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SARIL

Sustainability And Resilience for Infrastructure and Logistics networks

D4.3 Environmental and Economic Impact Assessment

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Executive summary

As disruptions from natural and anthropogenic events increase in frequency and scale, the logistics sector faces increasing urgency in the need to meet these disruptions with green resilience. To this end, the SARIL project (Sustainability and Resilience for Infrastructure and Logistics networks) aims to increase understanding of how to increase resilience in the logistics sector while considering sustainability aspects. SARIL 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-D6-02-071 - New concepts and approaches for resilient and green freight transport and logistics networks against disruptive events (including pandemics)".

This document represents the output of Task 4.3. The task uses a system perspective to extend the environmental and economic evaluation of the SARIL regional, national and European scenarios. This evaluation builds on the output from the work performed in Task 3.3, where the effects of disruptions on logistics networks were modelled for each scenario using natural hazard and traffic modelling tools and compared to a baseline undisrupted scenario. In addition to the disruption scenarios, the effects of various resilience measures were also assessed in Task 3.3. The results from Task 3.3 found on the operator level, greenhouse gas emissions and costs decreased when preventative mitigation strategies are implemented; these savings, however, are namely achieved at the operator level, such as through reduced trip length and fuel savings. The key aim of this work is to demonstrate the importance of adopting a broader, system-level scope rather than only considering immediate direct effects in the evaluation of environmental and economic impacts of disruption and mitigation scenarios.

Results from the impact assessment for the regional scenario found that infrastructure-based mitigation measures improve resilience indicators, but present trade-offs in overall environmental sustainability and economic impacts due to high investment requirements. For the national scenario, mitigating spread of forest fires can reduce both disruption impacts and greenhouse gas emissions, but come with environmental trade-offs, particularly ecological impacts from habitat fragmentation and land-use change. Furthermore, these mitigation measures involve actors outside of the transport value chain and would therefore require higher-level coordination to enact. For the European scenario, proactively replacing fossil-based freight trucks with battery electric vehicles and increasing share of rail freight both provide life cycle emission reductions, but the magnitude of these reductions is smaller than when only direct (tailpipe) emissions are considered. Finally, a global scenario was also evaluated, which considers a large-scale disruption of land-based rail freight originating from Asia. In this scenario, greenhouse gas emissions generally increased and value added decreased, while employment effects depend on the rerouting strategy, highlighting strong trade-offs between environmental and economic outcomes and the far-reaching impacts of disruptions in global supply chains.

Key findings of the impact assessment include that disruption mitigation measures may involve high upfront environmental and economic costs to implement in exchange for reduced consequences and impacts during a disruption. Consequently, trade-offs in both cost and different types of environmental impacts can occur when implementing measures to mitigate the effects of disruptions on transport and logistics. The magnitude of these trade-offs can be significant, such as when major infrastructure construction work is required. However, in some cases, the chosen mitigation measure may also have co-benefits beyond disruption events, such as adding further functionality or capacity to the transport network. Additionally, the approach used in the impact assessment finds that the responsibility for enacting disruption mitigation efforts is not limited to logistics stakeholders;

mitigation measures for the transport sector can be enacted by both private and public actors in other economic sectors. This is due in part to the central role transport plays in many economic sectors, but also the interdependence of economic sectors between themselves, and the environment. A major learning from this work is that taking too narrow of a scope in evaluating options for increasing logistics resilience may, in some cases, result in unintended increased environmental and economic impacts, as ripple effects are experienced beyond the logistics sector. Finally, different disruption scenarios may require different approaches due to geographical scale, the nature of the system and disruption, and the types of the stakeholders affected, presenting a challenge in developing a generalised and holistic decision-making framework for evaluating green resilience.

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List of Acronyms

Acronym	Definition
EEIO	Environmentally extended input-output
GHG	Greenhouse gases
LCA	Life cycle assessment
LCC	Life cycle costing
LOS	Level of service
MITECO	Ministerio para la Transición Ecológica y el Reto Demográfico (Ministry for the Ecological Transition and the Demographic Challenge in Spain)
RC	Reinforced concrete
TTW	Tank-to-wheel
VOC	Volume-to-capacity
WTT	Well-to-tank
WTW	Well-to-wheel

1. Introduction

The following work builds upon the findings from Task 3.3 described in Deliverable D3.3 (SARIL project D3.3, 2025). In Task 3.3, the Green Resilience Assessment (GRA) approach considers the transport system's ability to recover from a disruption, while also accounting for environmental sustainability. However, the key performance indicators (KPIs) used to assess environmental performance of the modelled scenarios only consider the direct environmental impacts of the transport activities, that is, the "tailpipe", or tank-to-wheel emissions (Figure 1), which occur at the operator level. While these impacts are indeed critical to include in considerations of green resilience, indirect emissions and impacts occurring in other areas of the system such as infrastructure or vehicle life cycles, and the rest of the fuel chain can be equal, if not greater contributions to overall environmental impacts. The field of industrial ecology, particularly the life cycle assessment (LCA) approach, takes a system-wide perspective on environmental and economic impacts.

The advantage of this approach is that it is more holistic and considers the total resulting environmental impact to avoid environmental trade-offs and shifting of emissions to other parts of the value chain. Conceptually, this approach would capture whether a means for increasing the resilience of the transport system by implementing a mitigation measure would result in increased total emissions. If this would be the case, resilience and environmental considerations would have to be weighed against each other.

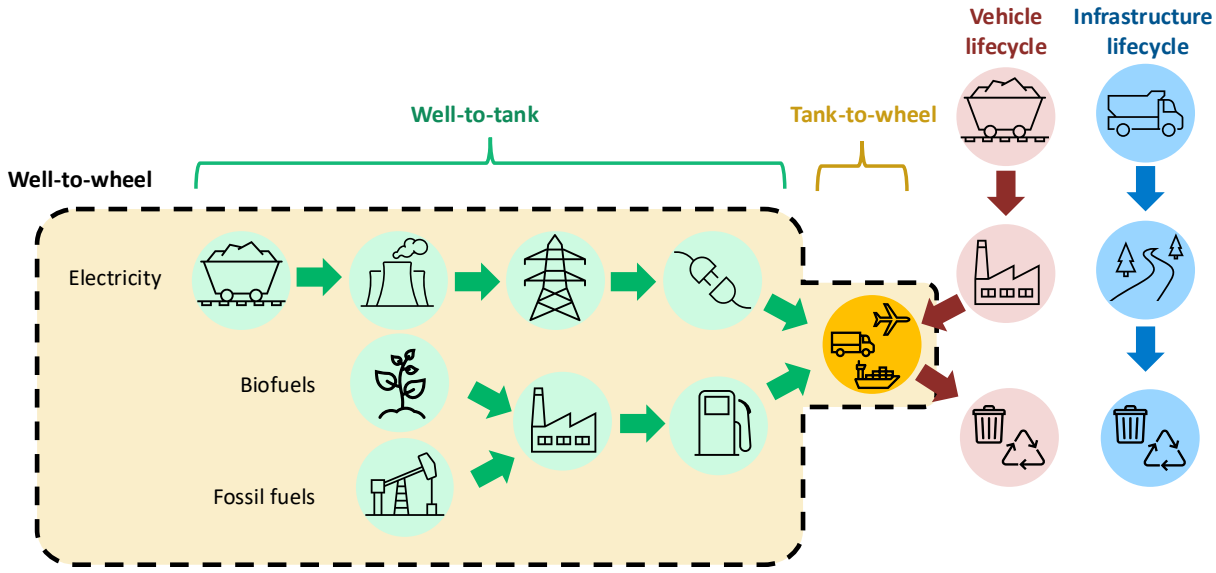


Figure 1: Scope of life cycle assessment in transport services.

This perspective entails expanding the boundaries, or scope of the assessment to include all relevant affected value chains. Consequently, the impact assessment considers environmental impacts spanning across all three of the stakeholder roles considered in SARIL, namely:

- Role 1: Developing and Maintaining Transport Infrastructures
- Role 2: Configuring Transport and Logistics Networks
- Role 3: Managing Logistics Operations

The three SARIL scenarios are considered in this task (Table 1). In addition, a Global scenario is considered in the impact assessment.

Table 1: Overview of SARIL scenarios.

Scenario	Disruption type	Mitigation measures considered in T3.3 and T4.3
Regional	Flood	- Road elevation/embankment strengthening - Network-level resilience measures (redundant transport routes)
National	Forest fire	- Firebreak - Forest mass management
European	War, labour disruption	- Electrification of goods vehicles - Trains

1.1 Resilience and Sustainability

Sustainability is defined encompassing three aspects, or pillars: environment, economy and society. In this work, we focus on the environment and economy pillars, considering impacts such as climate change, land use, employment and value added. The most commonly used tool for evaluating environmental sustainability aspects is LCA (Bocchini et al., 2014; de Paula Salgado et al., 2025; Leal, 2020), or life cycle perspective. In the face of increasing and more extreme climate events, efforts to improve the resilience of anthropogenic systems should also consider environmental sustainability so not to exacerbate these climate events. Life cycle costing (LCC) and input-output analysis are common methods used to quantify economic impacts, albeit at different scales.

While the body of work combining resilience and sustainability assessments is growing, previous literature has acknowledged that the sustainability and resilience of a system do not necessarily have a positive correlation (Bocchini et al., 2014; Santamaria-Ariza et al., 2023); rather, these are desirable goals to be achieved, and which must be mutually considered and optimised for when planning and designing of green, resilient systems (Santamaria-Ariza et al., 2023). Consequently, trade-offs or conflicts between environmental sustainability and resilience goals may occur; some actions or strategies prioritizing environmental sustainability may lead to lower resilience, or vice versa (de Paula Salgado et al., 2025).

