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How Disruption Information and Simulation Approaches Benefit Stakeholders in Transport

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The vulnerability of transport processes has been visible in various disruptions over the last years such as extreme weather events, the pandemic, and the war in Ukraine. Additionally, according to the International Energy Agency, the transport sector is globally responsible for more than 7000 $MtCO_2$ emissions with a large portion due to heavy trucks. These trucks are still widely used for goods transportation but also a popular choice in case of disruptions. The EU-project SARIL brings together researchers and stakeholders in the transport domain to study the impact of certain disruptive events, propose better handling strategies supported by technical solutions and enable sustainable transport also in the case of disruptions. This paper presents the SARIL tools and the respective improvements for the businesses of four main roles in the transport sector. An information interface that receives information about disruptive events, such as forest fires, flooding events and reduced infrastructure capacities, forms the basis for the other SARIL tools. Traffic simulations along with sensor data from the infrastructure provide decision support for (1) infrastructure and (2) traffic managers. A network-based simulation environment enables (3) strategic logistics managers to plan routes considering various management strategies such as synchro-modal approaches. The latter also serve (4) operational logistics managers in combination with detailed route attributes for more resilient and sustainable route planning.

Keywords: Transport, Resilience, Sustainability, Disruptions, Hybrid threats.

1. Introduction

The effects of climate change are becoming increasingly evident, resulting in more frequent and severe natural disasters. At the same time, human-induced threats such as wars, pandemics, and cyber-attacks are intensifying in our interconnected world. These challenges pose significant risks to the resilience of essential infrastructure, particularly transportation systems. Disruptions to these networks can severely impede the movement of people, goods, and services.

The research presented in this paper conducted in the the EU-funded project SARIL (Sustainability and Resilience for Infrastructure and Logistics Networks) aims to address these challenges with a focus on the combined assessment of resilience and sustainability of transport and logistics networks. Related work is e.g. (Fiksel, 2006) where the importance of combining the analysis of resilience and sustainability is generally described for various industry sectors. In (Santamaria-Ariza et al., 2023) existing knowledge on risk, resilience, and sustainability management in transport infrastructure systems is mapped and a bibliometric analysis of scientific works to identify research gaps and contributions is conducted. In (Goodarzi et al., 2024) the crucial role of intermodal freight transport in combating global warming while addressing the challenges of vulnerability to disruptions is highlighted. A two-stage stochastic optimization model is introduced aimed at enhancing the sustainability and resilience of intermodal networks by integrating consolidation strategies.

Further, related work is performed in the projects funded under the HORIZON cluster Climate Energy and Mobility in the Call Safe, Resilient Transport and Smart Mobility services for passengers and goods, with SARIL being one of them. They are organized into seven topics with specific research goals: optimized freight flows and climate neutrality through operational connectivity; urban freight generation and digitization; smart enforcement for resilient and efficient transport operations; new and shared mobility services; seamless door-to-door mobility for passengers and freight; zero-emission construction, maintenance, and decommissioning of transport infrastructure; and resilient, green freight transport and logistics networks in response to disruptions.

These projects are highly relevant to the research presented in this paper and some of them are briefly presented in the following. E.g. the SETO (Smart Enforcement of Transport Operations) project aims to create a digital solution to simplify access to essential transportation data for authorities. This project addresses challenges related to unstructured data, diverse sources, and safety regulations by reducing administrative burdens and enhancing efficiency. The sister project of SETO, namely KEYSTONE (Knowledgeable comprehensive and fully integrated smart solution for resilient, sustainable and optimized transport operations) aims to customize standardized digital solutions to create a unified, sustainable, and safe transport system. By leveraging past experience, it seeks to establish a seamless and interoperable digital transport ecosystem across Europe. The TRACE (Integration and Harmonization of Logistics Operations) project is developing a blockchain-based platform to transform logistics, reduce energy consumption and emissions, and ensure reliable deliveries, addressing increasing demand and environmental concerns. The sister project of SARIL, namely ReMuNet (Resilient Multimodal freight Transport Network) focuses on developing methods to quickly detect and notify disruptions in multimodal transportation routes and assess their impact. By promoting synchro-modal relay transport across Europe, the project seeks to improve network resilience, reduce emissions, and assist freight operators in finding alternative routes during disruptions (Simonsa et al., 2024).

