revealed the need for integrated evaluation systems that combine environmental data, socio-economic variables, and governance indicators. Assessment tools now draw from multiple domains, including Life-Cycle Analysis (LCA), Environmental Impact Assessment (EIA), ecosystem services valuation, and adaptive capacity models. These frameworks allow policymakers and organizations to quantify resilience levels, identify weaknesses, and prioritize sustainable adaptation measures (Engle, 2011) (Angeler, y otros, 2018) (Taelman, Sue Ellen, et al., 2024).

From a technical standpoint, the assessment process typically includes several core components:

- Data collection and integration: Gathering environmental, social, and economic data from multiple sources such as satellite imagery, climate models, and socio-economic databases. Modern approaches often rely on big data analytics and Geospatial Information Systems (GIS) to improve accuracy and spatial relevance.
- Indicator development: Selection of resilience indicators that capture ecological health (e.g., biodiversity, water quality, carbon footprint), social well-being (e.g., equity, access to resources), and governance capacity (e.g., institutional readiness, adaptive policies). Indicator frameworks such as the UN SDGs (United Nations, 2015), OECD resilience metrics (Organisation for Economic Co-operation and Development, 2018), or national green growth indices often serve as references (Kays, H. M.; Sadri, Arif Mohaimin, 2022).
- Modelling and evaluation: Use of quantitative and qualitative methods—such as scenario analysis, system dynamics modelling, or multi-criteria decision analysis—to evaluate resilience performance under different environmental and socio-economic conditions.

- Policy interpretation and communication: Translating assessment results into actionable strategies and policy recommendations, ensuring that resilience planning is aligned with environmental sustainability and climate adaptation objectives.

The current research and practice trends (2024–2025) in GRA emphasize the following aspects:

- Integration of climate risk analytics with resilience metrics to improve preparedness and adaptation planning.
- Expansion of nature-based solutions and ecosystem restoration as measurable components of resilience.
- Adoption of digital technologies—including remote sensing, AI-based predictive modelling, and blockchain for sustainability tracking—to enhance transparency and monitoring.
- A growing focus on urban and regional resilience, where green infrastructure, mobility, and energy systems are assessed together to measure cities' capacity to withstand and recover from environmental pressures.
- Inclusion of social equity and justice as fundamental elements of resilience, ensuring that sustainable transitions are inclusive and fair.

Despite the methodological progress, several challenges remain. One of the main obstacles is the lack of standardized frameworks and comparable data across regions, which limits the scalability of resilience assessments. Additionally, the interdisciplinary nature of the field complicates the integration of environmental, social, and economic dimensions into a unified metric. Institutional barriers, such as fragmented governance and insufficient policy coordination, also hinder the effective implementation of resilience strategies. Furthermore, translating assessment results into tangible actions often requires cross-sectoral collaboration and long-term investment, which are difficult to sustain (Andries, Ana, et al., 2023) (Ang, Junqing, et al., 2023).

The effectiveness of GRA depends on its ability to produce actionable insights and influence decision-making. Therefore, measuring the success of resilience initiatives involves both technical and policy dimensions. Quantitative indicators—such as reductions in carbon emissions, improved ecosystem services, or enhanced resource efficiency—are complemented by qualitative outcomes, including improved institutional cooperation, stakeholder engagement, and community awareness. Increasingly, organizations are linking resilience metrics to Environmental, Social, and Governance (ESG) reporting frameworks, thereby connecting assessment results to broader sustainability performance goals (Chopra, Shauhrat S., et al., 2024) (Job, Jovita Shanta; Khanna, Shivi., 2024).

Looking towards the future, GRA is expected to evolve into a more dynamic, data-driven, and participatory process. Emerging approaches such as adaptive governance, digital twins, and circular economy monitoring will enable continuous evaluation of resilience in real time. The integration of AI and machine learning will further enhance predictive capabilities, allowing early detection of environmental risks and optimization of resource management strategies. As a result, resilience assessments will not only measure system robustness but will also guide proactive transformation toward greener, more adaptive societies.

In conclusion, GRA stands at the intersection of sustainability science, environmental management, and technological innovation. Its goal is not only to evaluate how systems resist or recover from disturbances, but also to understand how they can transform to thrive within ecological limits. The future of resilience lies in linking data-driven analytics with inclusive governance and nature-based strategies—creating pathways that align environmental protection with social and economic prosperity. Organizations and governments that adopt such integrated approaches will be better positioned to build sustainable, climate-resilient futures capable of withstanding and adapting to the complex challenges of the 21st century.

3.2 Business Intelligence

Business Intelligence (BI) encompasses a set of practices, architectures, and tools whose main purpose is to transform both structured and unstructured data into useful information for business decision-making. It involves processes of data integration, storage, analysis, and visualization that support strategic and operational management across organizations. In this sense, BI plays a crucial role in digital transformation, enabling companies to make evidence-based decisions rather than relying solely on intuition or experience.

BI has evolved from systems focused primarily on reporting and dashboards into more intelligent and automated platforms. In its early stages, BI tools were mainly used to collect and present historical data through static reports. However, the current business environment demands more dynamic systems capable of delivering predictive and prescriptive analytics. Modern BI solutions integrate advanced analytics, machine learning, and artificial intelligence, significantly expanding the traditional scope of BI. These innovations make it possible to identify hidden patterns, anticipate market trends, and continuously optimize processes based on real-time insights. (Velosa & Pabon, 2021) (Linares & Ramírez)

A major transformation has also occurred at the architectural level, with the emergence of modern models such as data lakehouses, which combine the flexibility of data lakes (large repositories that store raw, unstructured data) with the reliability of data warehouses (systems that organize structured data for analysis and reporting) (Snezhana Sulova et al, 2019) (Prakash, 2020) This evolution responds to the growing need to manage large and diverse volumes of data coming from multiple sources such as IoT sensors, social media, e-commerce platforms, and enterprise systems (ERP). Current solutions allow real-time analysis and self-service access for business users, fostering a more collaborative and agile decision-making culture. (Paramesha, Rane, & Rane, 2024)

The current technical components of BI can be grouped into four main areas:

- Data ingestion and transformation: Extract-Load-Transform (ELT) processes handle large data volumes through automated pipelines that clean, transform, and load information from multiple sources. This stage is essential for ensuring the accuracy, consistency, and reliability of analytical results.
- Storage: Traditional data warehouses coexist with data lakes or lakehouses, designed to store massive, semi-structured, or unstructured data. These architectures offer greater flexibility and scalability, making them fundamental for advanced analytical environments and big data ecosystems.
- Semantic layer: This layer translates technical data into understandable and reusable business metrics. It facilitates data governance and enhances user experience by enabling access through natural language queries, thus reducing dependence on technical personnel.
- Information consumption: This area includes interactive dashboards, automated reporting, ad hoc analysis, and data storytelling tools aimed at supporting data-driven decisions. Modern BI solutions prioritize intuitive visualization, user-friendly design, and personalized experiences according to user roles within the organization.

Another key area of BI involves analytical methods and user experience. The self-service analytics approach allows business users to directly access data without constant support from the IT department, encouraging autonomy and agility in analysis. Augmented analytics—powered by artificial intelligence and natural language queries—automates data preparation and insight generation. These innovations democratize access to analytics but require strong governance policies, human validation, and proper training to ensure data quality and correct interpretation of results.

The current trends in BI (2024–2025) reflect a field undergoing continuous transformation:

- Integration of artificial intelligence and conversational agents into BI platforms, enabling more natural and accessible interaction with data.
- Adoption of the data mesh approach, which promotes decentralization and domain-based data ownership, improving scalability and accountability.
- Increased emphasis on data quality, lineage, and observability as key pillars for maintaining trust in analytical results.
- A growing interest in real-time analytics, which enables anomaly detection and instant decision-making in time-sensitive contexts.
- Consolidation of the lakehouse model and semantic layers as architectural standards for ensuring interoperability and consistency across data environments.

Despite technological progress, many organizations still face difficulties in obtaining tangible value from their BI initiatives. The main challenges are organizational rather than technical, including a lack of data-driven culture, shortage of hybrid talent (professionals combining business and technical skills), and resistance to change among teams. In addition, the integration of legacy systems and the management of large, diverse datasets continue to pose significant obstacles. (Paradza & Daramola, 2021) (Zanke & Sontakke, 2024)

Other critical challenges relate to data quality, governance, security, and regulatory compliance—particularly in environments subject to privacy regulations such as the General Data Protection Regulation (GDPR). To address these issues, organizations must implement comprehensive data governance strategies that ensure the integrity, availability, and confidentiality of information, while also establishing mechanisms for auditing and traceability.

The future of BI is moving toward convergence with artificial intelligence, giving rise to intelligent analytical ecosystems in which data copilots automatically generate reports, explanations, and actionable recommendations. Platforms are expected to become more open, interoperable, and governed, combining lakehouse architectures with robust semantic layers that guarantee data consistency and security. In this context, BI will no longer be seen merely as a passive reporting tool but as an active engine for business optimization and innovation (Weng, y otros, 2025) (Dubey, 2025).

Consequently, the focus will shift from technology itself to the organization's ability to transform insights into measurable actions and real business value. Companies that successfully integrate BI into their strategic and operational decision-making processes will not only gain a competitive advantage but also be better equipped to anticipate market changes, innovate with agility, and ensure long-term sustainability.

4 Resilience Patterns and Generalization

In this section, the most relevant developments are presented. Section 4.1 presents the description of the methodology applied for both the GRA assessment (4.1.1) and the development of the Resilient Platform dashboards (4.1.2). The final results are presented in section 4.2.

4.1 Methodology

In response to the objectives defined in Task 3.4, the proposed approach is based on the development of a generalization framework designed to quantify the GRA from the different project scenarios and the integration of results into interactive dashboards.

A generalization framework (further developed in section 4.1.1) is proposed based the project previous work developed regarding the GRA, summarized in section 2.3, to apply common indicators create a generalized approach to measure the green resilience of the different scenarios. This methodology relies on a set of shared indicators and a common evaluation framework, making it possible to extract general insights and transfer knowledge from specific cases. As such, it directly contributes to quantifying the different cases results to analyse them at all levels of the logistics network.

The outputs generated by the SARIL tools provide valuable insights for the management of various logistics systems. Leveraging this knowledge to support decision-making can significantly enhance the quality of decisions, reduce the time required for analysis, and enable the optimization of key parameters—such as fuel consumption and CO_2 emissions—thereby contributing directly to the green dimension of the assessment.

However, to be effectively utilized, this information must be presented in a format that is accessible, intuitive, and user-oriented. With this goal in mind, a series of interactive dashboards have been developed to serve as a centralized and user-friendly visualization platform. These dashboards which methodology is further developed in section 4.1.2 and which results are shown in 4.2.2, integrate the outputs of the tool analyses (D3.3 (SARIL project D3.3, 2025)).

The development of these dashboards is essential to bridge the gap between complex analytical outputs and practical decision-making. By translating large volumes of technical data into clear, visual, and interactive representations, the dashboards enable stakeholders to interpret key resilience indicators quickly and accurately. This is particularly relevant for infrastructure managers and logistics network operators, who require fast and reliable insights to assess vulnerabilities, test mitigation strategies, and prioritize interventions under varying operational or environmental conditions.

The selected information focuses on parameters that directly influence the operational efficiency and environmental sustainability of transport and logistics systems—such as travel time, cost, energy use, and CO_2 emissions—allowing users to identify trade-offs and synergies across different resilience scenarios. Through this visual environment, decision-makers can compare alternative mitigation options, explore spatial patterns of disruption and recovery, and monitor performance evolution across multiple scales. Ultimately, this development goal is to show that through this type of dashboards, SARIL analytical framework can be transformed into a practical decision-support tool, making SARIL results not only scientifically robust but also operationally actionable for the entities responsible for managing and planning Europe’s logistics and infrastructure networks.

4.1.1 Green Resilience Generalization

As it was presented in section 2 and detailed in D2.1 “Survey of methodologies for resilience management” (SARIL project D2.1, 2024), D2.4 “Integration of monitoring information into green resilience management” (SARIL project D2.4, 2024), D3.1 “Enhanced models and tools” (SARIL project D3.1, 2024), D3.2 “Models and tools closing gaps” (SARIL project D3.1, 2024) and D3.3 “Green Resilience Assessment Results” (SARIL project D3.3, 2025), this project proved the interconnection among tools and their applicability to relevant real-life scenarios. But even though all tools can be interconnected and applied in principle to any location (for further information on the transferability of tools, see D4.2 (SARIL project D4.2, 2025)), the limitation on available information and time motivated the creation of different scenarios in which the most relevant tools were fully applied in a practical way.

Table 1 depicts the different scenarios characteristics, providing an overall view on how their configurations are interconnected while covering for different needs. Therefore, this task is especially relevant, since an extra-step in needed to provide a generalization to all the results.

SARIL General Methodology is developed to be applicable to any system or logistic network, not limited to specific areas, networks or hazards. The different scenarios take information from different data sources, they interconnect different tools and allow for the execution of different types of traffic models such as SUMO or TransCAD enhancing the scope of generalization, as well as the Transferability aspect, further defined in D4.2 (SARIL project D4.2, 2025), which explores the extent to which the results and methodologies can be applied beyond the SARIL scenarios.

This GRA follows the methodology shown in Figure 2. Three types of simulations are performed:

- Base-case, the simulation performed in standard conditions.
- Disrupted-case, simulation performed when a hazard provokes a disruption on the network.
- Mitigated-case, simulations performed in which mitigation actions have been activated to respond to the disruptions.

For every case the tools are executed using the simulation inputs and the required information relative to disruptions and mitigation if necessary. Once the tools outputs are obtained, the analysis is enriched with SIN’s Energy Module, obtaining relevant parameters relative to duration, costs and CO_2 emissions. The combination of these outputs conforms the scenario outputs for the different cases. This methodology has been applied to all scenarios, and this task is oriented towards the last box: Generalization, with metrics to compare the different cases and scenarios.

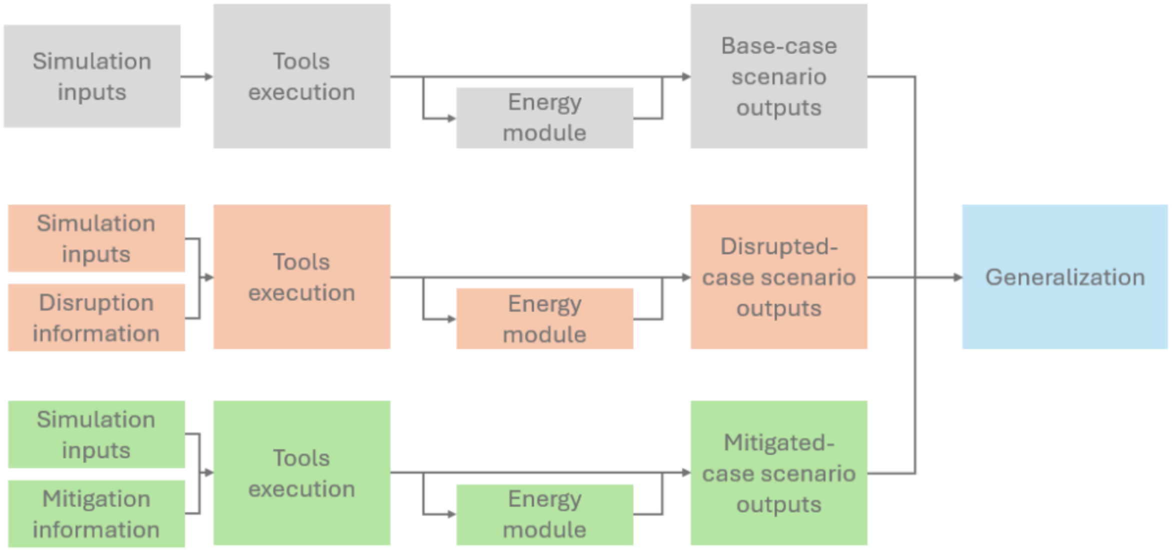


Figure 2: GRA methodology.