Despite the importance of considering both resilience and sustainability, there are relatively few studies that assess both aspects at the same time in a unified and comprehensive manner (Bocchini et al., 2014; Di Bari et al., 2025; Leal, 2020; Zhang et al., 2025).

2. Impact Assessment of SARIL Scenarios

2.1 General Analytical Approaches

The scenarios in SARIL are considered using a system-wide, life cycle perspective, which ensures that the complete emissions and environmental impact of the disruption and mitigation approaches are included in the assessment. This approach analyses environmental impacts beyond the direct emissions from changes in transport activity that arise from the disruption and mitigation approaches. Such impacts can occur across the entire transport sector, or even in transport-adjacent sectors such as construction.

LCA and environmentally extended input-output (EEIO) are two quantitative methods that are used in this analysis. The methodological approach used for each scenario is selected based on the geographical basis of the SARIL scenarios, and the chosen mitigation approaches analysed. Consequently, a different approach to analyse the environmental and economic impact is used for each scenario. The relevant environmental and economic KPIs for each scenario therefore also varies.

As the name implies, LCA considers all of the life cycle phases of a product or system: manufacture, use, and end-of-life. In this way, the environmental burdens arising from all of the associated material and energy inputs and outputs for each of these phases are included. To this end, LCA strives to capture the environmental impacts of all links in the supply chain; not only are the emissions from the manufacturing process considered, but also the emissions from the value chains of each component required as well. For transport systems, this entails the manufacture of the vehicle(s) in question, the production of fuel or energy carriers, and of required infrastructure (roads, rails, airports, etc), including use of machinery, transport of materials, etc.

The following sections describe the impact assessment approach and results for each SARIL scenario. The impact assessment builds on the simulated scenarios from Task 3.3; the relevant background and results of this work are described under the method chapter for each scenario. For all analyses in the impact assessment, a baseline, or business-as-usual case is considered for each scenario and used as a basis of comparison to the disruption case and the mitigation cases.

2.2 Regional Scenario

In this scenario, the road network in the Mincio River near Mantua, Italy, was evaluated using the Vulnerability and Traffic Tool in WP3. A summary of the tool and the outputs of this work is described below.

This tool uses traffic modelling combined with an evaluation of bridge vulnerability to flooding in order to determine required road closures in a flood scenario, and the resulting level of service (LOS) of the road network. The probability of failure (flooding) of key road segments and bridges (assets) are evaluated. The disruption scenarios consist of closing or reducing capacity of the assets with the highest probability of failure. This disruption scenario is compared to a base case scenario that is undisrupted. The outputs of the model include volume-to-capacity (VOC), which measures the traffic (e.g., congestion) of the segment compared to its rated capacity, total indirect costs due to fuel use and time lost due to delays.

In the impact assessment, two distinct mitigation scenarios have been evaluated. The first focuses on infrastructure reinforcement through the installation of concrete flood walls to mitigate flood risk. The second addresses network capacity, involving the upgrade of an existing road to a Class C1

standard, which adds an additional lane in each direction and is therefore better suited to receive increased traffic due to road closures elsewhere in the network.

The first mitigation action considered in the Regional Scenario is the reinforcement of existing infrastructure by building a flood wall along the road segment and bridge deck and therefore avoid road closure. In this impact assessment, this entails additional abiotic resource use through the demand of aggregate and pavement for building a flood wall along the segment, in addition to construction related impacts through combustion of fossil fuels, etc.



Figure 2: Examples of flood wall installation for roads.

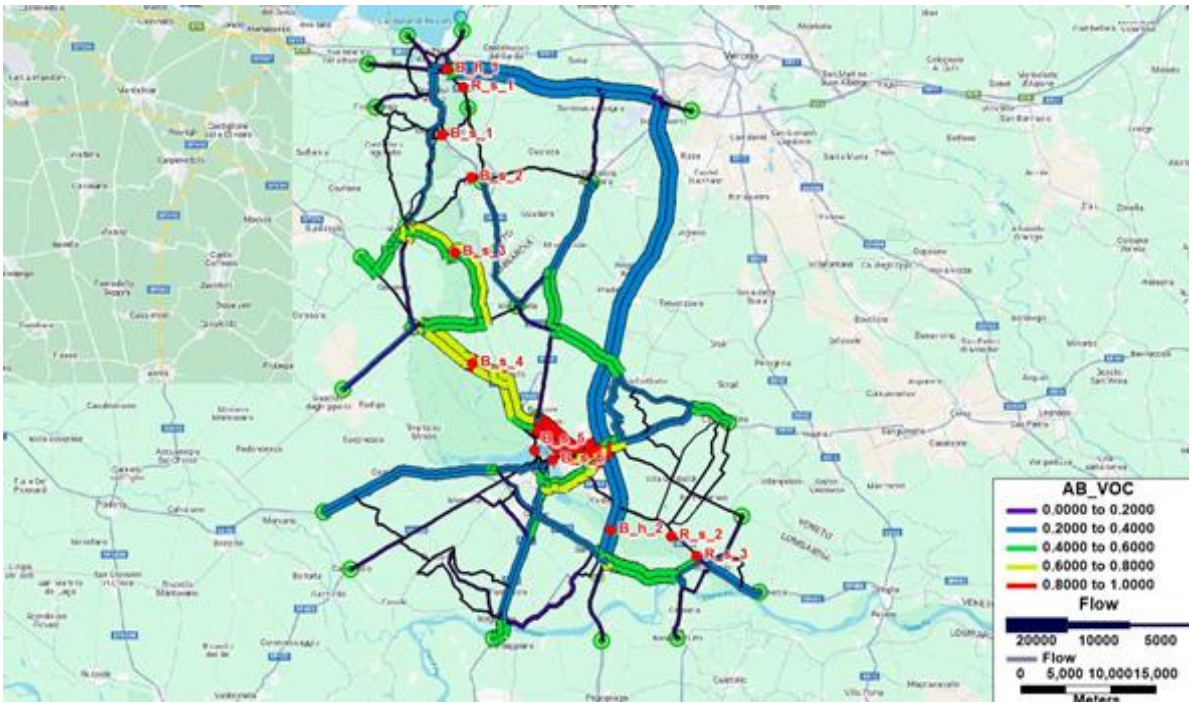


Figure 3: Traffic results from flood wall mitigation approach.

Concrete barriers are the industry standard for flood-prone areas because they are heavy, durable, and can act as a minor flood wall (Figure 2, Figure 3). These barriers (1.0 m to 1.5 m in height) are built taller and reinforced with water-tight seals to prevent overtopping of the road and bridge surface

during floods. Bilateral Protection (assumed here) is the standard for bridges crossing over water or roads situated in low-lying floodplains (basins). A network section covering eight bridges and three roads, each requiring a 100-m segment of flood wall on both sides, for a total of 2200 m, are protected by the proposed flood wall. Due to data limitations, these flood wall segment lengths, representing a mean extension length, were estimated using a representative analysis of satellite imagery and bridge and road extensions. This approach accounts for the disparity between minor and major segments to provide a weighted average of the network's physical characteristics.

The second mitigation approach evaluated is network reinforcement (Figure 4). More specifically, the project involves the functional upgrading of an existing road currently characterized by a limited cross-section. The upgraded road will be designed as a Class C1 road, with one lane per direction, each lane having a width of 3.75 m, and lateral shoulders 1.25 m wide. The total length of the road section subject to upgrading is approximately 12 km. The traffic capacity of the upgraded road is estimated at 3,000 vehicles per hour in total, corresponding to 1,500 vehicles per hour per direction, under normal operating conditions.

This entails the construction of a new road, with its associated emissions, as well as increased land use change, as previously vegetated area becomes a built-up area. Both mitigation approaches in this scenario increase the resilience of the transport network by providing alternatives to closing sections of the network in the event of a flood disruption.

The implementation of flood walls as a mitigation strategy significantly alleviates network traffic congestion compared to the disruption scenarios analysed in Task 3.3. As illustrated in Figure 3, these structural interventions result in a substantially smaller reduction in overall network mobility, maintaining higher service levels across the system. The second mitigation strategy yields a more visible rebalancing of traffic flows, as illustrated in the updated distribution model (Figure 4). The Volume Over Capacity (VOC) ratio, a key indicator of the Level of Service (LOS), decreased from an initial 0.46 (Disruption scenario 1) to 0.40 (Mitigation action 1), reaching a low of 0.28 (mitigation 2). This represents a significant optimization of network level of service. The VOC is calculated by taking the flow-weighted average of the saturation level for each segment (arc) of the network. Both mitigation measures are within the scope of R1 actors, who manage and operate transport infrastructure.