The project SARIL aims to develop decision support systems and offer recommendations for creating resilient and sustainable transport and logistics networks. The overall vision of the project is *Improving decision-making in transport and logistics systems in the face of disruptions by combining resilience and sustainability. A system is resilient and sustainable if it uses minimal resources* *to withstand and recover from disruptions.*

The research aligns with advancements towards achieving the European Green Deal (European Commission, 2019) and the United Nations Sustainable Development Goals (United Nations, 2016), as the transport sector is currently a major contributor to climate-relevant emissions (IEA, 2021). Multimodality is essential for reducing emissions, alongside effective data exchange. Synchro-modal approaches build on these two aspects and the concept of the physical internet, aiming to ensure that efficiency and sustainability can coexist harmoniously (ALICE, 2020).

The SARIL project unites research organizations, universities, and companies across Europe, alongside the European Technology Platform ALICE. This collaboration facilitates the development of resilience and sustainability management solutions tailored to industry needs. The proposed solutions are demonstrated at three different scales: a regional scenario, a national or cross-border scenario, and a European scenario. The scalability of the developed solutions is a major focus of the project.

Four main stakeholder groups are recognized in the project:

- Infrastructure management.
- Traffic management.
- Strategic logistics management.
- Operational logistics management.

These are categorized into three roles: R1: Infrastructure and traffic management, R2: Strategic logistics management, and R3: Operational logistics management.

The knowledge and tools developed in this project are tailored to the needs of various stakeholder groups. Three scenarios are refined through multiple rounds of interaction with end-users, as well as external stakeholders, including interviews, surveys, and workshops. The three scenarios being considered are:

- Regional: A flooding event poses a threat to bridges in the Mantua region of Italy. The availability of data on bridge scour monitoring is crucial for timely responses. In this scenario, the impact of data unavailability due to cyberattacks is analyzed, and countermeasures are proposed. The scenario and corresponding solutions are tailored for infrastructure and traffic managers.
- National: Weather extremes, such as bushfires, threaten traffic routes in Spain and Portugal. This hazardous event requires cross-border management, which complicates data acquisition for comprehensive decision support. This scenario is specifically designed for infrastructure and traffic managers.
- European: An incident that affects logistics and transport operations across Europe or even globally, such as the COVID-19 pandemic or the war in Ukraine, must be managed effectively. First, early warnings about the incident are gathered, then the impacts on specific areas of logistics businesses are quantified, and options for responding to the disruption are analyzed. Synchro-modal approaches are integrated into the analysis.

SARIL's unique contribution to research in this field lies in its comprehensive and quantitative analysis of resilience and sustainability in freight transport across various geographical scales, encompassing infrastructure, traffic, and logistics management. Additionally, it offers a holistic approach to simulating and visualizing the impacts of both short-term disruptions (e.g., accidents, strikes) and long-term challenges (e.g., pandemics, climate change, war), addressing a significant gap in the current industry practices.

The remainder of this paper is organized as follows: First, Section 2 presents the SARIL toolkit along with the tool architecture. Section 3 discusses simulation approaches illustrated through the ASTROIT simulation environment. In Section 4, the results are discussed. Finally, Section 5 summarizes the work and provides an outlook on the next steps in the project.

2. The SARIL toolkit

We categorize the tools developed in this project into three groups: tools that provide disruption data, tools that collect data, and tools that offer decision support based on data. The primary tools are listed in Table 1, and they are interconnected and organized by scenario and stakeholder group in the architecture illustrated in Figure 1.

Table 1. SARIL tools

#	Tool name
1	Natural Hazard Maps
2	Scour monitoring for decision support
3	Disruption information interface
4	Route Attributes (Energy Module)
5	Vulnerability and Traffic Tool
6	Traffic simulation
7	Transport Simulation (ASTROIT)

2.1. *Natural Hazard Maps*

The Natural Hazard Maps tool integrates geospatial and remote sensing information with elements such as climatic and historical data. Specifically, historical fire data is utilized to create forest fire risk maps and simulate the spread of a forest fire, akin to (Novo et al., 2024). These forest fire risk maps evaluate the likelihood of a fire occurring near infrastructure. Each map is structured as a grid where each pixel is assigned a value from 1 to 5, with 1 indicating very low risk and 5 indicating very high risk. These values are derived from the composition and risk reclassification of multiple layers, including fuel type maps, elevation maps, slope maps, aspect maps, NDVI maps, Fire Weather Index (FWI) maps, historical fire maps, road maps, and settlement maps (Novo et al., 2020).