The definition of relevant KPIs that can quantify the aforementioned parameters is a key aspect of this generalization. The KPIs from D1.2 “Framework for a sustainability and resilience evaluation of strategic logistics networks” (SARIL project D1.2, 2024), proposed at the beginning of the project have been analysed, and the ones suitable for the methodology and the actual project outputs have been selected as the most adequate ones for the GRA.

The preliminary KPIs, are shown in the scheme of Figure 3 as Resilient and Sustainability Factors. The resilient factors cover 9 different areas: Preparedness, Redundancy, Reliability, Flexibility, Visibility, Security, Collaboration, Recovery and Learning and are related to SARIL roles:

- Role 1. Developing and maintaining transport infrastructure. Typically taken by public authorities and transport infrastructure operators. For this role, resilience should be one of the attributes considered when the infrastructure is being planned and built but also during the operational phase
- Role 2. Configuring transport and logistics network. Typically adopted by those responsible for strategy in relevant logistics companies. This role needs to make long-term decisions about the configuration of the logistic network and resilience should be a factor when analyzing different logistics networks
- Role 3. Managing transport and logistics operations. it refers to those who are involved in the actual movement of goods. This role needs to make decisions about how to move goods daily, these decisions are directly impacted by disruptions.

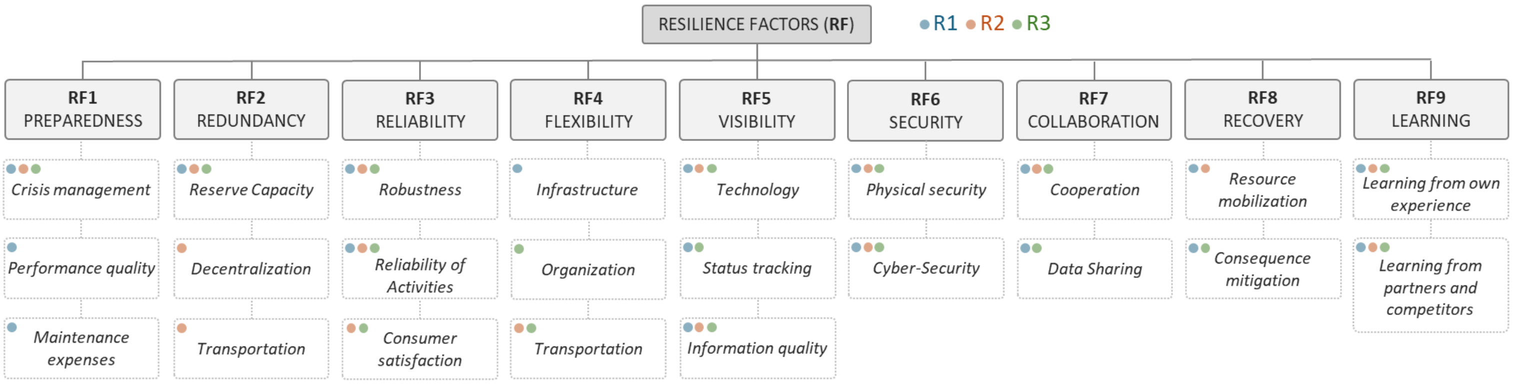


Figure 3: Resilience factors used in the SARIL framework.

These resilient factors are combined into a single resilience index following Equation [*1*]. The weights w_{RFi} represent the relative importance for the total resilience of the system. These weights have been obtained from the application of the Analytic Hierarchy Process (AHP) (Saaty, 1987) to the results of conducted surveys which detailed description can be found in D1.2 (SARIL project D1.2, 2024). This method uses a pairwise comparison between alternatives with respect to a common goal providing, as an outcome, a matrix of relative importance between alternatives. For this purpose, resilience factors have been used as alternatives and the resilience of a system as the common goal. In the survey carried out in Task 1.3, logistics experts were asked to perform a pairwise comparison between the resilience factors indicating, for each factor, its relative importance compared to each of the other factors. Finally, after carrying out the necessary matrix's operations. The final Weights are shown in Table 3. As previously explained, these results reflect the relative importance assigned by logistics experts. This assessment would differ if performed from the perspective of other management roles, such as infrastructure managers. Therefore, depending on the user profile and the scope of the analysis, these weights should be recalculated.

$$Resilience\ Index = \sum RFi\ (score) \times w_{RFi} \qquad [1]$$

Table 3: Suggested weights for each resilience factor

Resilience Factor	**Relative weight**
Preparedness	6%
Redundancy	14 %
Reliability	20 %
Flexibility	10 %
Visibility	10 %
Security	21 %
Collaboration	5 %
Recovery	6 %
Learning	8 %

This preliminary analysis of possible metrics is analysed once the results from SARIL tools is obtained and discussed, and the metrics that are better suitable are included in Table 4, which shows the area they cover, their definition, formula, measure unit, their relative factor, sub-factor and role and their relation to SARIL project, with the explanation of the selection of the factor.

Table 4: Selected KPIs from SARIL resilient factors.

Maintenance costs	*Definition*	Provides the maintenance cost per unit of output e.g. km of a road network or bridge. Establishment of a baseline maintenance cost based on historical data and comparison with current trends. Low expenditure in maintenance can indicate low robustness or inefficiency in performance quality.
	Formula	$MC = \frac{(total\ maintenance\ cost)}{road\ length\ or\ N\ of\ bridges}$
	Measurement unit	€/km or number of bridges
	Factor	Preparedness
	Sub-factor	RF1.3. Maintenance expenses
	Role	R1
	SARIL relation	Maintenance costs are estimated in the regional and European scenario. In both, costs are estimated for the different cases allowing the comparison among disruptions, mitigations and base-case.
Assets monitoring	*Definition*	Measures the number of assets that are monitored
	Assessment / formula	Count of monitored assets
	Measurement unit	Number
	Factor	Visibility
	Sub-factor	RF5.2 Status tracking
	Role	R1
	SARIL relation	SARIL project increases the assets monitoring index, since its applicability increases the roads and bridges which are monitored, analysed and assessed.
Information Sharing Platform	*Definition*	Indicates whether information sharing platforms (e.g., collaborative software, data-sharing systems) are utilized within the logistics network.
	Assessment / formula	0: information sharing platforms are not used 1: information sharing platforms are used
	Measurement unit	0/1
	Factor	Collaboration
	Sub-factor	Data sharing
	Role	R1
	SARIL relation	SARIL project increases the Information Sharing Platform index, through the development of the Disruption Information Interface. This task dashboards developments improves the project impact on this index.
Recovery time	*Definition*	Recovery time is defined as the duration from the commencement of restoration activities (t_e) to the point of full asset or system functionality (t_f). Different recovery functions are adopted depending on the level of preparedness.
	Assessment / formula	$T_{RE} = t_f - t_e$
	Measurement unit	Unit of time e.g. days
	Factor	Recovery
	Sub-factor	RF8.2 Consequence mitigation
	Role	R1

	SARIL relation	On the Regional Scenario, Strategic Planning Support Based on Vulnerability and Traffic Tool Assessment, the recovery time is measured through Recovery curves showing the functionality evolution of the asset with time. European scenario monitors the number of deliveries over time, ana analyses the days needed to deliver all products on the baseline, disrupted and mitigated cases.
Alternative route planning	*Definition*	Measures the presence of alternative routes in the network design
	Assessment / formula	$\frac{Number\ of\ Alternative\ Routes\ Identified}{Total\ Number\ of\ Routes\ in\ the\ Network}$
	Measurement unit	Ratio (No Units)
	Factor	Redundancy
	Sub-factor	RF2.3 Transportation
	Role	R2
	SARIL relation	In the regional scenario, rerouting is optimized after fire disruption. Roads Volume over Capacity (VOC) measurement is used. In the national scenario, the rerouting due to fire disruptions is optimized. The Betweenness Centrality (BC) index is used. In the European scenario, rerouting is used as a mitigation measure based on the traffic simulations.
Mode diversification	*Definition*	Measures the extent to which different transportation modes are utilized within the logistics operations.
	Assessment / formula	$\frac{Total\ number\ of\ modes\ used}{Total\ number\ of\ avaliable\ modes}$
	Measurement unit	Ratio (No Units)
	Factor	Redundancy
	Sub-factor	RF2.3 Transportation
	Role	R2
	SARIL relation	Mode diversification is used within the European scenario to mitigate the effect of the disruptions.
% information exchange through IT	*Definition*	Measures the percentage of information communicated via IT systems
	Assessment / formula	$\frac{Information\ Exchanged\ Through\ IT}{Total\ Information\ Exchanged} * 100$
	Measurement unit	Percentage (%)
	Factor	Visibility
	Sub-factor	RF5.1 Technology
	Role	R3
	SARIL relation	SARIL project increases the % information exchange through IT index, with the development of the Disruption Information Interface. This task dashboards developments improves the project impact on this index as well.

Table 4 presents the indicators identified as the most suitable based on the analysis of resilience and sustainability frameworks. In addition, drawing on the final results, a set of generalized KPIs has been defined to enable comparison across scenarios, which are displayed in Table 5.

These indicators work following the methodology explained in Figure 2, comparing the different cases simulated using different features: costs, time and CO_2 emissions as indicators of the network vulnerability. In this analysis Case 2 is the disruption case of study and Case 1 the base-case.

Table 5: New KPIs defined for GRA methodology.

Costs	*Definition*	Impact measure to quantify the costs.
	Formula	$KPI_C = \frac{Cost\ Case\ 2 - Cost\ Case\ \ 1}{Cost\ Case\ 1} x100$
	Units	*[%]*
Average Recovery Time	*Definition*	Impact measure to analyse the time needed to restore to normal behaviour
	Formula	$KPI_{RT} = \frac{Recovery\ time\ case\ 2 - Recovery\ time\ case\ 1}{Recovery\ time\ case\ 1} x100$
	Units	*[%]*
Travel time	*Definition*	Impact measure of the time spent by vehicles on the road.
	Formula	$KPI_{TT} = \frac{Time\ case\ 2 - Time\ case\ 1}{Time\ case\ 1} x100$
	Units	*[%]*
CO_2 increase	*Definition*	Impact measure to analyse the CO_2 emissions.
	Formula	$KPI_{co} = \frac{CO_2\ emissions\ Case\ 2 - CO_2\ emissions\ Case\ 1}{CO_2\ emissions\ Case\ 1} x100$
	Units	*[%]*

Finally, these indicators are used within the final Green Resilience Index (equation [*2*]), as a unified metric for assessment and comparison. This equation uses different weights (w) relative to each KPI. These weights represent the relative importance for the total resilience of the system. The different KPIs are normalized, to assign them to a same scale, making them comparable and avoiding one parameter dominance. This indicator is designed so that values closer to zero represent better performance, meaning higher resilience or lower impact depending on the context. As the indicator increases, it reflects a deterioration in results — indicating greater deviation from the desired condition or lower overall performance. Therefore, smaller values denote more favourable outcomes, while larger ones highlight areas that may require improvement.

$$KPI_{GRA} = w_c\overline{KPI_c} + w_{RT}\overline{KPI_{RT}} + w_{TT}\overline{KPI_{TT}} + w_{CO}\overline{KPI_{CO}} \quad [2]$$

$$\overline{KPI} = \frac{KPI - KPI_{mini}}{KPI_{maxi} - KPI_{mini}} \quad [3]$$

The results from the analysis are shown in Section 4.2.1.

4.1.2 Resilience Platform

Before generating the Business Intelligence dashboards displayed in section 4.2.2, it is essential to carry out a series of preliminary steps involving the analysis and preparation of the shared raw data. This phase is a fundamental part of the data science workflow, as it ensures that the information used in the dashboards is accurate, consistent, and meaningful.

The process involves several stages: data cleaning to remove errors and inconsistencies, normalization and transformation to align formats and scales, and Exploratory Data Analysis (EDA) to identify trends, correlations, and potential anomalies. In addition, the integration of multiple datasets requires defining clear relationships between variables to enable meaningful cross-analysis.

For this project, the process has been done partially by Spyder (an open-source integrated development environment for Python focused on scientific computing and data analysis) and partially by Power BI (a business intelligence platform developed by Microsoft that enables interactive data visualization, dashboard creation, and real-time reporting) itself. Spyder is especially useful for the first part of the analysis, when data is firstly explored, since it is a powerful environment for data analysis and file exploration, as it combines an intuitive interface with advanced coding, visualization, and debugging tools using popular Python libraries such as Pandas (a Python library for data manipulation and analysis) for data manipulation and Matplotlib (a comprehensive 2D plotting library for data visualization in Python) for graphical representation. The geographical information was processed by QGIS (an open-source geographic information system for spatial data analysis and mapping), and for the connection with Power BI, the dashboard maps were created using ArcGIS Online (a cloud-based mapping and analytics platform developed by Esri for geospatial data visualization and sharing). Tool developers provided their raw data per tool. This data sometimes covered results from the analysis (covering the different studied cases), models inputs in some cases, as well as geographical data and was provided in different formats (.csv, .json, .parquet…).

Once the data has been processed, it must be structured appropriately for Power BI. This includes designing data models that define hierarchies, relationships, and key fields, as well as optimizing table structures to ensure efficient loading and real-time performance. Establishing proper interconnections between datasets allows for a dynamic and coherent flow of information across dashboards, resulting in an efficient, effective, and analytically robust BI environment. Figure 4 shows a small section of the model view from the Power BI data connection done to prepare the dashboards. The figure shows one box per file added to the model. Each box has a series of columns which can be connected to the other files columns through the arrows. These connections can be configured following direction and cardinality.

The workflow to create dashboards in Power BI begins with data connection and preparation, where relevant datasets are imported from various sources and cleaned for consistency. Next, the data modelling phase establishes relationships between tables and defines key metrics or calculated fields. Once the model is ready, the visualization stage involves designing interactive dashboards that represent the data through charts, maps, and key indicators. These dashboards allow collaborative analysis, and informed decision-making across users and teams.

The final dashboards are shown on section 4.1.2.