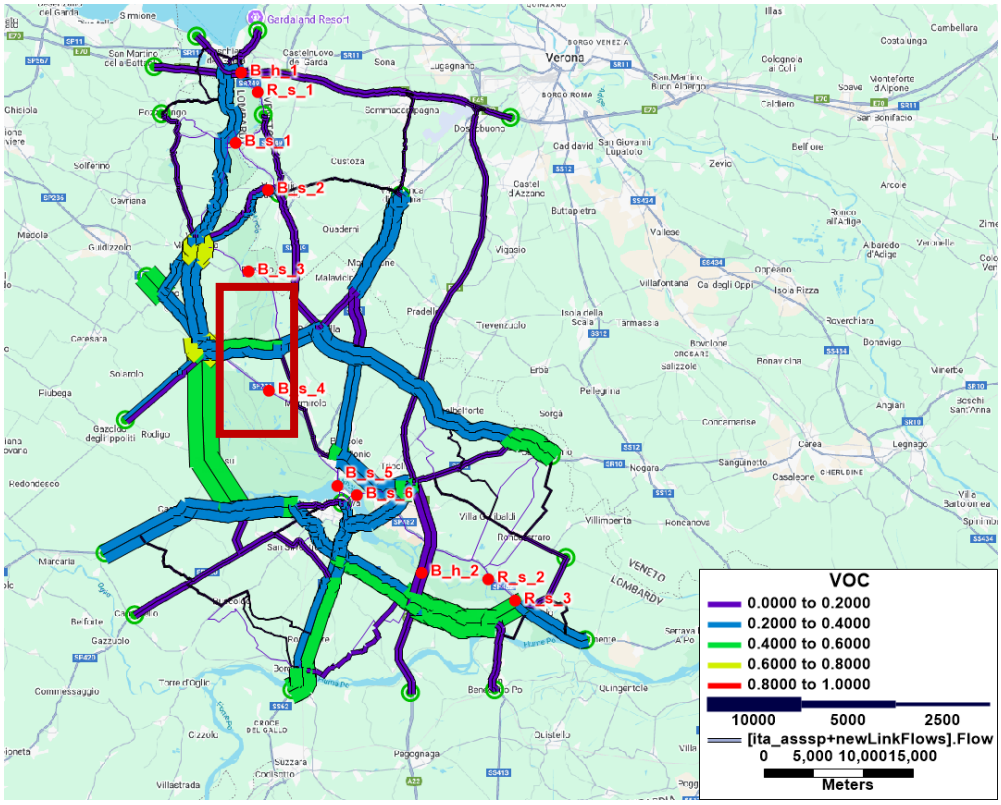


Figure 4: Traffic results from network redundance mitigation approach. The new road section is highlighted in the red box.

2.2.1 Method

In the regional scenario, estimates of materials and construction work required to establish the mitigation measures were made. These estimates were then used as inputs in an LCA to capture the environmental impacts in addition to the direct emissions from traffic as determined from the Vulnerability and Traffic tool. The commercial *ecoinvent 3.11* database[1] was used to calculate the environmental footprint of the mitigation measures. As the Vulnerability and Traffic tool does not report explicit emissions results, the indirect costs from fuel use are converted to volume amounts using a baseline cost factor of 1.67 EUR/L, as the current average diesel cost in Italy[2]. With the help of emissions factors for diesel fuel, we estimate well-to-wheel emissions. In addition to this, the cost estimates for the mitigation approaches in the Regional Scenario are estimated, including both site preparation, materials and equipment use. These costs are added to the indirect costs from the Vulnerability and Traffic tool to obtain the total economic impacts for these mitigation scenarios.

2.2.2 Environmental Impact

Table 2 describes the environmental impacts of the Regional Scenario. The indirect emissions encompass emissions from the construction process for the mitigation approaches, namely the flood wall and the additional road construction. Relative to the additional transport emissions under the studied disruption period, the embodied emissions associated with construction of the new infrastructure are, in absolute terms, overwhelmingly higher. However, when these emissions are annualised using expected lifetime of infrastructure elements, the total emissions of the mitigation scenario including both transport emissions and embedded emissions from constructing the flood

[1] https://ecoinvent.org/
[2] From fuel-prices.eu, average diesel price in the period 17/11/2025 to 09/02/2026

wall, are about 118.5 t CO_2-eq, which represents an approximate 65% emissions savings over the disruption scenario. In the case of the network redundancy mitigation measure, the emissions savings are even greater, as the new road segment, even in the face of a disruption, allows for lower transport emissions than the baseline scenario. Nevertheless, the flood modelled is a 100-year flood, so for years where there are no floods, the overall CO_2 emissions from the mitigation measures are higher than the disruption scenario. The environmental "break-even" where the additional emissions from installing the mitigation measures are compensated for by the emissions savings in disruption scenarios are 14 and 38 floods, for the flood wall and network redundancy cases, respectively. This means that these two scenarios represent a net environmental benefit on the 15th and 39th flood over the lifetime of the infrastructure.

Table 2: Comparison of life cycle CO_2 emissions (in t CO_2-eq) and VOC in SARIL Regional Scenario.

	Units	Baseline	Disruption	Mitigation	
				Flood wall installation	Network redundancy
Volume-over-capacity (VOC)	-	0.3978	0.4528	0.4280	0.2953
Transport emissions, over baseline	t CO_2-eq	0	335	63.5	-275
Infrastructure emissions	t CO_2-eq	n/a	n/a	3 440	20 958
Infrastructure emissions, annualised	t CO_2-eq/yr	n/a	n/a	55	419
Total emissions, relative to baseline	**t CO_2-eq**	**n/a**	**335**	**3503.5**	**20 683**

For the flood wall installation, concrete used in the flood wall structure was the greatest contributor to greenhouse gas emissions, representing 89% of the total emissions, with the use of diesel-fuelled heavy machinery in the installation representing the remaining 11%.

In the network redundancy mitigation measure, the production of the bituminous conglomerate used in the road surface was the single greatest contributor of emissions from the construction phase. Emissions from heavy machinery and production of gravel are the next two greatest contributors of emissions.

For both mitigation methods, "traditional" materials from primary sources are assumed. Construction impacts for both mitigation approaches, however, can be reduced by using, e.g., alternative materials (Negishi et al., 2022), by using waste material from other industrial processes (Balaguera et al., 2018) or transitioning to using electric machinery in the construction process (Wiik et al., 2023). Further emissions savings can be found by sourcing local or recycled materials when these are available to reduce transport needs for the large quantities of materials needed, and reducing the amount of primary materials to be extracted and processed. Careful selection of materials that ensure a longer service lifetime, or from producers using processes with lower emissions can also lower the environmental impacts associated with these mitigation measures.

While not a direct indicator of emissions, volume-over-capacity (VOC) values can be used to indicate eco-efficiency of the solution in addition to the traffic performance in the context of resilience. While a low VOC value represents relatively little traffic congestion, it also means there are inefficiencies in the environmental performance of the road. For example, when the road is never operating at capacity, the considerable embedded emissions associated with both the construction and

maintenance of the road are not providing as much service, i.e., transport functionality as possible, meaning the system is operating with lower eco-efficiency with network redundancy than without.

In addition to the greenhouse gas emissions, environmental impact considerations for the mitigation scenarios include additional land occupation of the new infrastructure, and the introduction of, or increase in traffic to the area, which in turn increase the potential disturbances for wildlife and humans living nearby. Adding more road infrastructure or installing the flood wall may further fragment ecosystems, which in turn may have negative implications for local wildlife and biodiversity. Furthermore, introducing a road to an area may over time induce land use chance in adjacent areas, for example, additional residential, commercial or industrial development in what may have earlier been agricultural or natural areas (Hadi et al., 2021).

For the flood wall, protecting the road from exposure to the floodwaters would prevent potential damage of the road surface. In turn, this extends the expected lifetime of the road and prevents the need for additional construction activities with heavy machinery and material demand for rehabilitation or reconstruction of the road. By preventing potential flood damage to the road, the flood wall may reduce the "break even" impact as these repair operations are avoided. On a similar note, selecting materials in road construction that are robust towards extreme events may reduce the amount of maintenance required or even extend the lifetime of the infrastructure and therefore lower the emissions relative to the service provided (Negishi et al., 2022). Unlike the flood wall mitigation measure, the network redundancy case does not prevent flooding on the original network segment, which may consequently increase the total environmental impact from the disruption due to required repair or rebuilding operations.

During the construction process, additional, albeit temporary land occupation of building materials and equipment is not insignificant. Furthermore, the use of fossil-fuelled equipment would contribute to particulate emissions to the detriment of local air quality during the construction activities.

2.2.3 Economic Impact

The disruption scenario induces economic losses due to extra fuel consumption from traffic and required detours, as well as indirect losses from delays to both passengers and goods transport. The installation costs of both mitigation approaches are significant, on the scale of millions of Euros. Table 3 illustrates the estimated unit costs for installing the flood wall, for a total of 4000 €/m. In comparison, the indirect costs due to time lost, increased fuel use, loss of life and goods in the disruption and mitigation scenarios are on the order of hundreds of thousands of Euros. As with the environmental impacts, the one-time investments in the mitigation approaches of flood wall or road construction are several orders of magnitude greater than the damages incurred by the disruption (Table 4).

Table 3: Construction phases and estimated unit costs for flood wall construction.

Construction Phase	Description	Estimated Cost (/m)
1. Site Prep & Safety	Mobilization, traffic management, and temporary water diversion (cofferdams).	€ 800
2. Foundations	Deep excavation and reinforced footings (essential to prevent under-wall seepage).	€1,000
3. Main Structure	High-strength reinforced concrete (RC) with integral waterproofing admixtures.	€1,000

4. Watertight Sealing	Specialized hydrophilic gaskets, polyurethane expansion joints, and surface membranes.	€500
5. Finishing & Safety	Traffic-facing guardrails/parapets, drainage valves, and anti-scour riprap.	€700
TOTAL	**All-inclusive construction estimate**	**€4,000**

Table 4: Costs associated with SARIL disruption and mitigation scenarios.