The Natural Hazard Maps tool also incorporates universal information from sources such as Earth Observation satellites and national meteorological services, ensuring the model developed for this case study can be applied to other areas of interest across different geographical contexts.

2.2. *Scour Monitoring for Decision Support*

The Bayesian Network (BN) developed for the SARIL project aims to predict the scour depth at bridge piers within a network, including those that are not monitored. The BN is a probabilistic modeling tool that has its roots in Artificial Intelligence (AI) and machine learning and is increasingly applied in engineering risk analysis (Straub and Der Kiureghian, 2010; Bensi et al., 2013). It utilizes a Directed Acyclic Graph (DAG) structure to illustrate the conditional dependencies among the Random Variables (RVs) related to scour depth assessment across various bridges in the network (Jensen and Nielsen, 2007; Maroni et al., 2021). When new observations regarding scour depth, water levels, or cybersecurity threats are reported at a given location, the BN is employed to estimate the scour depth at unmonitored bridges.

2.3. *Disruption Information Interface*

The Disruption Information Interface is designed to gather information about disruptions across three main transport modes: road, rail, and sea, and to relay this information to other tools within the project. The tool collects disruption data from the APIs of local government institutions that provide updates on traffic disruptions in a specific country. Additionally, it gathers information from websites that end-users rely on in their daily activities to stay informed about disruptions affecting their planned transport routes. The data is organized in the database so that partners can access basic information about disruptions in a specified area, including the location, date of occurrence, and impact on transport. Upon request, the application also provides estimates of the predicted duration of disruptions through previously trained AI models based on statistical methods and Survival Analysis.

2.4. *Route Attributes (Energy Module)*

The tool calculates travel time, distance, energy consumption, and emissions for the chosen vehicle and route, based on the route selection method in the Energy module (Hjelkrem et al., 2017). The values for level of service attributes (LoS), including travel time, energy usage, and emissions, are derived from a speed model. This speed model considers various factors such as speed limits, road width, number of lanes, curvature, and other

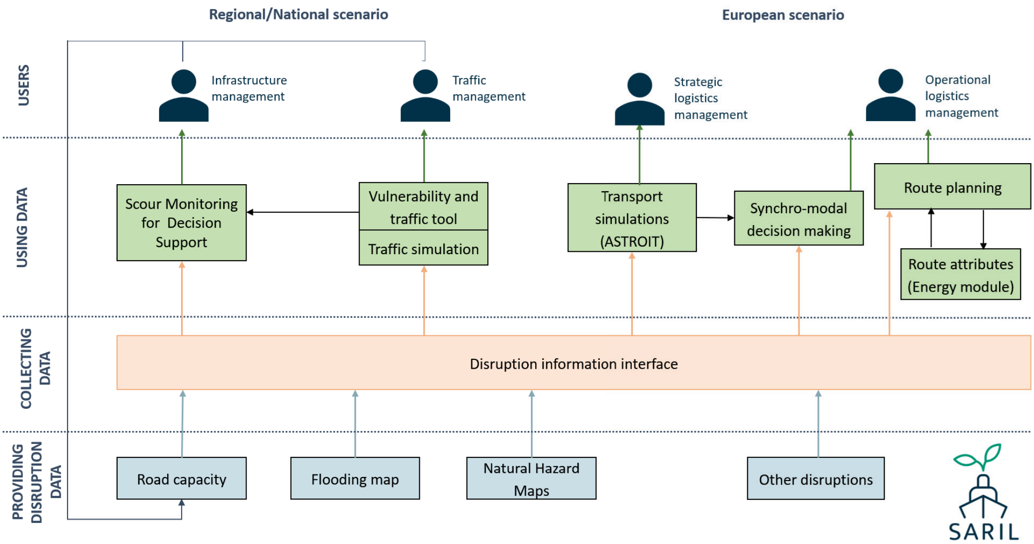

Fig. 1. SARIL tool architecture with tools classified into the three categories (providing, collecting and using disruption data) and the three scenarios (Regional, National and European).

road characteristics, as well as vehicle attributes and driving behavior.

This tool is primarily designed for integration with other models that support stakeholders such as traffic managers and strategic and operational logistics managers. To enhance information exchange between this tool and other models developed in SARIL, it features an API solution in addition to a web interface. The API can be utilized by other models to estimate the LoS for various routes.