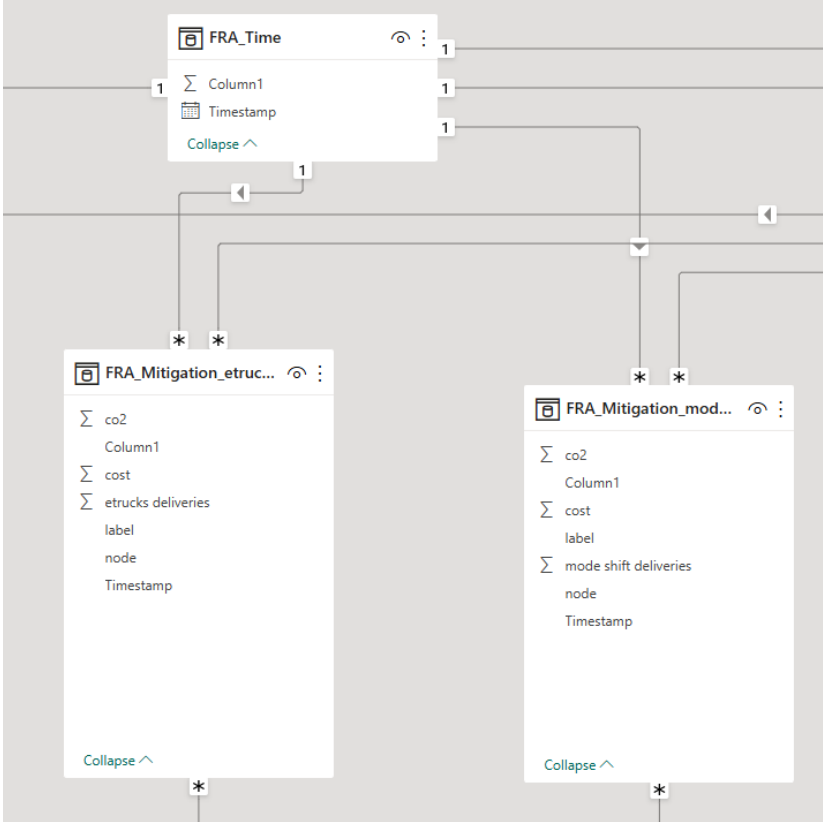


Figure 4: Exemplary outcut from the model view from Power BI dashboards.

4.2 Results

4.2.1 Green Resilience Assessment

The methodology presented in section 4.1.1 has been applied to SARIL outputs to calculate the defined KPIs. This section presents the analysis performed in each project scenario and the comparable final results.

European scenario

The European case scenario is used to assess how the inner European transport flow reacts to different disruptive scenarios. The base-case responds to the normal functioning of the European freight network while Ukraine war is on course, it stops any cargo entering the network through the northern silk road. The disrupted- case adds a strike in Hamburg harbour for two weeks. The mitigated-cases the following: adding E-trucks in south Germany and Austria, adding trains from Istanbul to the network and having a higher percentage of deliveries which can shift to another mode.

The results from this analysis are summarized in Table 6. These results are used to calculate the KPIs shown in Table 7, using the equations from Table 5. The normalized KPIs and the KPI_{GRA} calculated using equation [*2*] and [*3*]are shown next to the other scenarios' results in Table 13.

Table 6: European scenario results.

Case\Parameter	CO_2 [kg]	Costs [€]	Time [h]
Baseline	349148.58	364012.9	1705147.3
Disruption	358661.92	380114.03	1909727.3
Mitigation: etrucks	313877.36	502355.88	1908572

Mitigation: mode shift	356689.47	376860.13	1912773.3
Mitigation: train from Istambul	336613.66	421136.25	1951862.3

Table 7: European scenario KPI calculation

Case\Parameter	KPI_{CO2} [%]	KPI_{C} [%]	KPI_{tt} [%]
Unmitigated Disruption	2,72	4,42	12,00
Mitigation: mode shift	-10,10	38,00	11,93
Mitigation: train from Istambul	2,16	3,53	12,18
Mitigation: etrucks	-3,59	15,69	14,47

National scenario

This scenario includes main motorways as A-3, A-27, and A-28 in northern Portugal and AP-9 (known as the Atlantic Corridor), A-52, and A-55 in Galicia, which connect important infrastructure, including the Port of Vigo, PLISAN, Santiago Airport, the Port of A Coruña, Maia Airport, the Port of Leixões, and the Port of Aveiro. The base-case is the normal behavior of the road network without fire disruption. The considered disruptive events include forest fires on key segments of the road network. Two forest fires were considered: one on the A-55 and a second one on the access of Vigo, which count as two different disrupted-cases. Each disrupted-case has different mitigation-cases. The mitigation measures for A-55 disrupted case are: Firebreak Between the A-9 and A-55 Highways and Early warning digital system application. The mitigation measure for the Access of Vigo is Dynamic Route Guidance via Temporary Digital Signage application

The values from the different cases are displayed in Table 8. These values allow the calculation of time and CO_2 KPIs, as shown in Table 9 using the equations from Table 5. The normalized KPIs and the KPI_{GRA} calculated using equation [2] and [3]are shown next to the other scenarios' results in Table 13.

Table 8: National scenario results.

		Time [h]	CO_2 [t]
A55	Baseline	126013	4037,7
	Disruption	412268	3856
	Mitigation: fire break	330022	3964,5
	Adaptation: early warning system	367462	3805,8
Entrance	Baseline	126013	4037,7
	Disruption	147813	3966,9
	Adaptation: dynamic route guidance	130987	3692,9

Table 9: National scenario KPIs calculation.

		KPI_{co2} [%]	KPI_{tt} [%]
A55	Disruption	-4.500086683	227.16307
	Mitigation: fire break	-1.812913292	161.8952
	Adaptation: early warning system	-5.74336875	191.60642
Entrance	Disruption	-1.753473512	17.299802
	Adaptation: dynamic route guidance	-8.53951507	3.9472118

Regional scenario

This scenario studies a transport network (with special focus on highways and state roads) in relation to its high risk of flooding. The disruption-case corresponds with the traditional response when a river experiences high water flow beyond normal range, in this case all bridges are closed. The mitigation-cases corresponds with the application of the Scour Monitoring for Decision Support Tool, that would be applied to assess the possibility of different combinations of bridges to be closed

The values from the different cases are displayed in Table 11. These values allow the calculation of time and cost KPIs, as shown in Table 12, using the equations from Table 5. The normalized KPIs and the KPI_{GRA} calculated using equation [*2*] and [*3*] are shown next to the other scenarios' results in Table 13. Table 10 shows the opening-closure configuration of the different cases, marking with a 0 the bridges that are closed and with a 1 the bridges that are open per specific case.

Table 10: Regional scenario results.

	B-S-1	**B-H-1**	**B-H-2**	**B-S-4**
Disruption	0	0	0	0
Mitigation 1	0	0	0	1
Mitigation 2	0	0	1	0
Mitigation 3	0	0	1	1
Mitigation 4	0	1	0	0
Mitigation 5	0	1	0	1
Mitigation 6	0	1	1	0
Mitigation 7	0	1	1	1
Mitigation 8	1	0	0	0
Mitigation 9	1	0	0	1
Mitigation 10	1	0	1	0
Mitigation 11	1	0	1	1
Mitigation 12	1	1	0	0
Mitigation 13	1	1	0	1
Mitigation 14	1	1	1	0
Mitigation 15	1	1	1	1

Table 11: Regional scenario results.

	Travel time [h]	**Risk [millions €]**
Disruption	875.42	12.67
Mitigation 1	9.31E+15	15.40
Mitigation 2	6882.03	13.87
Mitigation 3	7.92E+15	16.61
Mitigation 4	9.31E+15	15.44
Mitigation 5	8.34E+15	18.17
Mitigation 6	-	16.61
Mitigation 7	-	19.34
Mitigation 8	-	13.86
Mitigation 9	-	16.60
Mitigation 10	-	15.05
Mitigation 11	8.34E+15	17.77
Mitigation 12	2883.09	16.61
Mitigation 13	2882.61	19.32
Mitigation 14	7.92E+15	17.78
Mitigation 15	2873.56	20.49

Table 12: Regional scenario KPI results.

	KPI_{tt}	**KPI_{c}**
Mitigation 1	1.06E+15	21.60
Mitigation 2	686.14	9.48
Mitigation 3	9.05E+14	31.08
Mitigation 4	1.06E+15	21.85
Mitigation 5	9.52E+14	43.44
Mitigation 6	-	31.11
Mitigation 7	-	52.62
Mitigation 8	-	9.42
Mitigation 9	-	31.02
Mitigation 10	-	18.78
Mitigation 11	9.52E+14	40.29
Mitigation 12	229.34	31.14
Mitigation 13	229.28	52.48
Mitigation 14	9.05E+14	40.32
Mitigation 15	228.25	61.71

Table 13 shows the normalized KPIs and the results from the final KPI_{GRA} calculation. The normalized KPIs have been calculated following equation [*3*] and the KPI_{GRA} using equation [*2*]. Equation [*2*] is applied using the available KPIs in each case as shown in equations [*4*], [*5*] and [*6*]. Since the surveys apllied in the project (Table 3) are related to the whole set of original KPIs of D1.2 (SARIL project D1.2, 2024) and not to the KPIs applied, it is assumed that all KPIs have the same importance for the assessment.

$$KPI_{GRA}(European) = w_c\overline{KPI_c} + w_{TT}\overline{KPI_{TT}} + w_{CO}\overline{KPI_{CO}};\ w_c = w_{CO} = w_{TT} = 1/3 \tag*{[4]}$$

$$KPI_{GRA}(National) = w_{TT}\overline{KPI_{TT}} + w_{CO}\overline{KPI_{CO}};\ w_{CO} = w_{TT} = 1/2 \tag*{[5]}$$

$$KPI_{GRA}(Regional) = w_c\overline{KPI_c} + w_{TT}\overline{KPI_{TT}};\ w_c = w_{TT} = 1/2 \tag*{[6]}$$

Table 13: Calculation of normalized KPIs of all cases and scenarios.

Scenario	Case		$\overline{\mathbf{KPI}_{CO2}}$	$\overline{\mathbf{KPI}_{C}}$	$\overline{\mathbf{KPI}_{TT}}$	$\overline{\mathbf{KPI}_{GRA}}$
European	**Disruption**		1.00	0.03	0.03	0.35
	Mitigation e-trucks		0.00	1.00	0.00	0.33
	Mitigation mode shift		0.96	0.00	0.10	0.35
	Mitigation Istanbul		0.51	0.35	1.00	0.62
National	**A55**	Disruption	0.60	-	1.00	0.80
		Mitigation: fire break	0.99	-	0.71	0.85
		Adaptation: early warning system	0.41	-	0.84	0.63
	Entrance	Disruption	1.00	-	0.06	0.53
		Adaptation: dynamic route guidance	0.00	-	0.00	0.00
Regional	**Mitigation 1**		-	0.23	1.00	0.62
	Mitigation 2		-	0.00	0.00	0.00
	Mitigation 3		-	0.41	0.85	0.63
	Mitigation 4		-	0.24	1.00	0.62
	Mitigation 5		-	0.65	0.90	0.77
	Mitigation 6		-	0.41	-	0.41
	Mitigation 7		-	0.83	-	0.83
	Mitigation 8		-	0.00	-	0.00
	Mitigation 9		-	0.41	-	0.41
	Mitigation 10		-	0.18	-	0.18
	Mitigation 11		-	0.59	0.90	0.74
	Mitigation 12		-	0.42	0.00	0.21
	Mitigation 13		-	0.82	0.00	0.41
	Mitigation 14		-	0.59	0.85	0.72
	Mitigation 15		-	1.00	0.00	0.50

Conclusions

These global KPIs calculated provide a standardized basis for comparing the impact of the GRA across different cases and scenarios. By consolidating key performance indicators into a common framework, these metrics enable objective evaluation of how various strategies or conditions influence resilience outcomes. This comparative approach supports the identification of patterns, strengths, and weaknesses among cases, facilitating evidence-based decision-making and guiding improvements in sustainable planning and adaptation strategies.

For the regional scenario KPI_C highlights which mitigation measures have the greatest impact on costs, identifying Mitigation 8 as the most cost-effective option and Mitigation 15 as the most expensive. The travel time impact, on the other hand, identifies various mitigations as the most suitable: 2, 12, 13 and 15, advising to avoid the rest, with values higher than 0.8. The combined $\mathrm{KPI}_{\mathrm{GRA}}$, which integrates both factors, identifies Mitigation 8 as the overall most suitable alternative. Nevertheless, a road manager may use their professional judgment to select a different mitigation-case, taking into account these results alongside other qualitative or context-specific considerations.

For the national scenario, CO_2 emissions and travel times KPIs clearly identifies the disruptions in both locations. The case of fire in A-55 causes the higher impact on travel time, this impact is effectively mitigated through the fire break. Early warning systems also mitigate the travel time impact. The impact on CO_2 shows how the early warning system decreases de emissions by decreasing delays caused by the disruption. Globally, early warning systems shows a higher mitigation impact. On the AP-9 entrance to Vigo, only one adaptation measure is proposed: dynamic route guidance, which decreases both emissions and travel time. With only one possibility, comparison within the sub-scenario is not possible, nevertheless, thanks to the global KPI, it is shown how this adaptation is the one with higher mitigation benefits within the whole National scenario.

The European scenario is the one providing the most complete information for the analysis. In relation to the emissions impact, it is shown how all the mitigated cases do reduce the emissions, with the use of e-trucks showing the higher impact, a logical result. This situation is not matched by all parameters, for example in terms of costs, only the mode shifts mitigation measure improves the disruption, while the use of e-trucks has a high negative impact on costs. This is also a logical result, since using mitigations measures, especially those which try to improve green aspects, can be expensive, as it is the case of the purchase or renting of e-trucks. Regarding the travel time impact, only e-trucks show an improvement on delays, mode shifts show a small negative impact on the travel times and the use of the trains from Istanbul provokes high delays. In a case like this one, with several relevant factors, the use of the global KPI takes more importance, and in this case, it shows how, weighting all the parameters the same, the most suitable solution would be the use of e-trucks. Nevertheless, since this methodology is adaptable, we could also theorize that a specific enterprise could prioritize the economic factor (w_c=0.5), as well as the inconvenience caused to their users (w_{tt}=0.35), while providing less importance to the ecological factor (w_{co2}=0.15), in this example, which results are summarized in Table 14, showing that it this case with this assumptions the best solution would be the mode shifts.

Table 14: Calculation of alternative KPIs for European scenarios with different weighting assumptions.