	Disruption	**Mitigation**	
		Flood wall installation	**Network redundancy**
Indirect costs, relative to baseline	214 298 €	173 035 €	393 554 €
Cost, construction of mitigation measures	n/a	8 800 000 €	18 000 000 €
Total costs, relative to baseline	**214 298 €**	**8 973 035 €**	**18 393 554 €**

The mitigation scenarios, however, differ from one another in that the network redundancy scenario adds functionality to the network outside of disruptions as well; the new road segment can be considered to be multifunctional in providing an alternate route for baseline traffic while also increasing the overall resilience of the local transport network. For example, a new road segment may have the co-benefit of reducing congestion on the original road segment and thus improve the overall transport performance and transport costs of the network in the baseline scenario. Thus, the entire cost of construction the road segment should not be wholly ascribed to the increasing resilience of the network against (rare) flooding event.

In contrast, the flood wall installation avoids losses and costs associated with direct damages to the road. This can be in the form of avoiding closures during flood disruptions, or by minimizing the damage to the road itself, and thus allowing the segment to re-open quickly after the disruption.

Expanding the network redundancy is a considerable cost in exchange for the additional security this mitigation measure provides; this is not an uncommon phenomenon (ITF, 2024), and trade-offs between the added cost associated with mitigation and adaptation measures and the resulting recovery capabilities of the network should be considered carefully by policymakers. Not directly considered in this scenario are broader socioeconomic impacts as such an analysis requires high-resolution data about the nature of the goods being transport within the studied network. Such data are therefore generally better suited to evaluating scenarios at a national or international level.

2.2.4 Conclusion

While the mitigation measures considered increased the recovery capabilities of the transport network in comparison to the disruption scenario, they have considerable additional environmental or economic impact associated with their construction. The Regional Scenario, however, highlights the importance of considering both resilience and sustainability in tandem, and the potential trade-offs that arise between these two goals, which can be considerable. The second mitigation scenario, however, also provides co-benefits in adding road capacity in non-disruption periods, albeit with trade-offs in cost and eco-efficiency. In particular, Role 1 actors need to account for natural hazards in the planning phase where possible and consider the relative importance of individual road segments

within the network; this consists of an evaluation of how critical the transport happening in the segment is to wider economic activities in the region or at the national level.

2.3 National Scenario

The National Scenario encompasses the disruption of a forest fire. In addition to causing road closures, forest fires lead to the environmental impacts of released CO_2, CO and particulate emissions due to combustion, which in turn contribute to greenhouse gas emissions and detrimental human health impacts. In addition to these emissions, forest fires lead to loss of nature areas and biodiversity, and direct damages to the built environment.

2.3.1 Method

Unlike the Regional Scenario, the mitigation measures in the National Scenario aim to mitigate the forest fire impacts on the transport sector by reducing the severity of the forest fire itself, rather than adapting the transport infrastructure or logistics operations. We consider two mitigation approaches in this impact assessment: the first, installing a firebreak (Figure 5) by removing flammable vegetation and the second, using forest mass management as a means to curb the ability of a forest fire to spread. As these mitigation measures fall within the domain of neighbouring private landowners, rather than that of the actors in the transport system, the stakeholder roles as defined in SARIL would not implement nor significantly influence the implementation of these measures. Consequently, we choose to describe the key pathways for environmental and economic impacts of this scenario qualitatively, rather than quantitatively. Furthermore, the level of detailed data required for a quantitative approach, such as ecological surveys and the organic carbon content of biomass in the affected areas, presents challenges, hence the qualitative approach chosen here.



Figure 5: Fire propagation on A55 highway after firebreak implementation.

The study area in this scenario consists of a mix of built-up area and forested area (Figure 6). The vegetated area consists of built area (motorway and scattered buildings) and a variety of ecoregions, including Cantabrian mixed forest, and a number of eucalyptus plantations. This vegetation information is obtained from the National Forest Map[3] provided by MITECO (Ministry for the Ecological Transition and the Demographic Challenge). The National Forest Map is a vector file that contains all the information related to cover land, vegetation, structure of the vegetation, fuels, etc. To conduct the analysis of the vegetation affected by the wildfire simulated in this case study, first, the layer containing the wildfire was overlaid with the National Forest Map to subsequently select the

[3] https://www.miteco.gob.es/es/cartografia-y-sig/ide/descargas/biodiversidad/mfe.html

polygons affected by the fire. The polygons are the elements that represent and contain the vegetation information within the National Forest Map layer. Among the information it contains, structural type, woodland type and number of predominant species have been considered. Structural type refers to the general structure and origin of the forest, describing how it is organised and managed (for example, whether it is a natural forest, a plantation, or a gallery forest associated with rivers); woodland type provides a more detailed ecological and functional classification, defining the forest according to its environmental setting, dominant vegetation characteristics, biogeographical region, and, in some cases, its productive use.

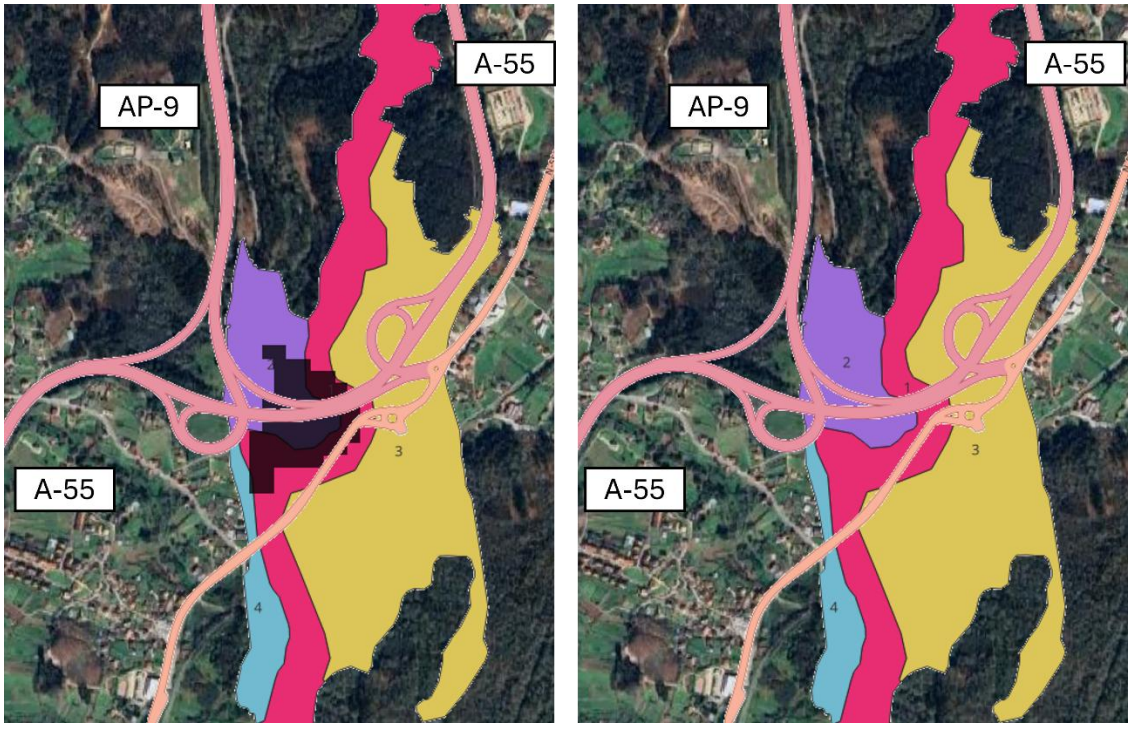


Figure 6: Land cover characteristics of the affected area in the SARIL National Scenario disruption. On the left, the map showing the vegetation distribution, the simulated fire (in black), and the main roads; on the right, the same figure but without the superimposed fire, showing only the vegetation areas together with the infrastructure.

Once the polygons—and therefore the affected vegetation—are identified, the total area and the area affected by the wildfire are calculated. Table 5 shows, for each affected polygon, the type of vegetation it represents, the dominant species, and the affected and unaffected areas expressed in hectares.

Table 5: Description of vegetation in affected area in National Scenario.

Area ID	Structural Type	Woodland Type	Species 1	Species 2	Area (ha)	Affected Area (disruption) (ha)	Affected Area (mitigation) (ha)
1	Gallery Forest	Riparian Forest	*Alnus glutinosa* (black alder)	*Quercus robur* (oak)	24.86	3.11	3.10
2	Plantation Forest	Maritime pine forest in the Atlantic region (Pinus pinaster)	*Pinus Pinaster* (pine)	*Eucalyptus globulus* (eucalyptus)	8.25	4.88	2.90
3	Plantation Forest	Other species for production in mixture	*Pinus Pinaster*	*Eucalyptus globulus*	34.27	0.01	0.01

4	Forest	Mix of native conifers and broadleaves in the Atlantic biogeographical region	*Pinus Pinaster*	*Quercus robur*	4.12	0.03	0.03

The area of the National Scenario is classified as the Cantabrian mixed forest ecoregion (One Earth, 2026). This ecoregion provides habitat to a number of endangered animals and bird species (One Earth, 2026). The area is also a protected area, and is nearby to a marine protected area (UNEP-WCMC & IUCN, 2022).

2.3.2 Environmental Impact

The environmental impacts in the National Scenario are varied. In terms of the disruption, the most obvious source of environmental impact is the release of embodied CO_2 from the combustion of the trees in the fire. In addition to the CO_2 emissions, there is the release of fine particulate matter (PM2.5 and PM10), which is detrimental to both ecological and human health, and which can be deposited long distances from the fire site (Kelley et al., 2025). Ozone, secondary aerosols and volatile organic carbons are also often present in wildfire smoke, and the smoke itself may have direct, negative physiological effects (Huang et al., 2026; Kelley et al., 2025). Furthermore, direct damage to buildings and infrastructure requires restoration activities, which use materials and require construction work, with potentially considerable environmental footprints.