2.5. *Vulnerability and Traffic Tool*

The Vulnerability and Traffic tool integrates sophisticated traffic modeling with comprehensive vulnerability and risk analyses. However, these capabilities require substantial computational resources and data. The tool provides infrastructure managers and public authorities with data-driven insights to enhance risk management and optimize budget allocation.

The Vulnerability and Risk Assessment forms the basis for evaluating infrastructure resilience. It entails a thorough analysis of potential disasters and risks, focusing on fragility, restoration, degradation, and loss functions to assess the possible impact of natural events on assets.

The traffic module serves as a numerical model illustrating how infrastructure transports different flows within its components. It simulates the effects of disruptive events on the transport network by analyzing changes in traffic flows, travel times, and speeds in the affected area (van der Tuin and Pel, 2020). The model primarily consists of network sections (road links) and nodes (infrastructure interchanges or intersections), characterized by capacity and speed parameters. The traffic module starts by defining the network encompassing the area affected by the riverbed, allowing us to observe how a service disruption in that region may impact the broader area. This selected area is connected to an origin-destination matrix using existing traffic data.

2.6. *Traffic Simulation*

The traffic simulation developed in SARIL is a tool designed to analyze the effects of extreme events on transport networks. Initially created for flood disruptions, it was subsequently adapted within the SARIL project to address fire-related disruptions. The tool incorporates SUMO (Simulation of Urban Mobility), an open-source platform (SUMO, 2024), to simulate traffic flows at an aggregate level, emphasizing interactions among groups of vehicles rather than individual ones.

The dynamic mesoscopic traffic model plays a crucial role in the SARIL project, supporting its overall objective of improving the resilience of transport networks to extreme events. By simulating real-time traffic conditions and evaluating the impacts of disruptions such as fires and slope collapses, the model offers valuable insights for resilience planning. This includes informing traffic management strategies, emergency response initiatives, and infrastructure investment decisions. Additionally, its potential for multimodal transport analysis positions it as a flexible tool for comprehensive assessments of transport resilience.

2.7. *Transport Simulations (ASTROIT)*

The tool ASTROIT (Agent-based Simulation for Resilience Of Intermodal Transportation) is an agent-based simulation platform designed for multimodal transport. Its development is grounded in a rail-based simulation approach outlined in (Köpke et al., 2023). An overview of similar methodologies can be found in (Tordecilla et al., 2021).

In this transport simulation, each cargo unit, referred to as a shipment, is modeled as an agent capable of identifying an optimal path from its origin to its destination. The optimal path is selected based on predefined preferences for minimizing various types of costs, including operational costs per kilometer, CO_2 emissions per kilometer, and route duration.

The simulation accommodates various vehicle types, each defined by its capacity, speed, CO_2 emissions per kilometer, and operational costs. Vehicles can only offer predefined services that correspond to their specific type and operate according to a predetermined schedule. Disruptions within the network are simulated by reducing the performance of hubs and/or services. A decrease in performance leads to increased transloading times at hubs and reduced speeds on routes associated with the affected service. If a hub or service's performance drops to zero, it fails, prompting each agent to recalculate its route after a specified reaction time.

3. Simulations for decision support

In alignment with the storylines of the scenarios and the overall architecture, the tools are integrated to predict the impact of specific disruptions on transport networks, analyze the effects of mitigation measures, and provide decision support. The Disruption Information Interface plays a crucial role in all scenarios by connecting the tools that collect information with those that utilize the respective data. Additionally, Route Attributes and Planning can serve as input across all scenarios, offering detailed information on emissions for specific segments of the transport network.

In the regional scenario, the Scour Monitoring for Decision Support is paired with the Vulnerability and Traffic tool. In the national scenario, the Natural Hazard Maps are integrated with the Traffic simulation. Lastly, in the European scenario, ASTROIT simulates disruption scenarios in transport networks, utilizing synchromodal approaches. In the following Section simulation results from the ASTROIT tool are presented.

3.1. *Transport and logistics networks*

The transport network analyzed in this study has been provided by Gebrüder Weiss and spans Austria and Italy. The network is illustrated in Figure 2. It comprises transport hubs with defined capacities and services that link these hubs.