Scenario	Case	KPI GRA
European	Disruption	0.172
	Mitigation e-trucks	0.500
	Mitigation mode shift	0.177

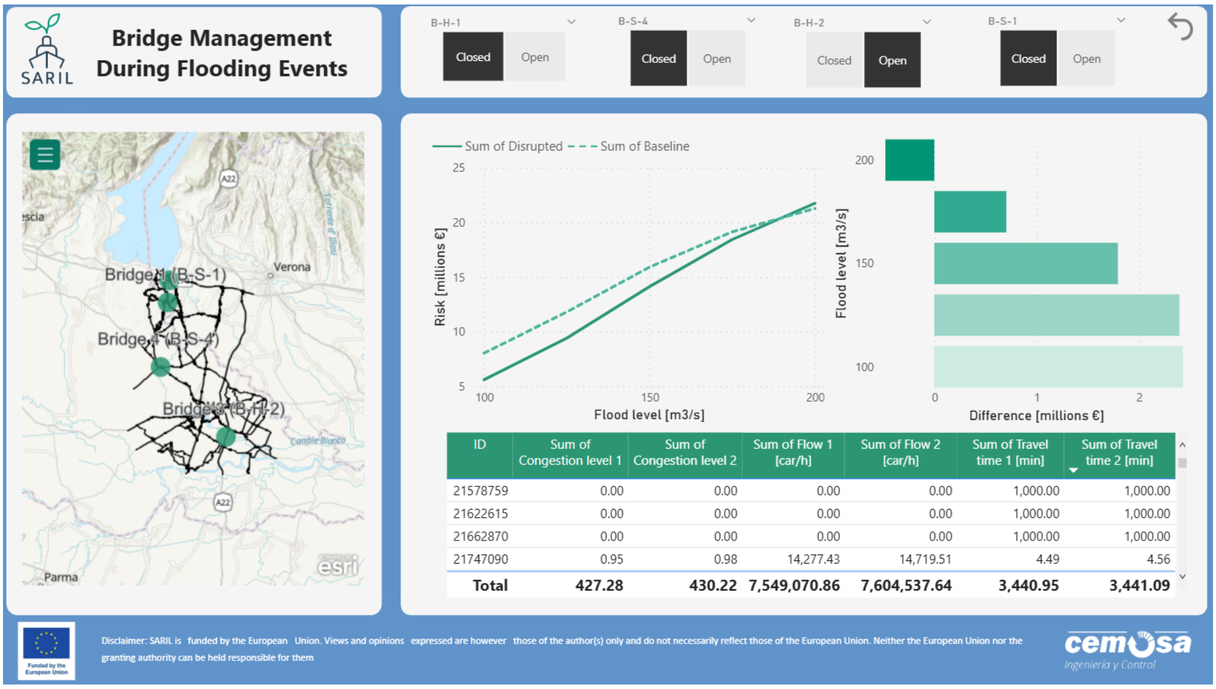
	Mitigation Istanbul	0.603

4.2.2 Resilience platform

As it was presented in Section 4.1, Business Intelligence tool (Power BI) was used to generate a series of dashboards, which centralize project results, in an interactive, accessible, intuitive and user-friendly way.

4.2.2.1 Dashboard 1. Bridge management during flooding events

This dashboard (Figure 5) has been designed to support management decisions regarding bridge operations during flooding events. It integrates SARIL results relative to the detailed analysis of the risks associated with opening or closing bridges under varying flood intensities.



Bridge Management During Flooding Events

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21578759	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21622615	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21662870	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21747090	0.95	0.98	14,277.43	14,719.51	4.49	4.56
Total	**427.28**	**430.22**	**7,549,070.86**	**7,604,537.64**	**3,440.95**	**3,441.09**

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Figure 5: Dashboard 1. Bridge management during flooding events. Main view.

The dashboard allows users to explore different closure scenarios, retrieving both risk assessments and traffic simulation results. This interactive functionality enables decision-makers to evaluate potential outcomes before acting.

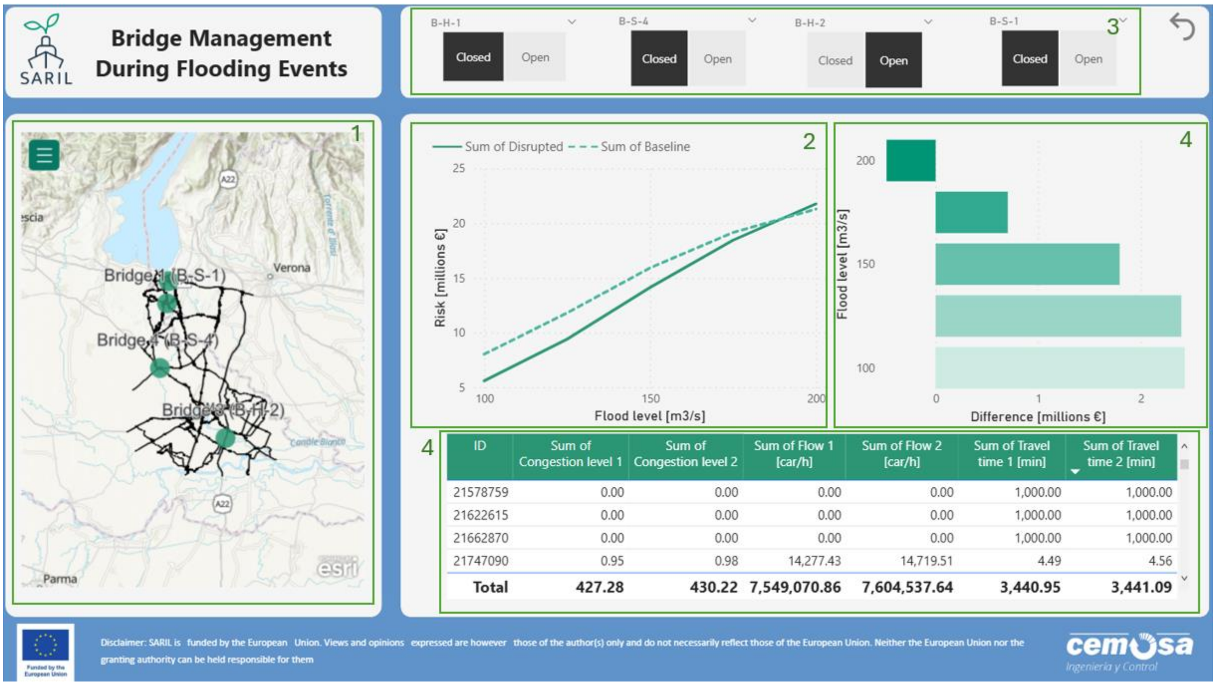
To enhance situational awareness, the dashboards incorporate GIS-based visualizations of bridges and connected road networks, allowing users to better understand the geographical context. Additionally, the dashboards link each operational scenario with its corresponding simulation outputs, delivering comprehensive and actionable insights that directly support flood-related decision-making.

The dashboard has the following elements, following the scheme of Figure 6:

1. Map showing the road network (black lines) and the location of the bridges to be managed (green circles). The map is fully navigable and dynamically linked to the other dashboard elements. Selecting a bridge or area on the map automatically filters the traffic simulation outputs, while choosing specific simulation results updates the corresponding visualization on

the map. This map is especially useful to connect the dashboard information and provide geographical context.

2. Risk value depending on flooding level graph comparison between disrupted-case (flooding) and mitigated-case (bridge management against flooding). The graph shows the risk, measured in millions of euros, of the different scenarios of bridges closing and opening with respect to the flooding level measured in m^3/s. This graph will change depending on the selection of bridges to be closed, comparing the disrupted-case to the different available scenarios. It is useful to understand how risk changes depending on the different scenarios, allowing fast and visual access to useful management information. This graph dynamically updates based on the selection of bridges to be closed, comparing the disrupted case with the different available scenarios. It provides a clear view of how risk levels vary across scenarios, offering quick and visual access to valuable management insights.
3. Bridges management filter that allows selecting which bridges will remain open or be closed in the scenario under analysis.
4. Bar plot of risk difference. Instead of showing both disrupted and mitigated-cases, it directly shows how the situation improves or worsens from the disrupted scenario after the selection of the bridges management scenario.
5. Traffic simulation output. This table shows the traffic outputs relative to each road section and their summatory for the variables: Congestion level, Car flow (measured in car/h) and travel time (measured in minutes) per traffic direction (1 and 2), and the total summatory of each of these variables. This feature provides additional insights to support bridge management by showing the impact of bridge closures in relation to traffic conditions.



ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21578759	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21622615	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21662870	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21747090	0.95	0.98	14,277.43	14,719.51	4.49	4.56
Total	**427.28**	**430.22**	**7,549,070.86**	**7,604,537.64**	**3,440.95**	**3,441.09**

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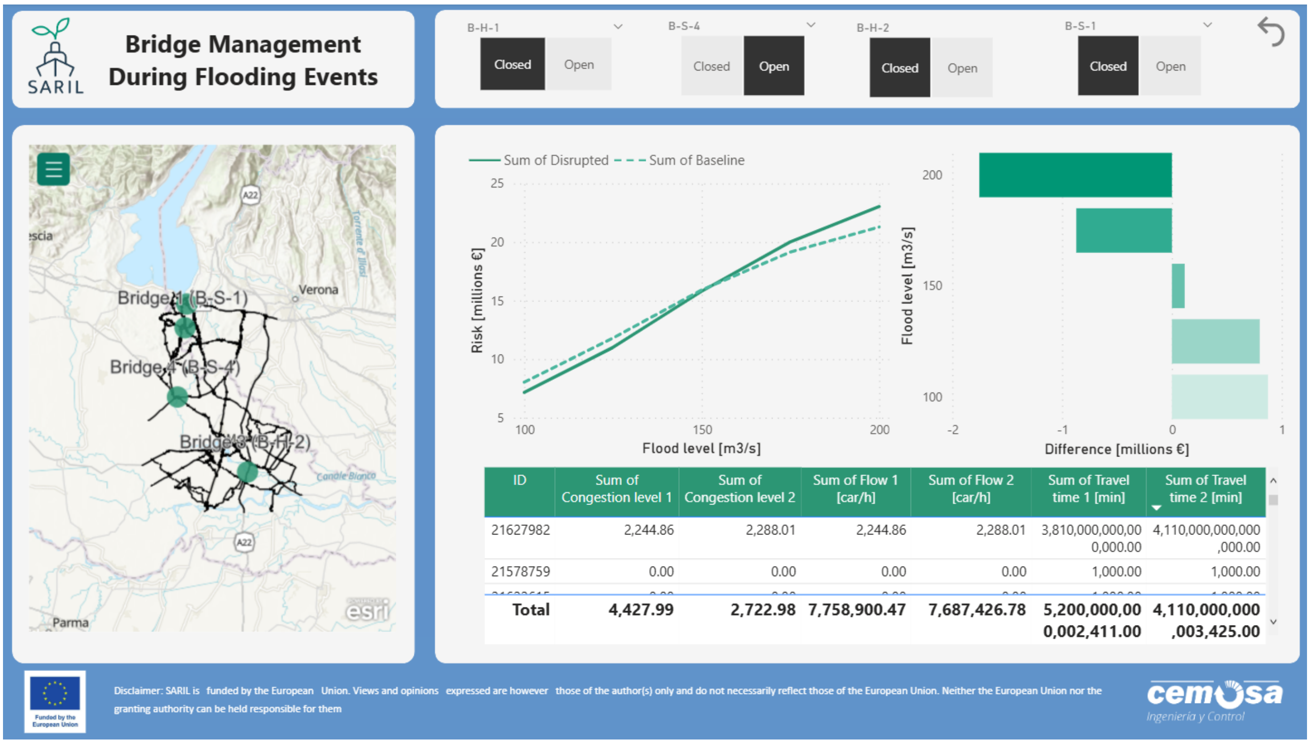
Figure 6: Dashboard 1. Bridge management during flooding events. Main view with elements highlighted.

Figure 7, Figure 8, Figure 9 and Figure 10show four different examples of schemes of bridge management (closure and opening of bridges configurations), and how this affects the results from the different Dashboard elements.



Bridge Management During Flooding Events

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21627982	2,244.86	2,288.01	2,244.86	2,288.01	3,810,000,000,000,000.00	4,110,000,000,000,000.00
21578759	0.00	0.00	0.00	0.00	1,000.00	1,000.00
Total	**4,427.99**	**2,722.98**	**7,758,900.47**	**7,687,426.78**	**5,200,000,000,002,411.00**	**4,110,000,000,003,425.00**

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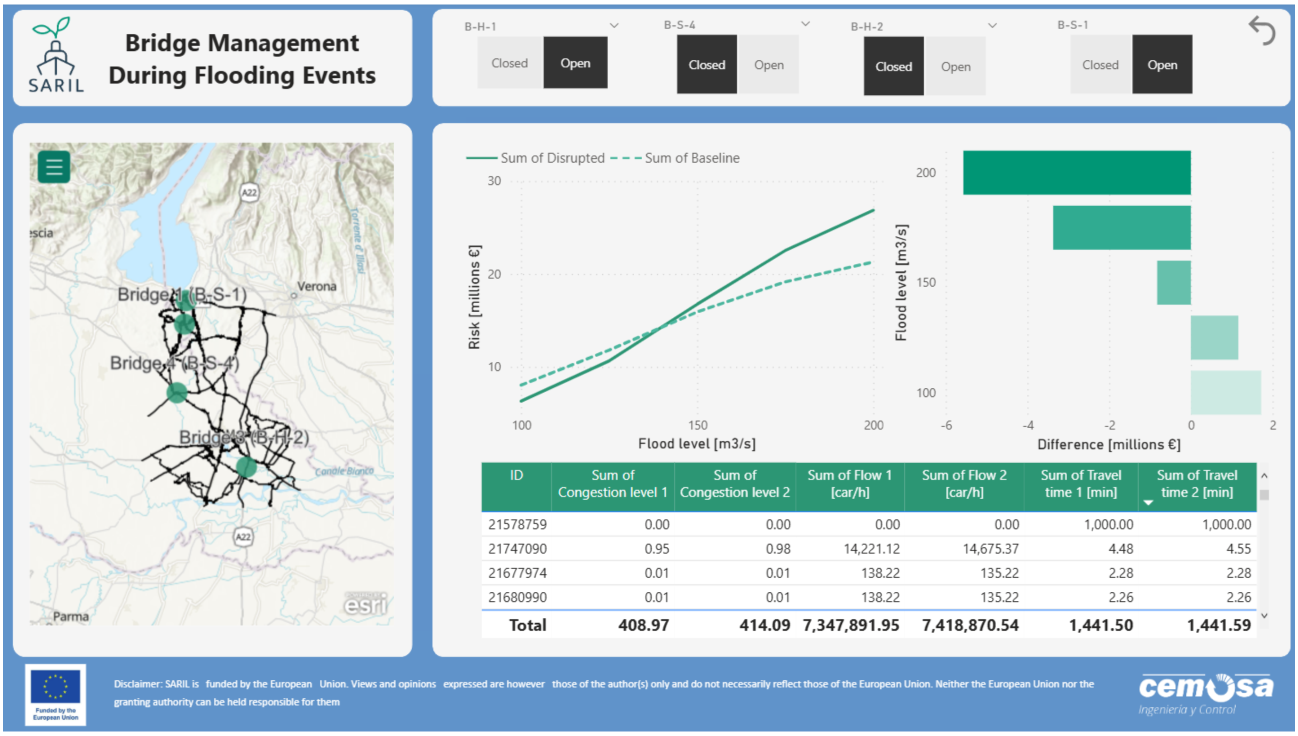
Figure 7: Dashboard 1. Bridge management during flooding events. Results for four different configurations of bridges management. Example 1.