In the disruption scenario, 101 ha of land are affected by the forest fire; the vegetation in this area consists of a mix of natural forests of alder, oak and pine, and plantations of pine and eucalyptus in a Catabrian mixed forest ecoregion, with plantations representing approximately 59% of the potentially affected area (Table 5). In particular, the study area and the corridor along the A-55 highway has a relatively high population density (Pigaiani et al., 2024); a forest fire in this area exposes relatively many people to the direct danger of the fire itself, but also the resulting air pollutants.

The firebreak mitigation scenario considers the removal of flammable biomass. Depending on how and where a firebreak is implemented, environmental impacts may include reduced nature areas, including loss of habitat, ecosystem fragmentation and an increased risk of erosion (Mahmoud, 2024). Some firebreak areas may be implemented as built area such as roads, or buildings; this approach, however, requires proper planning, such as ensuring sufficient distance between combustible elements, or using non-combustible or fire resistant construction elements (Giammanco et al., 2023). The presence of humans in close proximity to forests, despite the introduction of a buffer area, may also increase the probability of human activities inducing a fire event (Mahmoud, 2024).

Forest mass management as a mitigation approach is a broader, long-term strategy aimed at enhancing the resilience of forest ecosystems to wildfire. This approach includes practices such as thinning dense tree stands, removing deadwood and underbrush, conducting prescribed burns, and promoting fire-resistant plant species. The goal is not only to reduce the fuel load that can feed wildfires but also to improve biodiversity, support ecological balance, and facilitate natural regeneration. This avoids the detrimental effects of land use changes that often occur with the firebreak strategies, however, the biomass removal activities may nevertheless disturb the ecosystem by affecting species richness or soil fauna or changing the forest structure (Biryol et al., 2026; Yao et al., 2024). The extent and nature of these effects, however, may vary depending on the type of ecosystem and the microclimatic conditions in question, although the mechanisms of these effects are complex and require further research (Biryol et al., 2026; Yao et al., 2024).

2.3.3 Economic Impact

In the disruption scenario, the disruption itself may induce direct costs through damage to the transport infrastructure and local built area, as well as the emergency response such as firefighting and evacuations. However, the disruption may incur indirect costs as well, such increased fuel use from detours and congestion arising from the closure of transport corridors, and consequently, through delays, or unsuccessful shipments. Furthermore, there are major transport arteries in Galicia connecting ports such as the Port of Vigo to inland Spain and Europe. A disruption along these arteries may have considerable impacts on cargo transport in and out of Spain. With the logistics sector contributing significantly to the regional GDP, at 4.2% (Galicia Logistics, 2022), interruptions in logistics activities may induce considerable economic impacts in this sector. In addition to the direct economic impacts of potential loss of plantations and the related sectors, a disruption may also potentially blockage of supplies to industries and prevent the movement of goods destined for export or import at the ports, leading to ripple effects in the economy even beyond the disrupted area.

Apart from the indirect economic impacts due to the interference with transport activities, the disruption scenario has impacts in other sectors as well. The area surrounding the fire site is heavily adapted for human use in the form of eucalyptus plantations, which accounts for approximately 28% of total forest area in Galicia (Merino & Gil, 2023), and has a considerable economic importance to the region. Galicia is the leading producer of timber in Spain; the eucalyptus plantations can provide up to 2500 EUR/ha/yr and are a relatively rapidly maturing, non-native species that adds highly combustible biomass to the area (Merino & Gil, 2023). The wood is generally used as feedstock to the paper industry, where the pulp is mainly exported (Merino & Gil, 2023). Forest fires cause a surge in timber stocks due to the forced harvesting of damaged trees, which local actors do not have the capacity to handle; this generally results in the excess stock being exported, and a local loss of value added (Hoeben et al., 2025).

Additionally, this area of Spain is characterised by a relatively prosperous rural tourism industry (De Diego et al., 2023). Fire disturbances can therefore influence this sector, as noted in Carta (2025). Meier et al (2023) found that forest fires in Southern Europe reduced GDP growth ranging from 0.11 to 4.8%, depending on the severity of the fire. They also found negative employment effects, which they hypothesized was due to the disruptions to the tourism industry. The damage caused by a forest fire may also reduce the value of ecosystem services provided by the forest, such as hunting or tourism (Román et al., 2013).

In terms of the mitigation measures, if plantation area is sacrificed in establishing the firebreak, this would clearly result in economic ripple effects on the forestry sector as previously productive land must be cleared. Similarly, if natural forest area is cleared for the firebreak, the loss of ecosystem services and potential tourist income may incur a loss of economic value in the area. However, if a firebreak is established through increasing a built-up area such as an industrial park (as opposed to only clearing the land), this may induce increased economic activity to the area.

Forest matter management programs may take several forms, from clearing excess matter, to changing the species being cultivated at the plantations. For the former, the increased activity necessitated in clearing and managing the biomass may increase employment within the forestry sector, but would also add further costs to the landowners in the form of labour, fuel and capital investments for machinery (Bayham et al., 2022).

On the other hand, introducing more resilient species into plantations, including multi-species mixed forest plantations or more fire-resistant varieties, while avoiding monoculture plantings like

eucalyptus, makes areas more resilient and less vulnerable to future fires and the losses they suffer (Schifferdecker et al., 2025).

2.3.4 Conclusion

The mitigation approaches considered in the National Scenario primarily concern private landowners, rather than actors in the transport value chain. Consequently, to enact these measures, transport infrastructure developers and maintainers would need to cooperation from landowners with properties near or adjacent to the transport infrastructure. In this scenario, the greatest points of environmental significance are likely to be related to minimizing the forest fire disruption itself, rather than mitigating its effects on the transport sector. Nevertheless, one can point to the co-benefits of building a firebreak or ensuring a forest matter management program near the study corridor, which leads to fewer disruptions in traffic, and reduces the amount of forest burned. The concrete effects of these mitigation strategies, however, are highly sensitive to the area under consideration, and further research regarding the nature area in question should be conducted before these measures are enacted. Consequently, when approached from the system perspective, reduced CO_2 emissions from reduced biomass combustion offsets the CO_2 emissions from the forest fire, although the extent of the offset is unknown. This is expected in both the proposed firebreak and forest mass management scenarios, although the implementation contexts of these mitigation approaches (i.e., how the firebreak is constructed or how biomass management is performed) may add some environmental impacts as well. However, again depending on how it is implemented, a firebreak structure may lead to ecosystem fragmentation, while some well-managed forest mass management regimes may support improved ecosystem health and biodiversity conditions.

2.4 European Scenario

In the European Scenario, the disruption is considered under the context of the Ukraine war; the disruption is a two-week strike in the Port of Hamburg, wherein cargo ships are rerouted to Rotterdam and Bremerhaven. The two mitigation measures from the scenario considered in this impact assessment are the increased usage of trains from Istanbul and the electrification of the fleet between Germany and Austria. This builds on the modelling performed in ASTROIT, which considered a transport network consisting of truck and train routes across Europe (Figure 7).

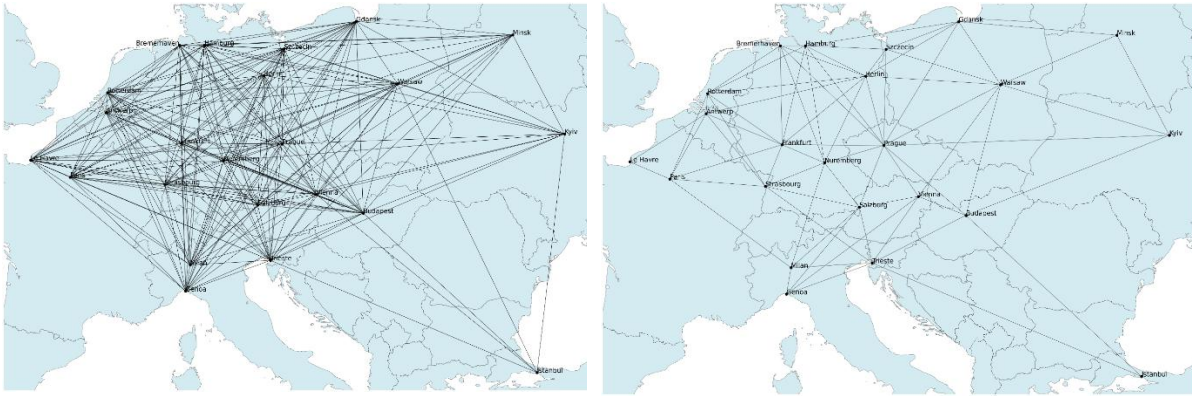


Figure 7: Truck (left panel) and train (right panel) networks considered in the European scenario. Figure from D3.3 (SARIL project D3.3, 2025)

2.4.1 Method

For the evaluation of increased train transport and electrification scenarios, the outputs from ASTROIT and the Energy Module were used to determine the life cycle impacts of the alternative modes of

transport. These approaches and the resulting outputs, performed in SARIL Deliverable 3.3, are briefly summarised below.

At its core, ASTROIT is an agent-based model. The model consists of a network of European cities acting as hubs (warehouses) connected by train and truck services. The Energy Module is used to determine the route length, travel duration and direct tailpipe CO_2-eq emissions for each edge[4] in the network and for each service type. Fuel and labour costs are also calculated for each edge trip. The cargo flows, modelled as individual shipments (agents) as determined from logistics stakeholders Gebrüder Weiss and CSL. The output of ASTROIT includes the movement of completed deliveries over time, and the resulting direct emissions and costs of these deliveries over the entire network.