Vehicles, including trucks and trains, operate on roads and tracks connecting the transport hubs according to fixed schedules. The specific road or track is reflected only in the properties of the edges (e.g., length, slope) of the network that represent the corresponding service offered. Vehicles are characterized by attributes such as type, capacity, emissions, operational cost per kilometer, and maximum speed.

3.2. *Disruptions in the network*

Disruptions in the transport network are triggered by lowering the performance of services or hubs, leading to decreased capacities and/or increased transloading times. To illustrate a substantial impact on the network that is not easily manageable, two disruptions are implemented: (1) from day 8 to day 13, the performance of four hubs is abruptly

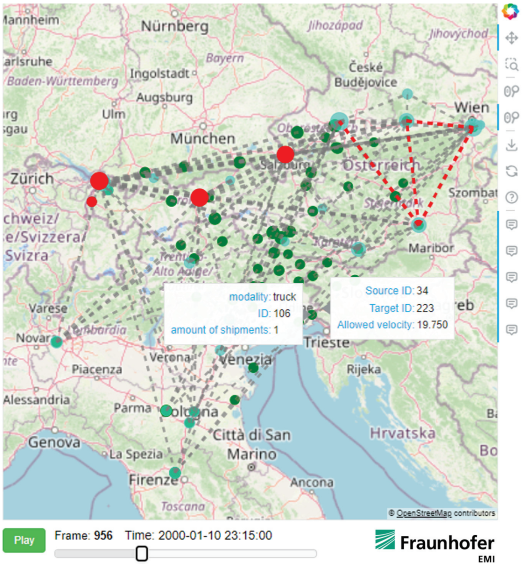

Fig. 2. Transport network visualization in ASTROIT. Hubs and services interrupted are highlighted in red. Vehicles are depicted as green circles. The size of vehicle-circles is defined by the number of shipments in the vehicle. Hubs are shown as turquoise circles. The size of hub-circles is given by their degree. Services are given as grey lines.

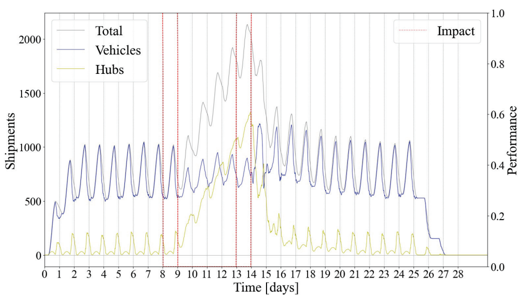

Fig. 3. ASTROIT simulations during two disruption events (red step functions). Shipments in the network in total (grey), in vehicles (blue) and in hubs (yellow).

reduced to zero, and (2) from day 9 to day 14, the performance of four services is similarly decreased to zero (see Figure 3).

The simulation results for these extreme overlapping disruption events are presented in Figure 3. The simulation begins with shipments entering the network, reaching a normal equilibrium state from days 3 to 8. During the disruption, a deviation from normal operations is evident, as some shipments can no longer reach their destinations, while others must take longer routes. This leads to a backlog of shipments in the network, particularly at the hubs. Once the disruption concludes, it takes approximately four days for the system to return to normal operations.

4. Discussion

The initial simulation results of ASTROIT, presented in Section 3, illustrate the analysis of resilience through performance indicators during disruptions in transport networks. This capability serves as a foundation for the quantitative assessment and visualization of both resilience and sustainability. While the current focus has been on quantitative resilience assessment, it is essential to integrate sustainability aspects into the evaluation metrics.

The SARIL tools, operating within the architecture described in Section 2, facilitate decision support for both short-term and long-term disruptions, taking into account the needs of infrastructure, traffic and logistics managers. User stories are being developed for each tool and will be discussed in upcoming workshops with stakeholders to ensure that the development aligns closely with industry requirements.

5. Summary

The SARIL toolkit is designed to assist stakeholders such as infrastructure, traffic, strategic logistics, and operational logistics managers in their decision-making processes. The development of the tools within the project is organized into three scenarios: regional, national, and European, along with a structured tool architecture. These tools are specifically aimed at supporting decisions made by stakeholders in traffic, infrastructure, strategic logistics, and operational logistics management.

Future development of the tools will focus on adapting them to meet end-user needs and validating them through data. Additionally, the tools will aid in formulating recommendations for the transport sector to promote more resilient and sustainable operations in the face of hybrid disruption events.

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