Bridge Management During Flooding Events

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21578759	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21747090	0.95	0.98	14,221.12	14,675.37	4.48	4.55
21677974	0.01	0.01	138.22	135.22	2.28	2.28
21680990	0.01	0.01	138.22	135.22	2.26	2.26
Total	**408.97**	**414.09**	**7,347,891.95**	**7,418,870.54**	**1,441.50**	**1,441.59**

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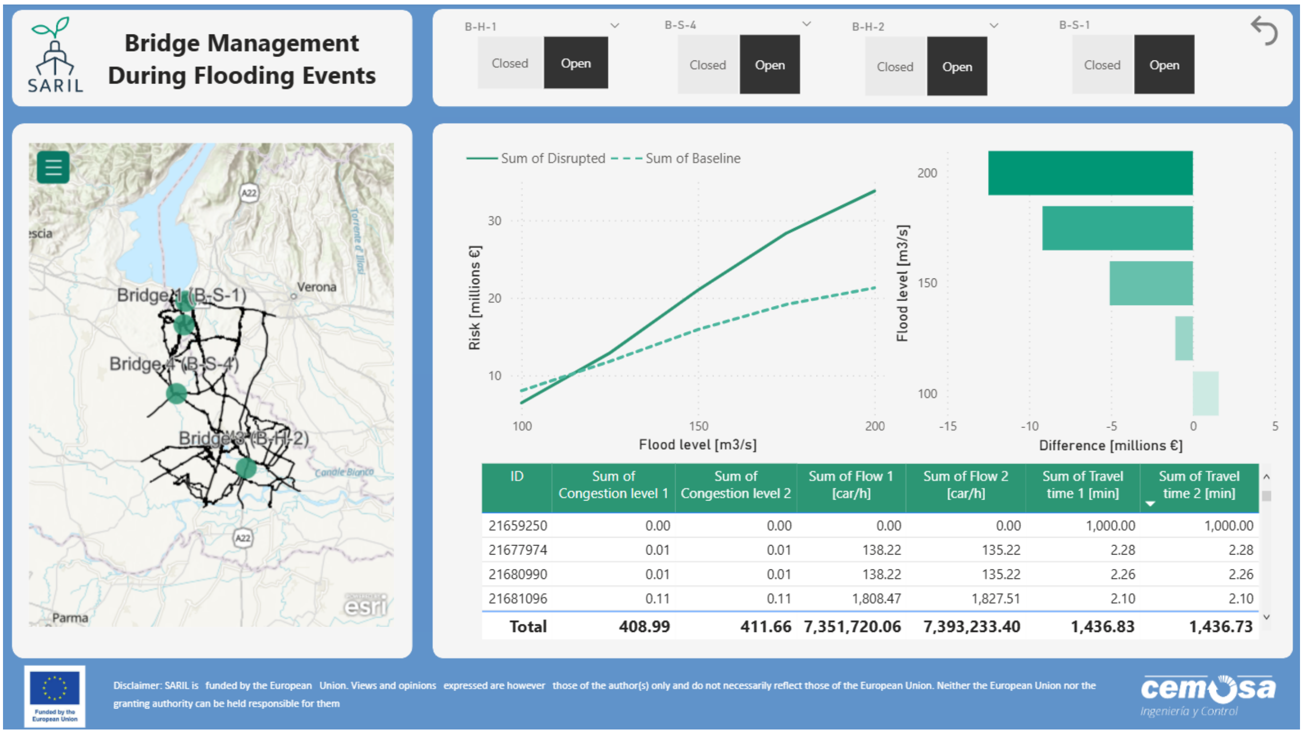
Figure 8: Dashboard 1. Bridge management during flooding events. Results for four different configurations of bridges management. Example 2.



Bridge Management During Flooding Events

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21659250	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21677974	0.01	0.01	138.22	135.22	2.28	2.28
21680990	0.01	0.01	138.22	135.22	2.26	2.26
21681096	0.11	0.11	1,808.47	1,827.51	2.10	2.10
Total	**408.99**	**411.66**	**7,351,720.06**	**7,393,233.40**	**1,436.83**	**1,436.73**

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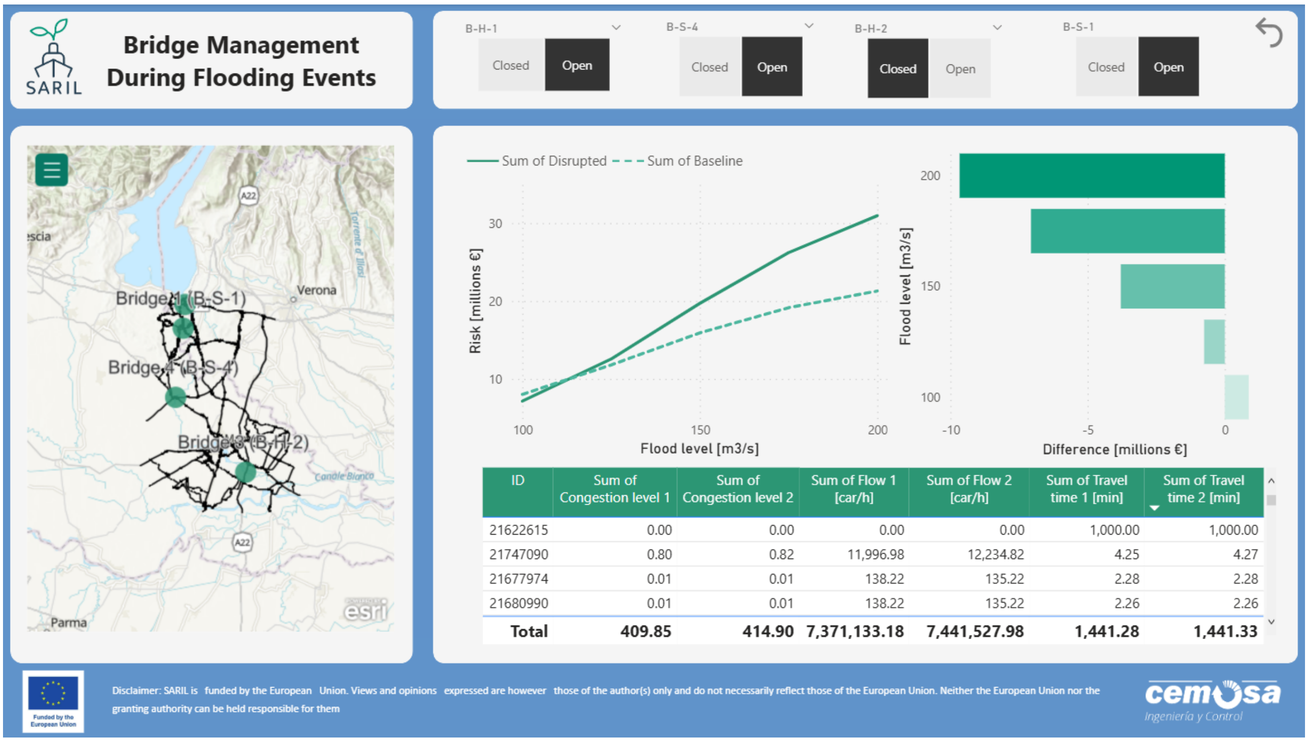
Figure 9: Dashboard 1. Bridge management during flooding events. Results for four different configurations of bridges management. Example 3.



Bridge Management During Flooding Events

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21622615	0.00	0.00	0.00	0.00	1,000.00	1,000.00
21747090	0.80	0.82	11,996.98	12,234.82	4.25	4.27
21677974	0.01	0.01	138.22	135.22	2.28	2.28
21680990	0.01	0.01	138.22	135.22	2.26	2.26
Total	**409.85**	**414.90**	**7,371,133.18**	**7,441,527.98**	**1,441.28**	**1,441.33**

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Figure 10: Dashboard 1. Bridge management during flooding events. Results for four different configurations of bridges management. Example 4.

The dashboard provides detailed information that can be explored in different ways, such as navigating the graphs (Figure 11), which allows to obtain the exact value for a specific X-axis location for both measured variables. The same detailed information can be provided from the bar plots (Figure 12). Zooms can also be applied to all dashboard elements.

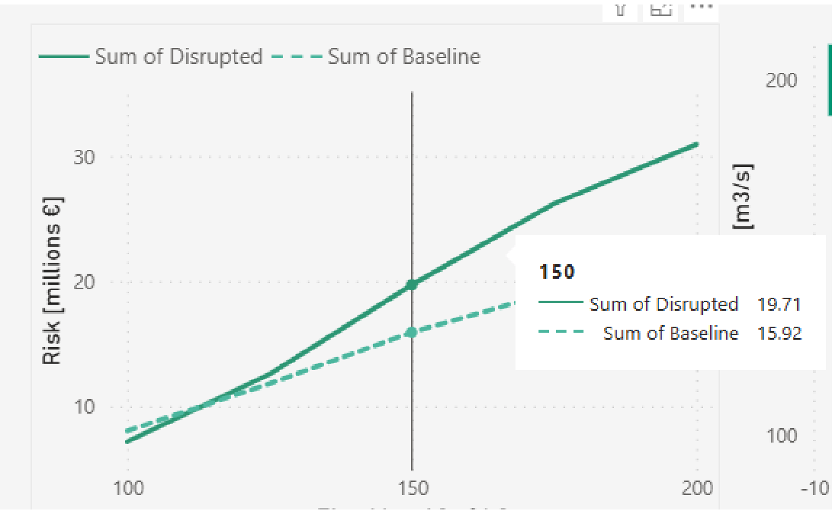


Figure 11: Dashboard 1. Bridge management during flooding events. Zoom on detailed information provided by graph.

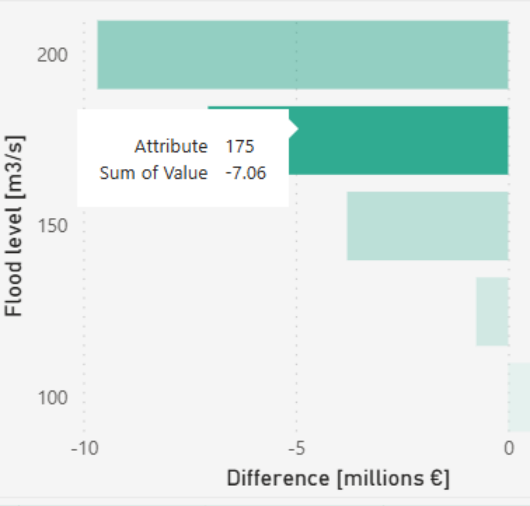


Figure 12: Dashboard 1. Bridge management during flooding events. Zoom on detailed information provided by bar-plot.

Figure 13 shows the interconnection with the geographical context. In this case one of the roads which works as bridge access is selected within the map, and this selection filters the simulation output chart, easing the access to its relative information.

Use the selection tools below to highlight an area on the map

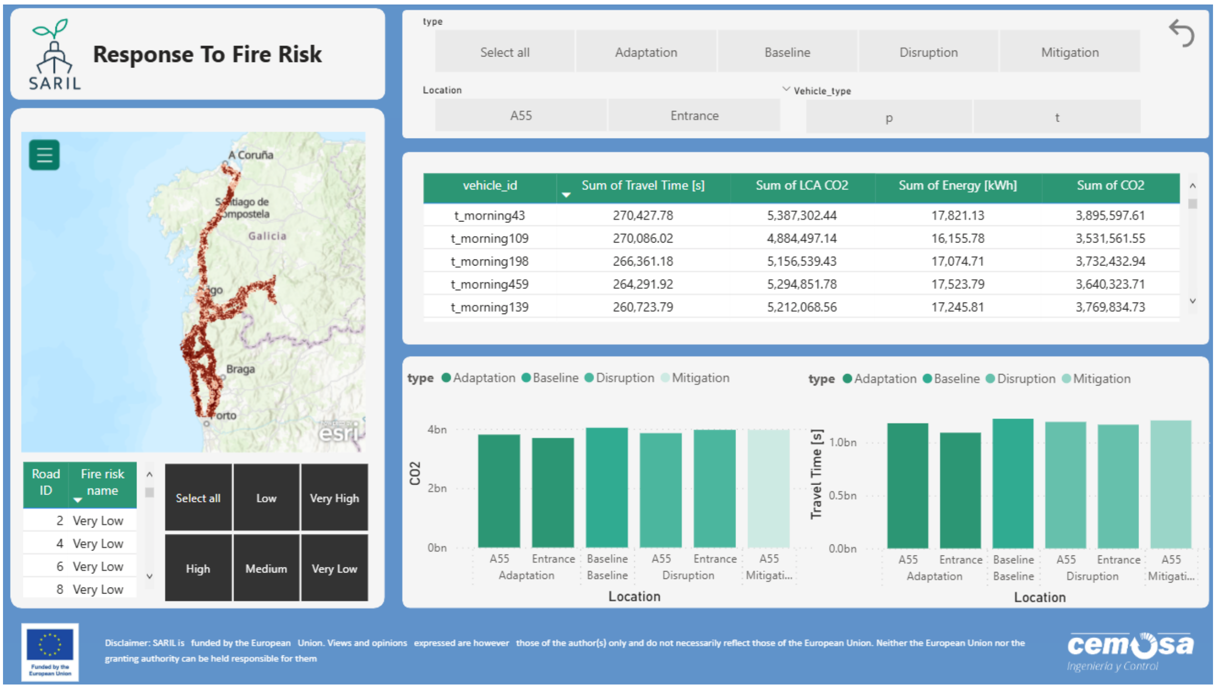
1 feature(s) selected.

ID	Sum of Congestion level 1	Sum of Congestion level 2	Sum of Flow 1 [car/h]	Sum of Flow 2 [car/h]	Sum of Travel time 1 [min]	Sum of Travel time 2 [min]
21662247	0.23	0.18	8,122.41	6,326.52	0.38	0.38
Total	**0.23**	**0.18**	**8,122.41**	**6,326.52**	**0.38**	**0.38**

Figure 13: Bridge management during flooding events. Interconnection between data simulation outputs and geographical context.

4.2.2.2 Dashboard 2. Response to fire risk

Response to fire risk dashboard (Figure 14) focuses on the simulation of traffic under different disruption and mitigation scenarios related to fire events in the area of the national scenario. It has been developed to provide decision-makers with actionable insights that improve road management and emergency response strategies.



vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning43	270,427.78	5,387,302.44	17,821.13	3,895,597.61
t_morning109	270,086.02	4,884,497.14	16,155.78	3,531,561.55
t_morning198	266,361.18	5,156,539.43	17,074.71	3,732,432.94
t_morning459	264,291.92	5,294,851.78	17,523.79	3,640,323.71
t_morning139	260,723.79	5,212,068.56	17,245.81	3,769,834.73

Road ID	Fire risk name
2	Very Low
4	Very Low
6	Very Low
8	Very Low

Figure 14: Dashboard 2. Response to Fire Risk. Main view.