The European scenario assessed a baseline, non-disrupted scenario, a disruption scenario, and two mitigation scenarios. The disruption scenario assumes a two-week strike in Hamburg harbour in addition to the Ukraine war. Consequently, shipments are rerouted through Rotterdam and Bremerhaven. The two mitigation scenarios consider the effects of using electric heavy-duty trucks in south Germany and Austria ("E-trucks" scenario); and the use of trains from Istanbul to avoid routes crossing Russia or Ukraine ("Trains" scenario). The latter mitigation scenario results in increased truck traffic to and from Istanbul to the rest of Europe.

In this work, the total number of trips performed by each vehicle type along each edge in ASTROIT was determined for each scenario, and the well-to-wheel emissions compiled according to the emission factors considered in Table 6. For modes using electricity as an energy carrier, we calculated the carbon intensity of electricity for each edge; it is assumed that this carbon intensity is the average of the origin and destination node. For example, the electricity for trips on the edge connecting Budapest and Warsaw has a carbon intensity of 456.6 g CO_2-eq/kWh (average of 677 and 236). Electricity mixes for each node were used as the annual 2025[5] country average consumption mix[6] according to Electricity Maps[7].

Table 6: Well-to-wheel emission factors for transport energy carriers used in SARIL EU scenario.

Energy carrier	Region	Emission factor	Units
Electricity, consumption mix	Austria	169	g CO_2-eq/kWh
	Belarus	287	g CO_2-eq/kWh
	Belgium	182	g CO_2-eq/kWh
	Czechia	468	g CO_2-eq/kWh
	France	32	g CO_2-eq/kWh
	Germany	336	g CO_2-eq/kWh
	Hungary	236	g CO_2-eq/kWh
	Italy	294	g CO_2-eq/kWh
	Netherlands	262	g CO_2-eq/kWh

[4] An edge is the route between two nodes, i.e., cities, in the modelled transport network.
[5] The exception is Ukraine, for which we use 2022 values as the latest data available. This difference is not expected to make a major impact on results.
[6] Consumption mixes in terms of electricity consider the electricity produced locally, plus the electricity imported, less the electricity exported; for certain countries such as Switzerland and Austria, the difference in carbon intensity between production mixes and consumption mixes can be significant.
[7] https://app.electricitymaps.com/map/live/fifteen_minutes

	Poland	677	g CO_2-eq/kWh
	Turkey	440	g CO_2-eq/kWh
	Ukraine	240	g CO_2-eq/kWh
Diesel, with 19% biodiesel share	All	2 870	g CO_2-eq/L

In addition to the fuel chain emissions, the consequences of the addition of alternative vehicles to the existing fleet (i.e., battery electric trucks) was taken into account. The emissions due to the manufacture of these vehicles were assumed to be 57.43 t CO_2-eq per vehicle, or approximately 50 g CO_2-eq/km. This takes into consideration the increased production emissions of battery electric vehicles in comparison to similarly sized fossil-fuelled counterparts (Jahangir Samet et al., 2023). For a similarly sized fossil-fuelled vehicle, the production emissions are 22.6 t CO_2-eq per vehicle, or 19.6 g CO_2-eq/km. These production emissions are the average values for long-haul trucks published by Volvo (Volvo, 2026) and Scania (Algesten & Ritzman, 2025) LCA reports, and assumes the average lifetime assumed between the two makers as 1.15 million km.

2.4.1 Environmental Impact

Figure 8 shows the absolute total fuel cycle emissions for each vehicle type and energy-carrier pair. Overall, the figure illustrates the importance of considering the entire value chain when evaluating emissions. Although electric powertrains have no direct (tailpipe) emissions, the electricity used as an energy carrier has a carbon footprint, the magnitude of which is dependent on whether it originates from fossil fuels such as coal, or from renewable energies such as hydropower or wind power. But even with fossile diesel fuels, the well-to-tank emissions represent a considerable portion of the total emissions. Ignoring these WTT emissions would therefore constitute a significant underestimation of not only overall emissions, but also the emissions attributable to specific transport modes and energy carriers.

Across all scenarios, diesel trucks are by far the greatest source of emissions. This is due to the dominance of this mode in the network, with most of the trips performed by diesel trucks. In terms of environmental impact, large scale shifting of these deliveries to more efficient and low-carbon modes such as trains or e-trucks would reduce network emissions, as would increasing the utilisation factor of individual vehicles (and thus allowing for fewer trips). However, to make a considerable difference in overall emissions, a relatively large number of trips driven by diesel trucks would have to be displaced.

Also, of note in Figure 8 is the emissions from trains. Although the 62% of all train trips are performed by electricity-based trains, with the remaining being diesel, the inclusion of the emissions from electricity supply chain is makes the total emissions from electric trains nearly as much as those from diesel.

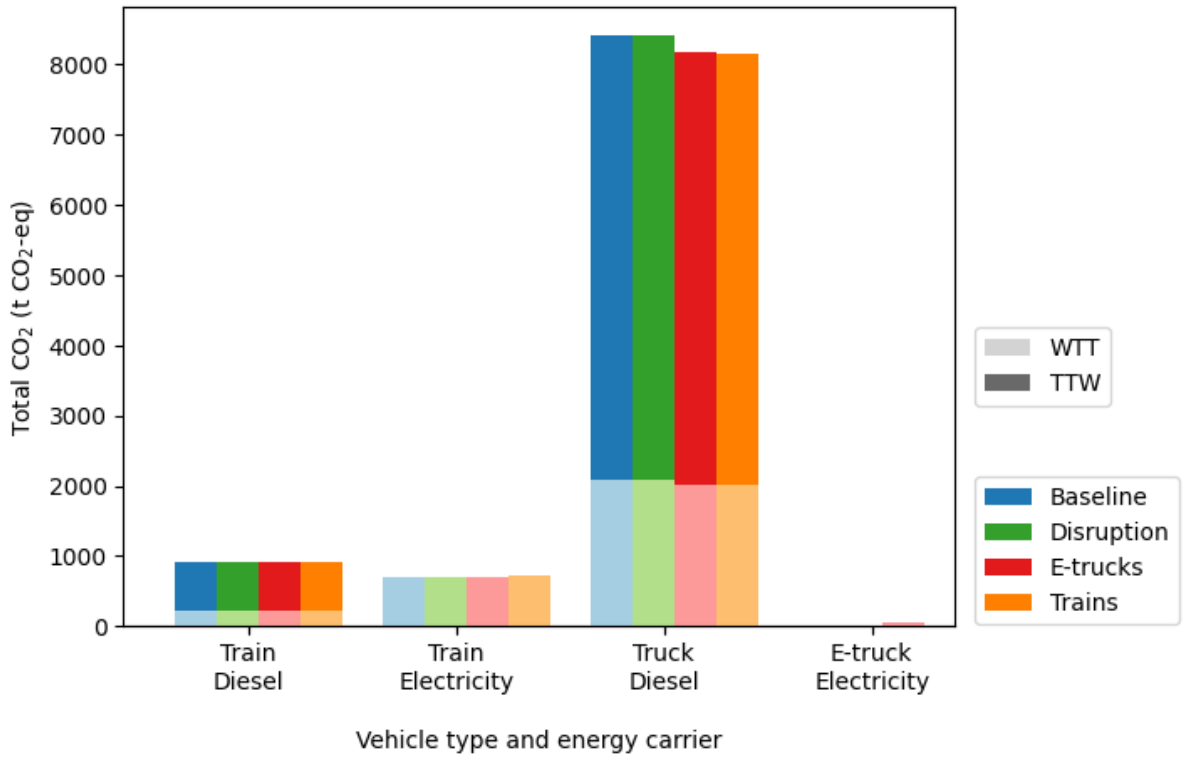


Figure 8: Breakdown of life cycle environmental impacts of European scenario Baseline, Disruption, E-trucks and Trains sub-scenarios by vehicle type and energy carrier. WTT (light): well-to-tank, TTW (dark): tank-to-wheel.

Adding the vehicle cycle, which represents the emissions associated with the production of the vehicle itself, to the fuel cycle results, adds to the absolute emissions for each scenario, but represents relatively little to the total for the scenario (Table 7). However, as electrification of road transport in particular increases, these production emissions are likely to represent a larger share of total emissions. Reduced operating emissions (well-to-tank and tank-to-wheel) are generally expected to overcome the increased vehicle cycle emissions of e-trucks over the vehicle lifetime. The overall climate benefit from electrification, however, is sensitive to the country in which the vehicle is charged due to differences in regional and national electricity mixes.

Table 7: Total scenario results for European scenario distributed across different life cycle phases to the total emissions for each sub-scenario.

	Scenario emissions (t CO_2-eq)			
Life cycle phase ↓	**Baseline**	**Disruption**	**E-trucks**	**Trains**
Vehicle manufacturing	169	169	176	164
Well-to-tank	3007	3008	3003	2975
Tank-to-wheel	7017	7017	6838	6824
Total emissions	**10193**	**10194**	**10017**	**9963**

Between the scenarios, the changes in life cycle CO_2 impacts are described in Table 8. In comparison to the relative changes using only direct tailpipe emissions, the same trends between the scenarios are observed, although the magnitude of these changes are different. This is attributable to increased emissions intensity for electric vehicles compared to diesel vehicles from a life cycle perspective; as both the carbon footprint of electricity for charging the batteries and the production emissions for the electric truck are considered, overall emissions are higher and decrease the difference between the

mitigation scenario and the disruption case. Similarly, in the train scenario, a relatively small difference in emissions is observed between the disruption and mitigation scenario due to the inclusion of well-to-tank emissions for both electricity and diesel, as illustrated in Figure 8. Including the well-to-tank emissions decreases the total difference observed between disruption and baseline scenarios. Nevertheless, the difference in emissions show a net benefit from moving shipments from diesel trucks to more energy-efficient trains.