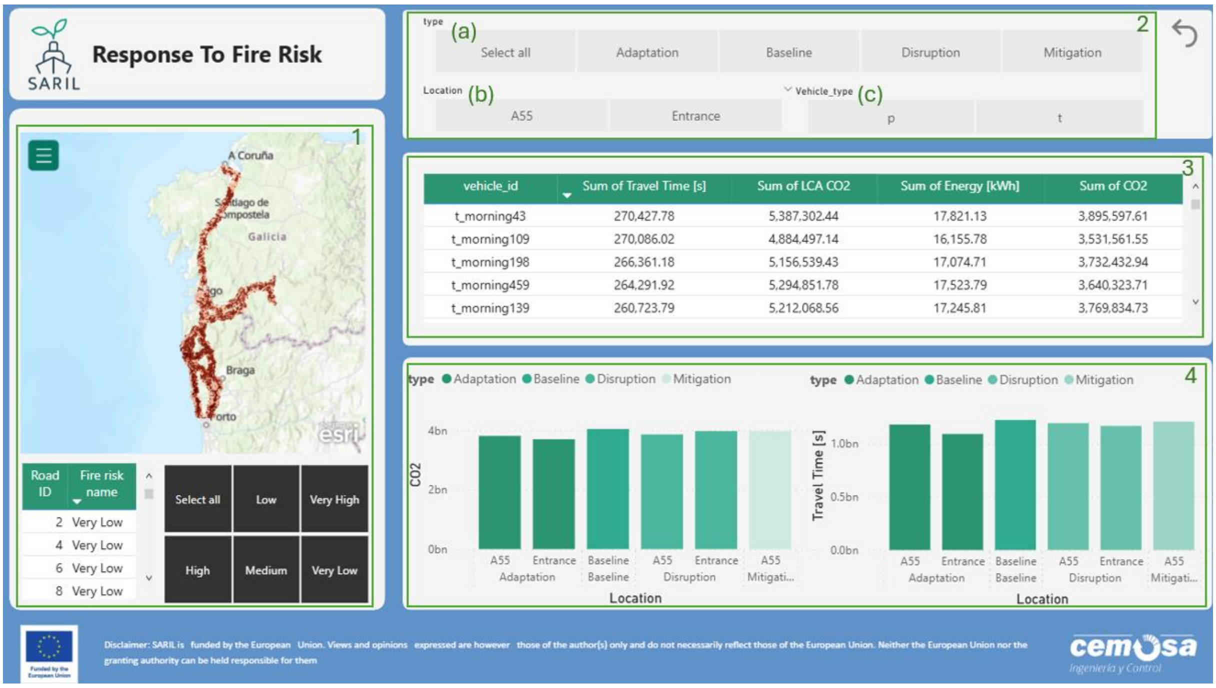
The dashboard enables visualization of simulations at the vehicle level, allowing users to understand how traffic flows are affected in various conditions. Beyond individual cases, it also supports global comparisons across vehicle types and locations, offering a broader perspective to guide effective decision-making.

An integrated fire risk map further enriches the analysis by displaying risk levels linked to specific road IDs. This interactive component allows users to filter and select information directly from the map and related controls, making it easier to identify critical areas and prioritize management actions.

Overall, the dashboard combines traffic simulations and fire risk analysis into a practical tool that enhances situational awareness, facilitates scenario evaluation, and supports timely and well-informed decisions for managing roads under fire-related disruptions.

The different elements highlighted in Figure 14 are the following:

1. Map with the different network areas coloured relative to their fire risk level. This map is navigable and can be filtered by the rest of the dashboard elements. This map is above fire risk level chart and selector, allowing the filtering depending on the value of fire risk level that wants to be analysed and the fire risk level associated to each road ID. This provides geographical context to the analysis and enriches the simulation outputs with the possibility of fire in the different areas of study.
2. Filters. There are filters to select and interact with the dashboard to obtain the most useful information for the desired analysis:
    a. Which type of simulation data will be displayed: Baseline, Disruption, Adaptation or Mitigation simulations.
    b. Which location will be analysed, the two available are the A55 (A-55 motorway, which connects Vigo (Galicia) with the Portuguese border) and Entrance (AP-9 highway at the entrance to the city of Vigo).
    c. Two types of vehicles simulated: p (passengers' car) and t (trucks).
3. Outputs chart. This table shows the detailed results of the vehicles simulation, showcasing per vehicle their relative value for travel time, CO_2 usage, CO_2 relative to the whole LCA analysis, and Energy usage (kWh).
4. Bar plots of relevant variables. To provide easy comparison between the different scenario and take informed decisions, the bar plots show the CO_2 emissions and Travel time consumption summed values for each of the selected scenarios.



Road ID	Fire risk name
2	Very Low
4	Very Low
6	Very Low
8	Very Low

vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning43	270,427.78	5,387,302.44	17,821.13	3,895,597.61
t_morning109	270,086.02	4,884,497.14	16,155.78	3,531,561.55
t_morning198	266,361.18	5,156,539.43	17,074.71	3,732,432.94
t_morning459	264,291.92	5,294,851.78	17,523.79	3,640,323.71
t_morning139	260,723.79	5,212,068.56	17,245.81	3,769,834.73

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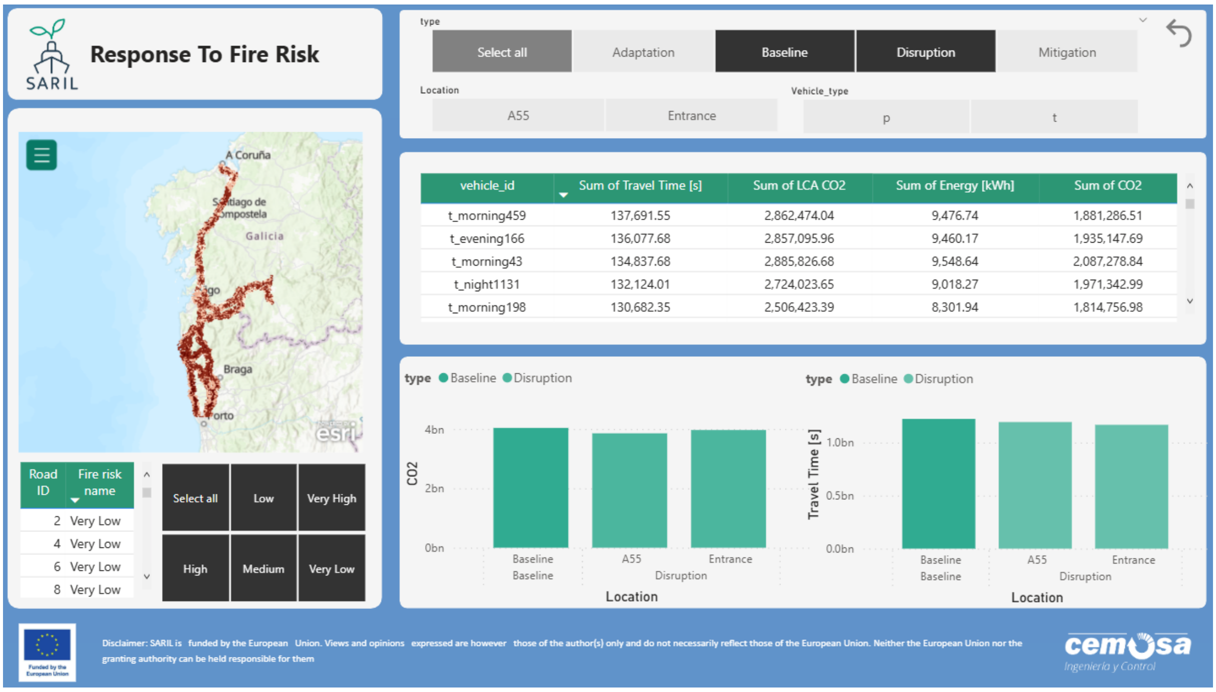
Figure 15: Dashboard 2. Response to Fire Risk. Main view with elements highlighted.

Figure 16 shows another one of the possibilities that can filter the dashboard. In this case, both location and all types of vehicles are included, but we can compare the baseline situation with the disrupted one, minimizing the quantity of information on the panel. Figure 17 shows another possible filtering of the information, allowing access to one of the locations, and comparing the disrupted case with one of the mitigated cases, allowing to assess how suitable this mitigation-case is. As it is shown in the figure, detailed information is provided when hovering over the graphs.



Road ID	Fire risk name
2	Very Low
4	Very Low
6	Very Low
8	Very Low

vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning459	137,691.55	2,862,474.04	9,476.74	1,881,286.51
t_evening166	136,077.68	2,857,095.96	9,460.17	1,935,147.69
t_morning43	134,837.68	2,885,826.68	9,548.64	2,087,278.84
t_night1131	132,124.01	2,724,023.65	9,018.27	1,971,342.99
t_morning198	130,682.35	2,506,423.39	8,301.94	1,814,756.98

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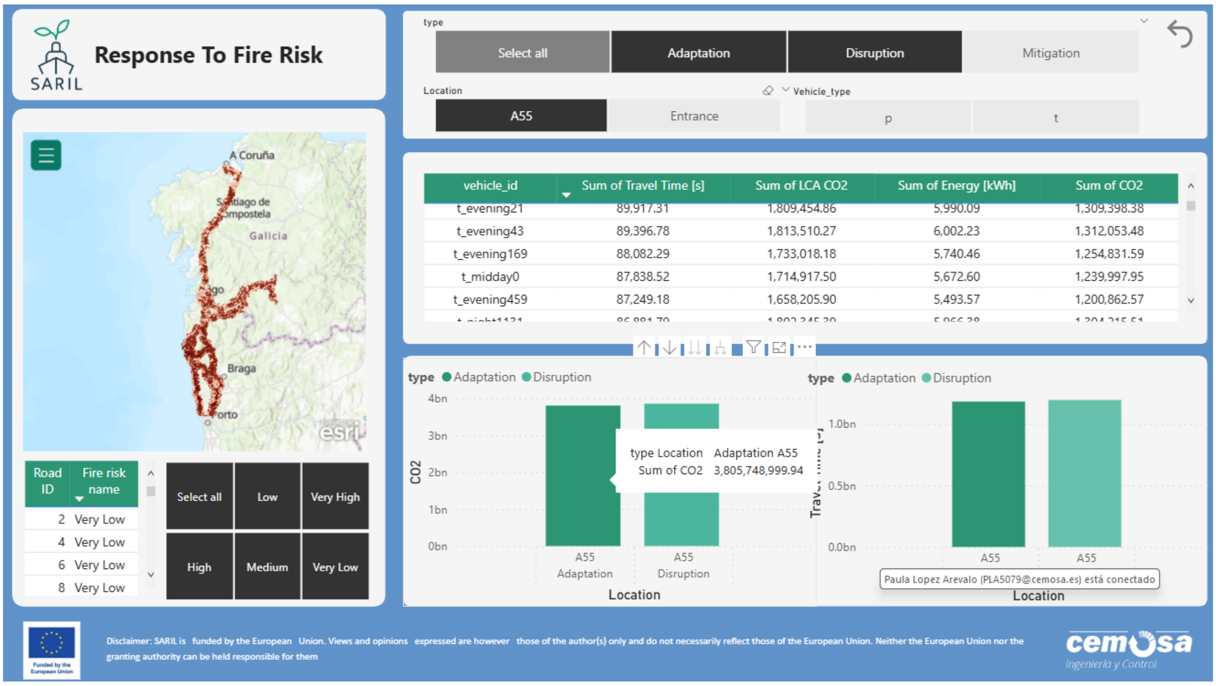
Figure 16: Dashboard 2. Response to Fire Risk. Alternative filtering.



vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_evening21	89,917.31	1,809,454.86	5,990.09	1,309,398.38
t_evening43	89,396.78	1,813,510.27	6,002.23	1,312,053.48
t_evening169	88,082.29	1,733,018.18	5,740.46	1,254,831.59
t_midday0	87,838.52	1,714,917.50	5,672.60	1,239,997.95
t_evening459	87,249.18	1,658,205.90	5,493.57	1,200,862.57

Road ID	Fire risk name
2	Very Low
4	Very Low
6	Very Low
8	Very Low

type Location Adaptation A55
Sum of CO2 3,805,748,999.94

Paula Lopez Arevalo (PLA5079@cemosa.es) está conectado

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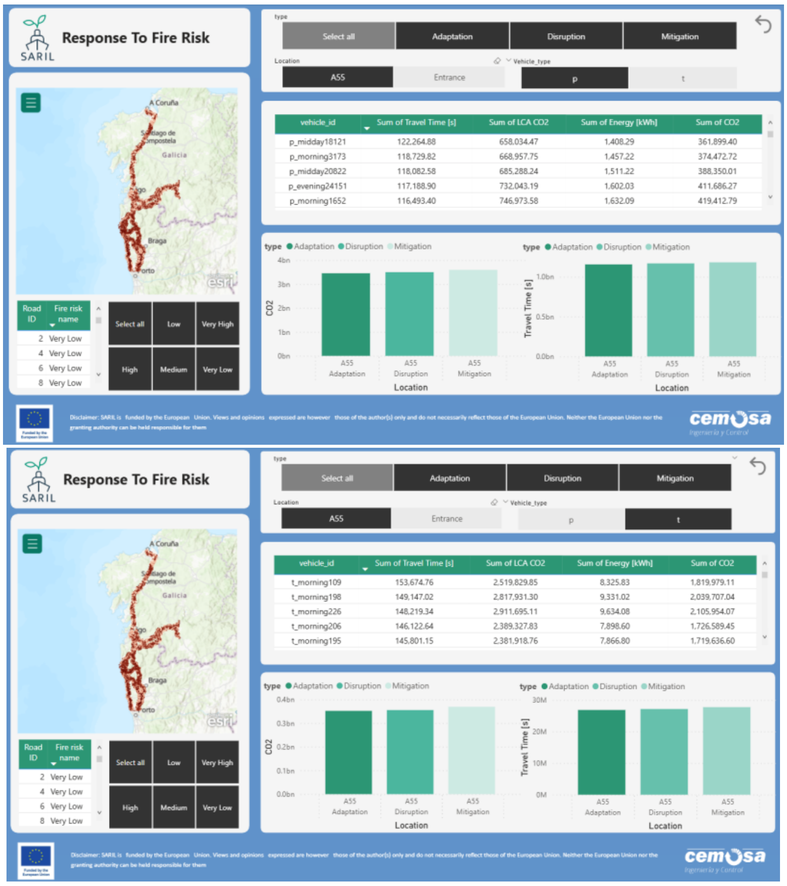
Figure 17: Dashboard 2: Response to Fire Risk. Alternative filtering with detailed information from graphs.

Another interesting analysis that can be retrieved from this dashboard is the comparison of the impact of the different types of vehicles of the analysis. As it is shown in Figure 18, in which for the same location and cases of study, the results are obtained only for passenger cars (top) or trucks (bottom).

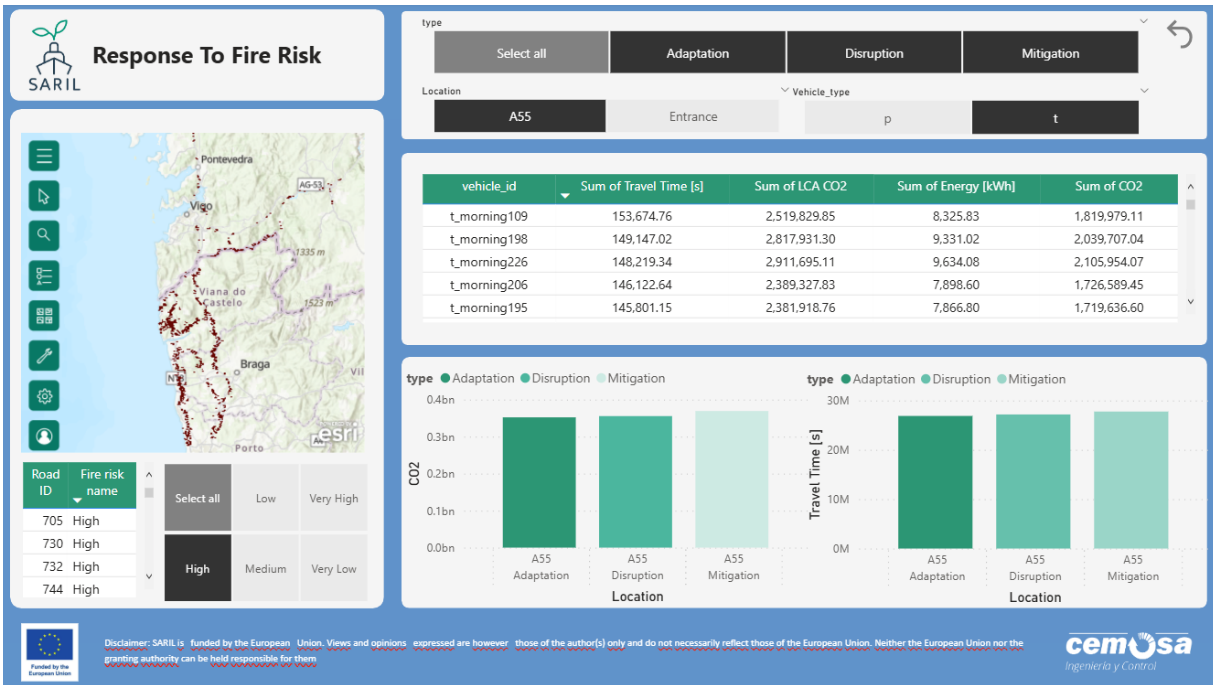


vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
p_midday18121	122,264.88	658,034.47	1,408.29	361,899.40
p_morning3173	118,729.82	668,957.75	1,457.22	374,472.72
p_midday20822	118,082.58	685,288.24	1,511.22	388,350.01
p_evening24151	117,188.90	732,043.19	1,602.03	411,686.27
p_morning1652	116,493.40	746,973.58	1,632.09	419,412.79

vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning109	153,674.76	2,519,829.85	8,325.83	1,819,979.11
t_morning198	149,147.02	2,817,931.30	9,331.02	2,039,707.04
t_morning226	148,219.34	2,911,695.11	9,634.08	2,105,954.07
t_morning206	146,122.64	2,389,327.83	7,898.60	1,726,589.45
t_morning195	145,801.15	2,381,918.76	7,866.80	1,719,636.60

Figure 18: Dashboard 2. Response to Fire Risk. Selection of type of vehicle filtering. Passenger cars filtering (top) and Trucks filtering (bottom).

The last dashboard feature is related to the fire risk areas. The map can be filtered by the selected fire risk level as shown in Figure 19 (filtering of high risk areas) and Figure 20 (filtering of medium and low areas). The filtering can also be done by selecting in the map specific areas as it was done in the example of Figure 21. All the selected roads are displayed in the chart, which can also be used as a filter.



Response To Fire Risk

Road ID	Fire risk name
705	High
730	High
732	High
744	High

vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning109	153,674.76	2,519,829.85	8,325.83	1,819,979.11
t_morning198	149,147.02	2,817,931.30	9,331.02	2,039,707.04
t_morning226	148,219.34	2,911,695.11	9,634.08	2,105,954.07
t_morning206	146,122.64	2,389,327.83	7,898.60	1,726,589.45
t_morning195	145,801.15	2,381,918.76	7,866.80	1,719,636.60

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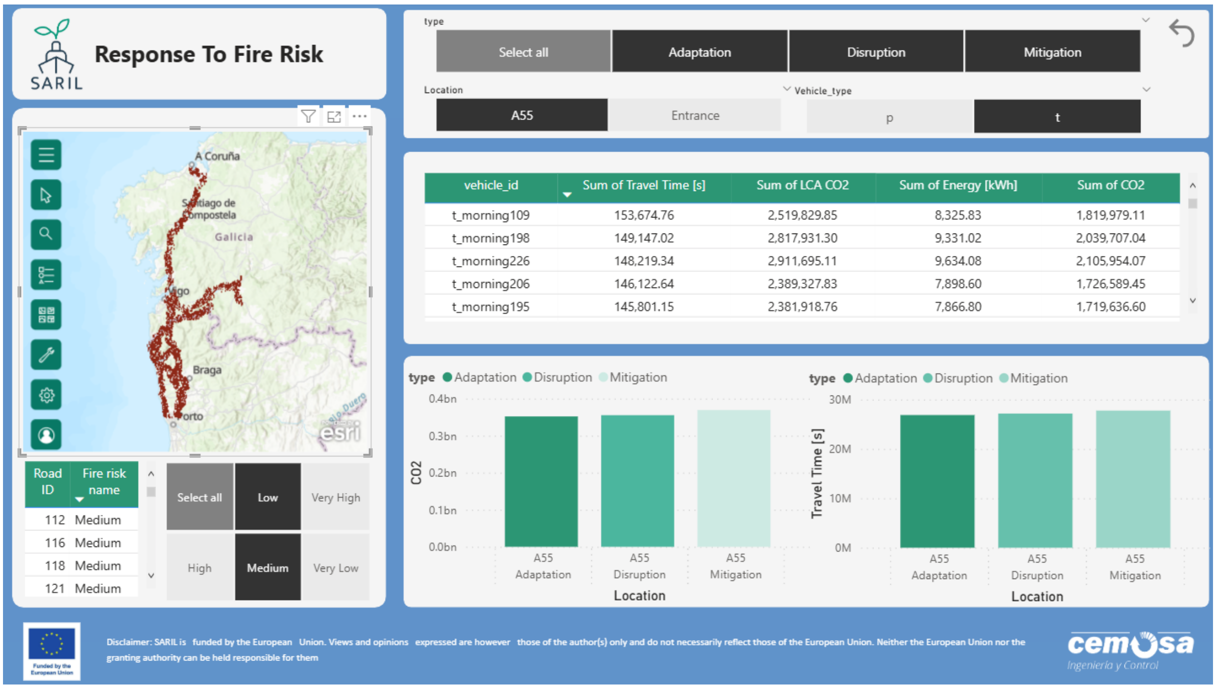
Figure 19: Dashboard 2. Response to Fire Risk. High fire risk filtering.



Response To Fire Risk

Road ID	Fire risk name
112	Medium
116	Medium
118	Medium
121	Medium

vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning109	153,674.76	2,519,829.85	8,325.83	1,819,979.11
t_morning198	149,147.02	2,817,931.30	9,331.02	2,039,707.04
t_morning226	148,219.34	2,911,695.11	9,634.08	2,105,954.07
t_morning206	146,122.64	2,389,327.83	7,898.60	1,726,589.45
t_morning195	145,801.15	2,381,918.76	7,866.80	1,719,636.60

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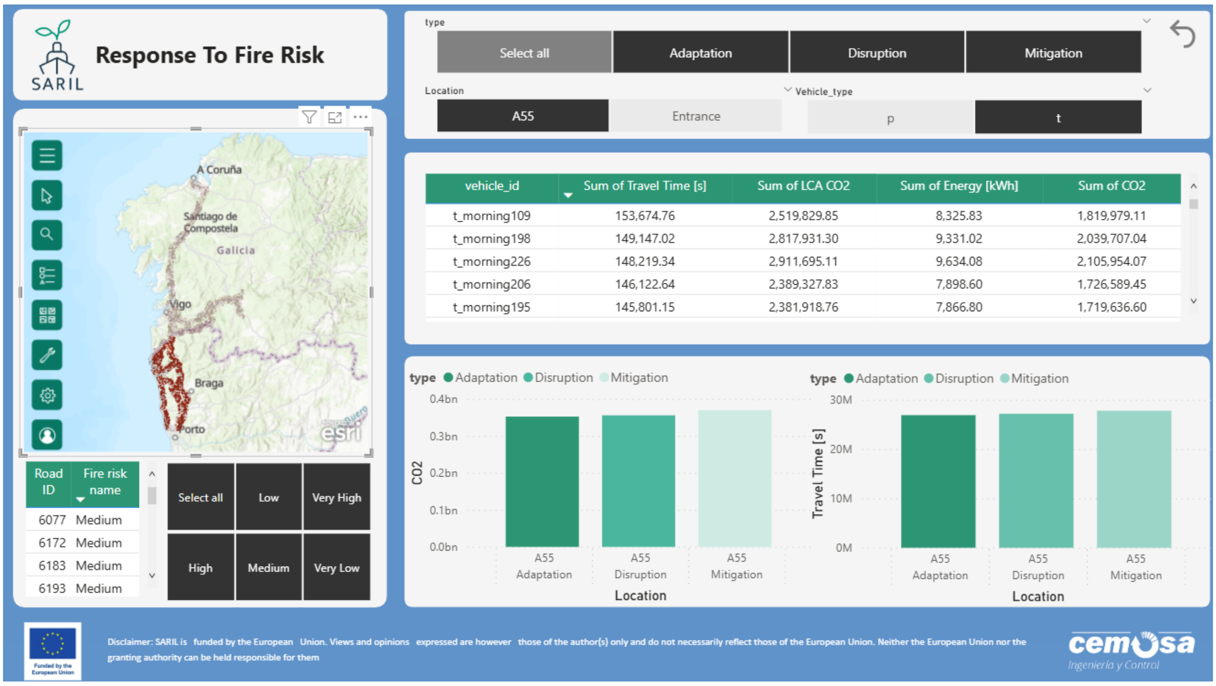
Figure 20: Dashboard 2. Response to Fire Risk. Medium and low fire risk filtering.



vehicle_id	Sum of Travel Time [s]	Sum of LCA CO2	Sum of Energy [kWh]	Sum of CO2
t_morning109	153,674.76	2,519,829.85	8,325.83	1,819,979.11
t_morning198	149,147.02	2,817,931.30	9,331.02	2,039,707.04
t_morning226	148,219.34	2,911,695.11	9,634.08	2,105,954.07
t_morning206	146,122.64	2,389,327.83	7,898.60	1,726,589.45
t_morning195	145,801.15	2,381,918.76	7,866.80	1,719,636.60

Road ID	Fire risk name
6077	Medium
6172	Medium
6183	Medium
6193	Medium

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Figure 21: Dashboard 2. Response to Fire Risk. Road ID filtered by maps selection.

4.2.2.3 Dashboard 3. European logistic network

European Logistic Network (Figure 22) dashboard provides a comprehensive view of delivery operations, focusing on deliveries counts, CO_2 emissions, and cost evolution over time. By visualizing these indicators, the dashboard enables users to monitor trends, evaluate performance, and assess the impact of different scenarios.

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Figure 22: Dashboard 3. European logistic network.

All information is fully filterable, allowing comparisons between cases or across specific timeframes through the date filter. In addition, users can select individual nodes to analyse detailed information at specific locations, enhancing the depth of the analysis.

The dashboard is also directly connected to the interactive map of nodes. This means that selections made on the map filter the data displayed in the charts, and vice versa, ensuring a consistent and intuitive exploration of the information.

Overall, the dashboard offers a flexible and interactive tool for monitoring key delivery metrics, supporting better decision-making on efficiency, costs, and environmental impact.

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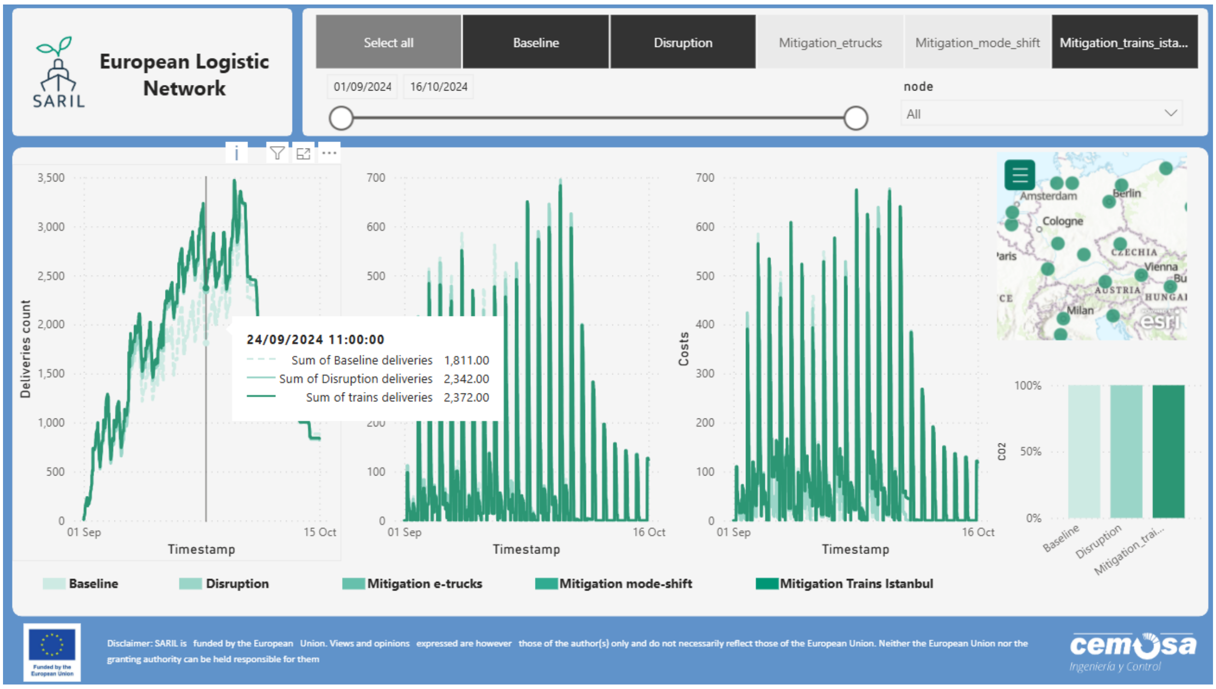
Figure 23: Dashboard 3. European logistic network. Main view with elements highlighted.

The dashboard counts with the following elements, which are highlighted in Figure 23:

1. Filters to interact with the dashboard, selecting the simulations which information wants to be visualized (baseline, disruption and the three different mitigation scenarios), date filter, to select specific periods for the analysis and node filter, to select the ID of the network node that wants to be included in the analysis.
2. Evolution of parameters over time. These three graphs display the progression of key study variables (number of deliveries, CO_2 emissions, and costs) across different time periods. They enable direct comparison between scenarios, helping to better understand how various measures influence these critical indicators.
3. Summatory bar chart. This graph presents the overall aggregated results of each scenario in terms of CO_2 emissions. By comparing the total values across scenarios, they provide a clear and concise overview that simplifies the interpretation of results and supports quick comparisons.
4. Nodes map. It shows the location of the different nodes of the analysis. It provides geographical context and allows the filtering of the dashboard.

Detailed information from the graphs can be obtained hovering over them, as shown in Figure 24, which provides the exact information of the sum of deliveries for the three different cases selected for the study. Also, all elements can be zoomed by using their own windows as shown in Figure 25.



24/09/2024 11:00:00
Sum of Baseline deliveries 1,811.00
Sum of Disruption deliveries 2,342.00
Sum of trains deliveries 2,372.00

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Figure 24: Dashboard 3. European logistic network. Detailed information from graphs.