Table 8: Relative change in CO_2 emissions between cases in the European scenario.

	Relative change in CO_2 (direct emissions only)	**Relative change in CO_2, this work (life cycle emissions)**
Disruption case, relative to base case	+2.7%	0
E-trucks mitigation case, relative to disruption case	-12.6%	-1.7%
Trains from and to Istanbul mitigation case, relative to disruption case	-6.1%	-0.5%

Note that battery electric freight trucks are a relatively new technology and consequently improvements to their environmental impacts are expected as the technology matures. Production emissions for these vehicles are highly dependent on the battery type and size, and the lifetime of both fossil and battery-electric vehicles are dependent on the use case and will influence the emissions intensity (g CO_2-eq/km) of operating these vehicles.

Overall, the disruption and mitigation scenarios did not show a significant difference from the baseline scenario in terms of absolute emissions, even with the life cycle perspective is considered. This is likely in part due to the sheer size of the system; although the disruptions are occurring at major hubs, the shipments that experience a shift in mode represent a relatively small proportion of the total network. Nevertheless, some general trends can be observed and can provide some insights into areas for reducing emissions while avoiding hidden effects upstream in the value chain.

2.4.1 Economic Impact

The systemic economic impacts in the European scenario can vary depending on the mitigation measure taken. In addition to additional fuel and labour costs associated with detours and delays, large disruptions may also have significant direct costs due to additional warehousing storage requirements, the loss of goods and business interruptions. Indirect economic effects and costs include changes in household spending patterns due to shortage of goods, and prices increasing. The nature of modern, global value chains means these repercussions can be experienced far beyond the disrupted region, and the prevalence of modern just-in-time supply chains reduces buffer stocks and manufacturing capacities that can mitigate or delay the negative effects of the disruption.

In terms of the electrification of freight truck fleet, these will incur higher capital costs for the logistics operator in comparison to fossil fuel equivalents. Although operating costs for electric vehicles are generally thought to be less than fossil fuel vehicles, a dependence on commercial public fast chargers over depot charging may reduce the economic advantage for operators (Lanz et al., 2022). This consideration, in combination with longer charging times in comparison to refuelling, may present limitations in the use case for current electric heavy-duty vehicles in terms of which routes and schedules the vehicle is suited for.

2.4.2 Conclusion

In the European scenario, there was relatively small differences between the studied cases due to the large size of the network compared to the magnitude of the studied disruption and mitigation scenarios. Nevertheless, some general conclusions can be drawn from the findings. First, omitting life cycle emissions by considering only direct (tank-to-wheel) emissions will result in a considerable underestimation of total emissions attributable to transport. Secondly, when comparing different powertrain technologies, trade-offs in environmental performance that occur elsewhere in the life cycle would otherwise not be captured, such as the higher production emissions attributable to battery electric vehicles compared to their fossil-fuelled counterparts. While the upstream emissions from the fuel chain (well-to-tank) in this assessment represented a larger share of total transport emissions in this scenario than the vehicle production, it is nevertheless important to include vehicle production impacts to have holistic perspective of total impacts.

2.5 Global scenario

In the widescale disruption case, EEIO is used to evaluate the socioeconomic and environmental impacts of a hypothetical scenario where land-based rail freight is deviated. This scenario was not considered in the previous modelling work in SARIL but nevertheless is helpful in illustrating long-reaching environmental and economic impacts of large-scale disruptions that block major trade routes over longer time periods and between continents, such as that which was experienced under the Covid-19 pandemic. In this scenario, a complete blockage of land-based transport between Asia and Europe, simulating a wide-scale disruption such as global pandemic, is analysed.

2.5.1 Method

The data from this scenario is from the EXIOBASE 2022 dataset multi-regional input-output (MRIO) tables. These MRIO tables contain economic data capturing domestic production for 49 countries and regions, as well as imports, international trade flows and domestic intersectoral trade. For the purposes of this study, the world was aggregated into three regions: Asia, including China; Europe; and the rest of the world, including Russia.

In addition to the intersectoral exchanges, EXIOBASE contains sector-specific value-added data, final demand, as well as environmental and social indicators such as greenhouse gas emissions and employment, respectively. The indicators used in this case are greenhouse gas emissions for environmental impacts, and value added and employment for the economic impacts.

EXIOBASE is used in a basic macroeconomic input-output framework to perform the analysis. The detailed technical description of the approach, including equations, can be found in Miller and Blair (2009) or in Fugger et al (2026). In short, the MRIO tables are used to describe how economic sectors depend on one another and allows IO analyses to show the economic effects caused by shocks in the economy. Environmental extensions, such as those provided in EXIOBASE, use average sectoral impact factors to allow for calculation of environmental impacts of these shocks.

This analysis focuses on the environmental and economic effects that are associated with each monetary unit. These effects are captured in a multiplier matrix, M_i, which captures the change to both direct and indirect contributions to indicator *i* for all originating and demand sectors. This multiplier can therefore be used to evaluate the effects of a 1 million EUR change in final demand of a given sector on the given environmental or economic indicator *i.* For the purposes of this scenario, the sectors in question are the transport sectors, comprising of rail, other land transport, pipelines, sea and coastal, inland water and air transport services in Asia and Europe.

In the scenarios described in Table 9, it is assumed that in the case of a global disruption, the business-as-usual transport modes can be shifted to alternative modes. Each of the mitigation scenarios assume re-routing of rail cargo transport from Asia to Europe via maritime or air freight to varying degrees. For each re-routing scenario, two efficiency subcases are assumed to assess the consequences of inefficiencies arising from the re-routing. This assumption is a simplification intended to act as an umbrella measure to account for e.g., adjusting existing routes to harbours instead of rail depots, increased warehousing, longer routes or mixing modes.

Table 9: Description of hypothetical large-scale sub-cases in impact assessment.

Scenario		Re-routing of rail transport in Asia	Assumed efficiency, sea transport
Sea	i	100% re-route via sea transport	Unchanged
	ii		Disrupted efficiency – 20% higher transport costs
Mixed	i	75% re-route via sea transport, 10% re-route using airfreight, and the remaining 15% is cancelled after the disruption	Unchanged
	ii		Disrupted efficiency – 20% higher transport costs
Cancel	i	25% re-route via sea transport, 5% re-route using airfreight, and the remaining 70% is cancelled after the disruption	Unchanged
	ii		Disrupted efficiency – 20% higher transport costs

The second adjustment accounts for different per-unit costs amongst the transport modes, i.e., costs for moving a given load of cargo varies depending on whether it is moved with rail, ship or air. Adjustments must be made to reflect these differences when shipments are re-routed on different modes. To this end, freight rates for a standard shipping container between Asia and Europe were used (Economic Commission for Europe, 2018). The factors used to adjust the multipliers of the re-routed cargo relative to the original rail transport are presented in Table 10. As an example, a 1 mill EUR rail shipment would cost 4 mill EUR to re-route by air.

Table 10: Relative freight rates.

Freight mode	Cost of transport, relative to rail	Source
Rail (disrupted mode)	1	(Economic Commission for Europe, 2018)
Sea	0.5	(Economic Commission for Europe, 2018)
Air	4	(Zheng, 2025)

Using the adjusted multiplier matrices and the scenario definitions in Table 9, the change in impact indicators was calculated (Equation (1)). The final result of the calculation is a set of impact indicators that show the change in impact from shifting 1 mill EUR of rail transport services in Asia (as the

baseline scenario) to other transport modes on the larger economy[8] in both Europe and Asia. Due to the global nature of greenhouse gas emissions, environmental impacts consider the emissions in both Asia and the rest of the world (Europe and rest-of-world regions aggregated). Due to the European focus of SARIL, the economic impacts focus on effects on local (Asian) and European economies.

$$\Delta\, impact_{Asia} = M_{sea} s_{sea} a_{sea}(1+\eta) + M_{air} s_{air} a_{air} - M_{rail} \quad (1),$$

where M_t is the unadjusted multiplier matrix for transport mode *t,*
s_t is the re-routed share to mode *t,*
a_t is the cost-adjustment factor adapting rail costs to mode *t,* and
η is the assumed transport efficiency

2.5.2 Environmental Impact

For GHGs, the results of the scenarios when shifting €1 million worth of rail transport in Asia to other modes is shown in Figure 9 for all scenarios. Overall, we see increased emissions in all scenarios, ranging from 100 to 830 tonnes of CO_2-eq per €1 million displaced rail transport, evidencing that the rail transport sector generates less emissions than the sea transport sector when it is normalised according to the price per volume. The greatest increase of emissions was found in the Mixed scenarios, most likely due to the effect of including re-routing through air transport. Meanwhile, the Cancel scenarios performed best for GHGs, most likely due to the avoided emissions from cancelled shipments, but it is still not enough to drive a net positive result; the transport emissions from the re-routed goods in this scenario are greater than the transport emissions saved by cancelling the remaining shipments. The overarching trend in the results of increased emissions across all scenarios imply that using rail transport is an environmentally optimised mode of transport.