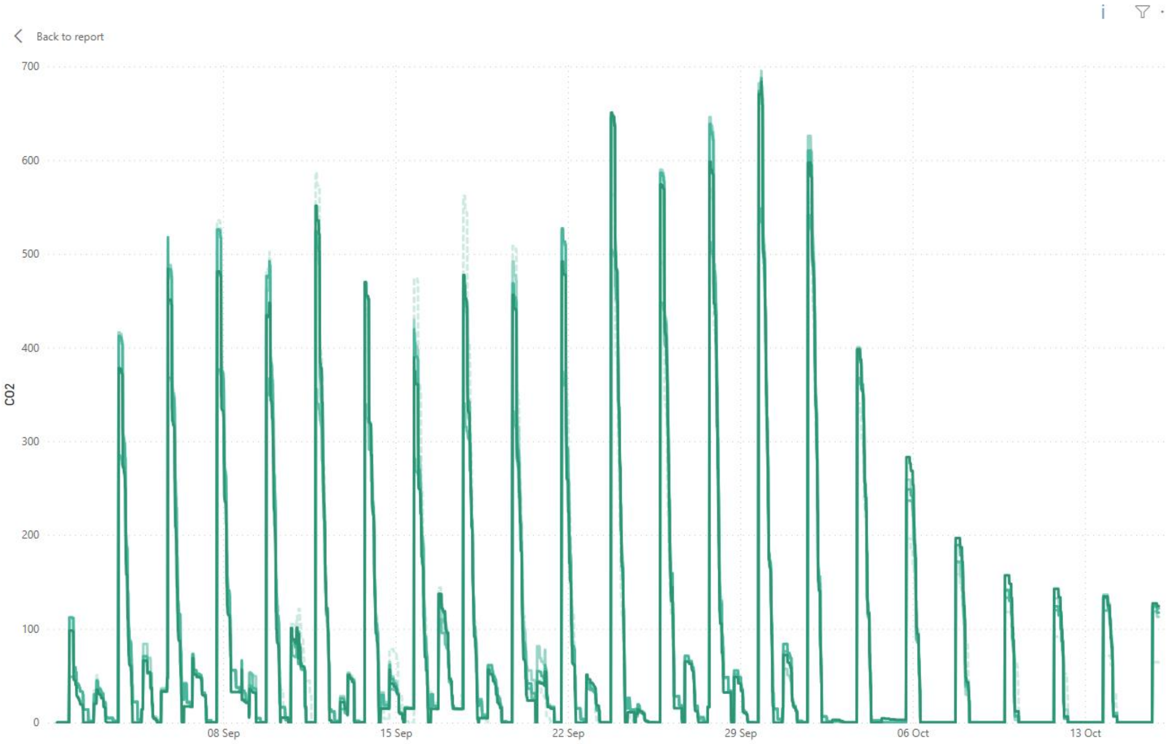

Figure 25: Dashboard 3. European logistic network. Detailed information from CO_2 emissions with respect to time graphs, using zoom window.

The different filters from the dashboard allow to access relevant information in a user-friendly way. Figure 26 shows a different filtering scheme, in this case the three different mitigation cases are selected, and a specific time period between 20/09/2024 and 25/09/2025 is selected.

20/09/2024 25/09/2024

node
All

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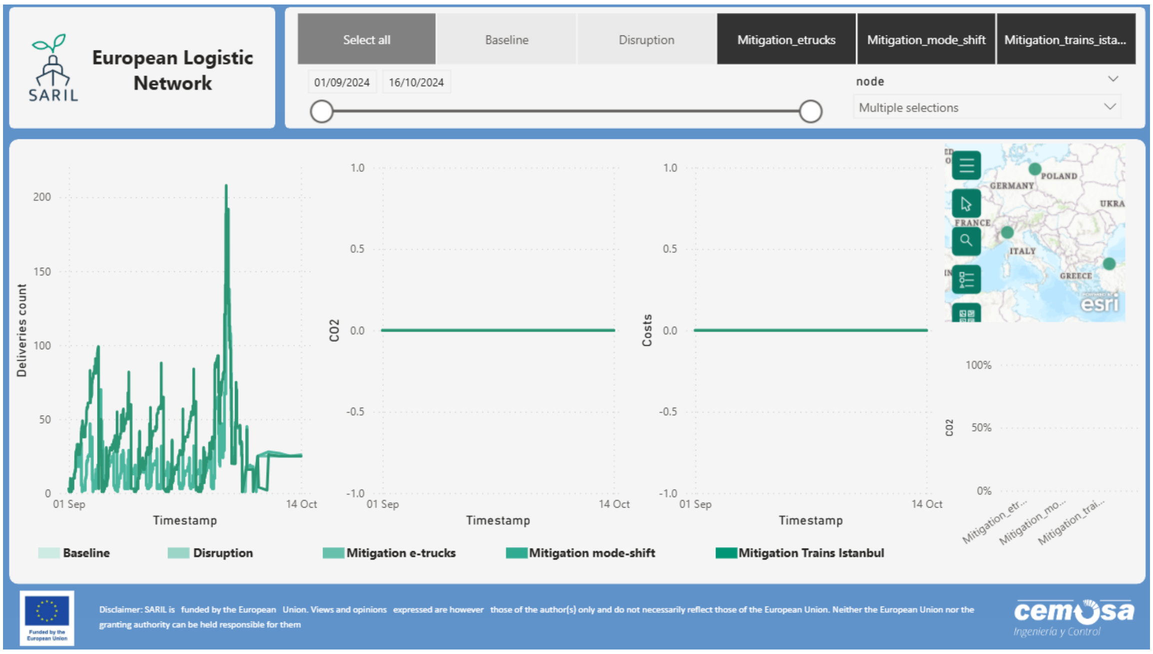
Figure 26: Dashboard 3. European logistic network. Filtered example.

A different analysis can be analysed in Figure 27. In this case the analysis is centred on specific nodes of the network. Once these nodes are selected from the filtering panel or directly from the map visual, only the information gathered for those elements is displayed. Only the deliveries graph is relevant in this case, since costs and CO2 emissions in this model are assumed to be directly associated to the vehicles transport among logistic nodes.



01/09/2024 16/10/2024

node
Multiple selections

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Figure 27: Dashboard 3. European logistic network. Nodes filtering.

5 Final Remarks and Conclusions

Deliverable D3.4 – "General Solutions for the Resilience of Logistic Networks" concludes the analytical cycle of Work Package 3 within SARIL, translating the scenario-specific results developed in earlier stages into a coherent, generalizable framework. The work presented here is grounded on the comparative evaluation of three distinct but interlinked scales—regional, national, and European—that represent the diversity of Europe's transport and logistics systems. Using the outputs of SARIL tools and the GRA methodology, the deliverable demonstrates how resilience patterns can be measured, compared, and synthesized into transferable solutions that improve both operational robustness and environmental sustainability.

The results confirm that resilience in logistics networks can be quantified, benchmarked, and generalized through a combination of Key Performance Indicators, simulation data, and business intelligence (BI) tools. Across all case studies, the methodology proved capable of identifying consistent patterns linking the operational, economic, and environmental dimensions of resilience. Specifically, three global observations emerge from the comparative analysis:

- Cross-scenario consistency: Despite the differences between flood-related, fire-related, and geopolitical disruptions, the relative behaviour of the systems follows similar patterns when analysed through the selected KPIs of cost, time, and CO_2 emissions.
    - In all scales, disruptions lead to an increase in travel time and cost, as well as a rise in emissions.
    - Mitigation measures, when correctly designed and executed, systematically reduce the magnitude of these impacts, though the degree of improvement varies.
    - The general methodology, based on comparing *base*, *disrupted*, and *mitigated* cases, enables a consistent numerical representation of improvement levels across diverse contexts.
- Interdependence between resilience and sustainability: Measures that improve the system's adaptive behaviour often reduce its environmental footprint. For example, optimized rerouting in the regional and national cases not only shortened recovery time but also decreased unnecessary detours, resulting in lower emissions and energy use.
- Feasibility of generalization: The GRA, originally tailored to individual scenarios, has been successfully extended to a generic framework through normalization and weighting procedures. The formulation of the Green Resilience Index (KPI_{GRA}) allows for comparison between distinct networks and hazard types, demonstrating that quantitative resilience assessment can be standardized across multiple scales.

The three scenarios analyzed during SARIL project, had a series of technical implications:

(1) Regional scenario (flooding and bridge management)

The regional analysis, based on the Mincio River network in eastern Italy, explored the impact of different bridge closure combinations under flood conditions. The main insight from this study is that selective bridge management—guided by monitoring tools such as the Scour Monitoring for Decision Support Tool—significantly reduces both travel time and associated economic losses. While full closure of all bridges maximizes safety, it produces severe mobility restrictions and economic costs. The application of real-time monitoring enables partial or selective closures, maintaining acceptable levels of functionality even during extreme events.

The use of Power BI dashboards in this context was oriented towards diverse objectives:

- Allow operators to visualize the relationship between river discharge levels, bridge failure probabilities, and network performance indicators.
- Allow the testing of alternative closure configurations interactively. The dashboard helped identify the combination that minimizes risk while preserving the highest possible traffic throughput.

The normalized KPIs confirmed that certain mitigations outperform others, balancing cost and time more effectively. The ability to visualize these trade-offs supports evidence-based flood management and demonstrates how SARIL's approach bridges technical modelling with operational decision-making.

(2) National scenario (forest fires and road network disruption)

The national scenario, covering the cross-border transport corridor connecting northern Portugal and Galicia, Spain, focused on disruptions caused by forest fires affecting critical motorway segments (A-55 and AP-9). The SARIL methodology assessed the effects of these disruptions on travel time and CO_2 emissions and tested the performance of mitigation strategies such as firebreaks, early-warning systems, and dynamic route guidance.

The results indicate clear performance differences among mitigation measures:

- Firebreaks reduce the physical exposure of the network, lowering the travel-time impact but with moderate influence on emissions.
- Early-warning systems provide greater overall effectiveness by allowing earlier responses and traffic redistribution before congestion peaks, leading to both lower travel times and reduced CO_2 output.
- Dynamic route guidance, applied at the Vigo access, proved especially efficient, bringing the KPIs of disrupted traffic close to baseline levels.

These outcomes demonstrate the complementary nature of preventive (firebreaks), reactive (early-warning systems), and adaptive (dynamic guidance) measures. When combined, they offer a layered defence that increases both the robustness and the environmental performance of the transport corridor. The comparative use of normalized KPIs showed how even localized interventions can have measurable effects when assessed through a unified resilience framework.

(3) European scenario (continental freight disruptions)

At the European scale, the analysis focused on freight transport disruptions caused by external geopolitical and systemic events—specifically, the war in Ukraine and a two-week strike in Hamburg Port. The model incorporated mitigation options such as deployment of electric trucks in central Europe, introduction of new rail connections from Istanbul, and modal shift toward alternative transport modes.

The results quantify the trade-offs inherent in large-scale resilience measures:

- An, expected, result proved that electric trucks reduce CO_2 emissions at the expense of higher operating costs, the SARIL analysis quantifies this relationship within a realistic European freight context. The results demonstrate the magnitude of the trade-off and show how weighting different criteria—such as cost versus emissions—affects the selection of optimal mitigation strategies.
- Mode shifting, involving greater use of rail, moderately improves emissions and costs, while maintaining similar travel times.

- The Istanbul rail connection reduces dependence on affected routes but introduces higher delays.

When aggregated into the Green Resilience Index (KPI_{GRA}), the electric truck strategy yields the best overall performance, balancing emissions, travel time, and operational continuity. However, when user priorities are adjusted to give greater weight to cost factors, the mode shift alternative becomes more favourable. This sensitivity demonstrates the flexibility of the methodology to adapt to different stakeholder preferences and policy objectives.

Overall, the European scenario illustrates how SARIL's integrated toolchain—combining ASTROIT, Energy Module, transport simulation, and business intelligence visualization—can quantify continental-scale resilience in a structured and transparent manner.

The implementation of the GRA across the three scenarios validates the robustness and adaptability of the methodology. Several methodological strengths are confirmed by the D3.4 analysis:

- Standardized indicators and normalization: The selection of KPIs based on previous deliverables ensures coherence across scenarios. Normalization eliminates scale bias, enabling fair comparison between different types of hazards and transport systems.
- Weighting of resilience factors: The Analytic Hierarchy Process (AHP) provides a rational basis for defining the relative importance of nine resilience factors—Preparedness, Redundancy, Reliability, Flexibility, Visibility, Security, Collaboration, Recovery, and Learning. Even with limited survey data, this structure proved consistent with observed scenario behaviours.
- Integration of environmental and operational metrics: The inclusion of emissions and energy indicators in the same analytical space as cost and time allows a balanced evaluation of both resilience and sustainability.
- Dynamic visualization for decision support: The Power BI dashboards effectively translate complex simulation results into an interactive environment accessible to technical and non-technical users alike.

The methodological framework thus meets its design objectives: it allows for quantitative, comparable, and operationally meaningful assessment of resilience while maintaining a strong link with environmental performance metrics.

The D3.4 results hold several implications for the practical management of logistic networks:

- Decision support through BI dashboards: The visualization environment enables stakeholders to explore different mitigation combinations and observe the quantitative effects.
- Transferability of KPIs: The defined indicators (cost, travel time, and CO_2 emissions) are general enough to apply to any transport network, yet detailed enough to reflect context-specific dynamics. This balance ensures their usability across projects and governance levels.
- Prioritization of mitigation strategies: The comparative use of the KPI_{GRA} enables clear prioritization of interventions according to the specific objectives—minimizing cost, time, or emissions—without losing overall system perspective.
- Support for adaptive planning: The methodology accommodates feedback and continuous improvement. As new data or mitigation options become available, they can be directly incorporated into the dashboards and recalculated without altering the core framework.

Overall, these practical outcomes demonstrate that the deliverable's framework is not limited to research but is ready for pilot testing and potential deployment in real-world decision-making environments.

The experience highlights several lessons:

- Harmonizing formats and variables across tools requires meticulous pre-processing but ensures interoperability at later stages.
- Combining Python-based data exploration (using Spyder and Pandas) with Power BI visualization creates a flexible analytical pipeline that can handle heterogeneous datasets.
- The integration of GIS layers—through QGIS and ArcGIS Online—enhances the spatial understanding of results, linking resilience indicators directly to geographic locations.

In conclusion, the D3.4 deliverable demonstrates the feasibility of translating complex simulation and analytical outputs into generalized, operational knowledge. By establishing a unified GRA methodology and demonstrating its application through interactive BI platforms, the work bridges the gap between theoretical modelling and actionable decision support.

Across regional, national, and continental, i.e., European, scales, the approach consistently identifies which mitigation measures best balance efficiency, cost, and environmental sustainability. The methodology's adaptability confirms that a single, harmonized framework can serve multiple stakeholders—from local infrastructure managers to European policymakers—while maintaining scientific rigor and transparency.

Ultimately, this deliverable validates the SARIL vision: that Europe's transport and logistics networks can become simultaneously resilient and sustainable through data-driven assessment, informed decision-making, and continuous learning. The results achieved in D3.4 not only complete the analytical objectives of Work Package 3 but also establish the methodological and technical foundation for future transferability and implementation activities within the project (primarily WP5) and beyond.

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