Between the effects in Asia and the rest of the world, the effects are more drastic in Asia. This is most likely due to the emissions associated to the combustion of fossil fuels, which are accounted directly in the transport sectors in Asia.

[8] What is meant by larger economy here is all economic sectors, such as agriculture; energy and fuels, manufacturing; raw materials processing; services, etc

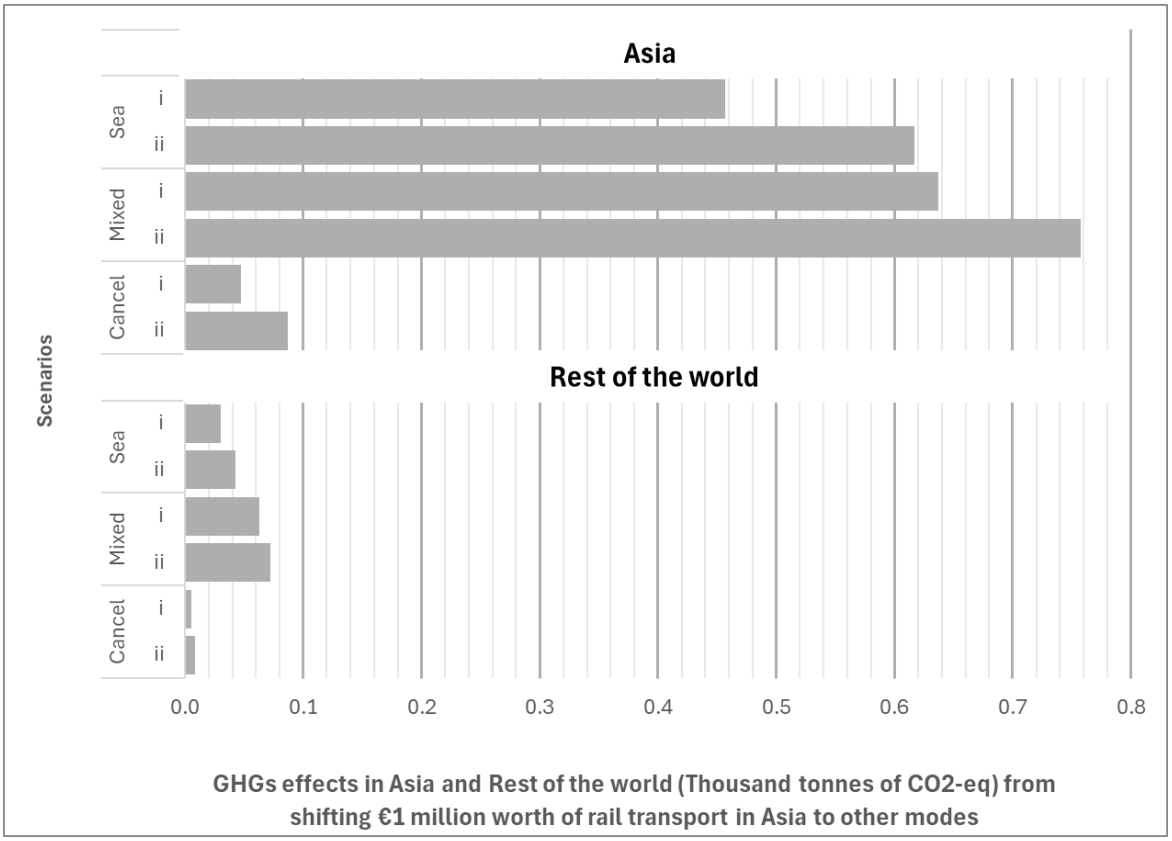


Figure 9: Changes in GHGs after a decrease of 1M€ in Asia and Europe transport demand.

2.5.3 Economic Impact

Regarding employment, the scenario results for shifting €1 million worth of rail transport in Asia to alternative modes (Figure 10) show a strong dominance of impacts within the Asian economy. Most scenarios indicate an overall decreased employment (ranging from 2 to 12 jobs[9]), except for the Mixed scenario in which 9 to 13 jobs are created. This increase in employment may be due to the higher re-routing with air transport sector, which induces relatively high employment per monetary unit of demand in comparison to the other transport sectors, thus yielding increased employment when greater demand is placed on air transport. This outcome reflects that in Asia, the air transport sector is connected to highest employment per monetary unit, followed by the railway transport sector. As with the emissions effects observed, cancelling a large portion of shipments outright leads to a decrease in employment as this necessarily reduces activities in other sectors.

Overall, employment effects in Europe from the shifting of rail transport in Asia are relatively subdued, showing a neutral to slight increase in employment in the European economy across the scenarios studied. This observation might be due to a lower "employment intensity" in Europe compared to Asia, that is, a given sector in Asia has more employees per €1 million than the same sector in Europe.

[9] Here, "jobs" is the KPI for employment used in EXIOBASE and refers to the number of individuals employed in a given sector, without distinguishing between part- or full-time positions.

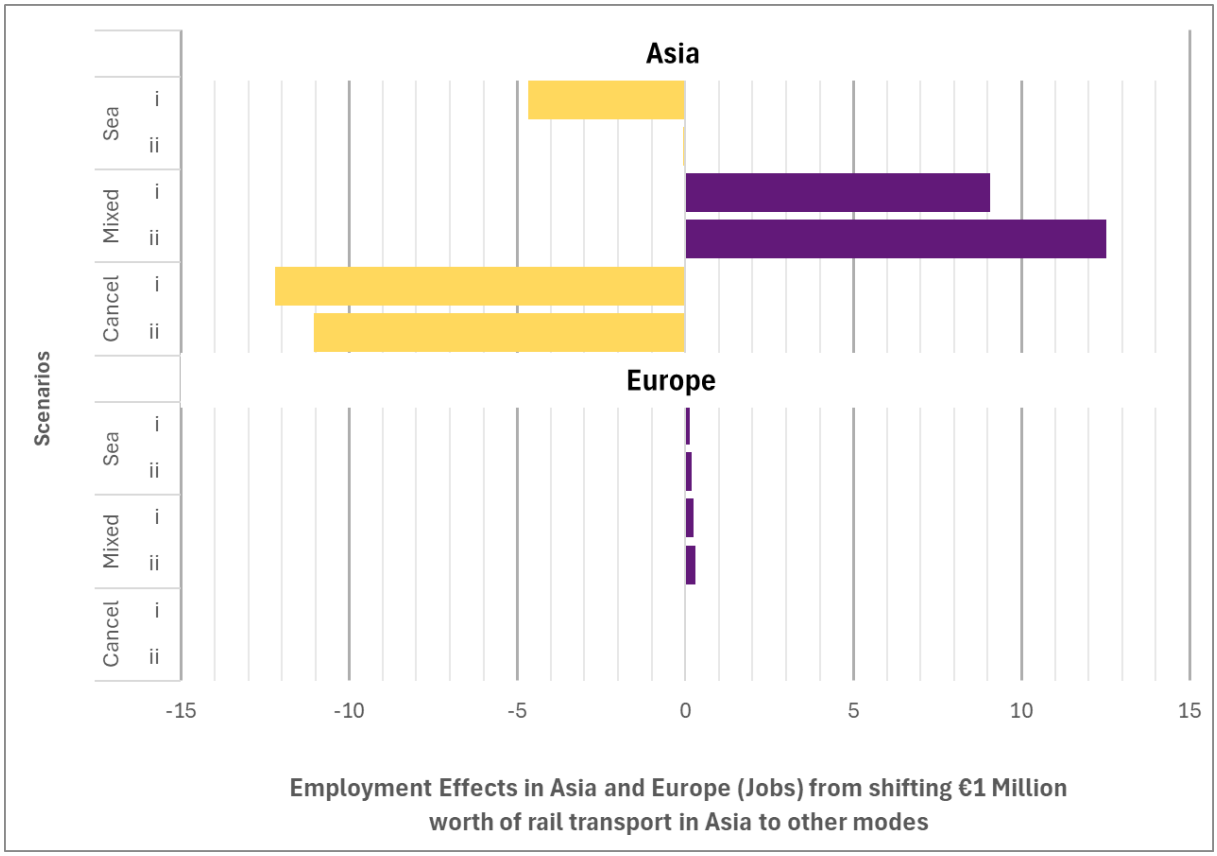


Figure 10: Changes in employment when shifting €1 million worth of rail transport in Asia to other modes.

Effects on value added

With respect to value added, the scenario results show that all scenarios lead to a decrease in value added in Asia, ranging from €230,000 to €680,000 per €1 million worth of rail transport in Asia shifted (Figure 11). This outcome reflects the relatively high contribution of rail transport to value added in Asia in comparison to sea and air transport. Failing to re-route the rail shipments on other modes has the most negative effects on value added in both Asia and Europe, as a lack of shipments presumably reduces activity in both economies. Slight increases in value added in the European economy are observed; these positive effects are attributable to the Asian air and sea transport sectors having greater value-added intensity in Europe than rail transport. In the Mixed scenario, greater effects are shown in the European economy than the Sea scenario, likely because air transport is generally linked with higher value-added goods.

In the scenario analysis, when we adjust the transport sectors according to the price needed to mobilize a similar volume, we observe that modal shifts to sea transport translate into increased GHG emissions, highlighting the positive environmental effects of the rail transport mode in Asia, which can be connected to a high electrification rate in the rail sector, and suggesting that possible disruptions in the rail transport sector are expected to result in higher GHGs emissions when re-routing is considered. However, apart from the electrification variable, there might be other reasons to explain why the rail transport in Asia shows less emissions intensity than the sea transport sector.

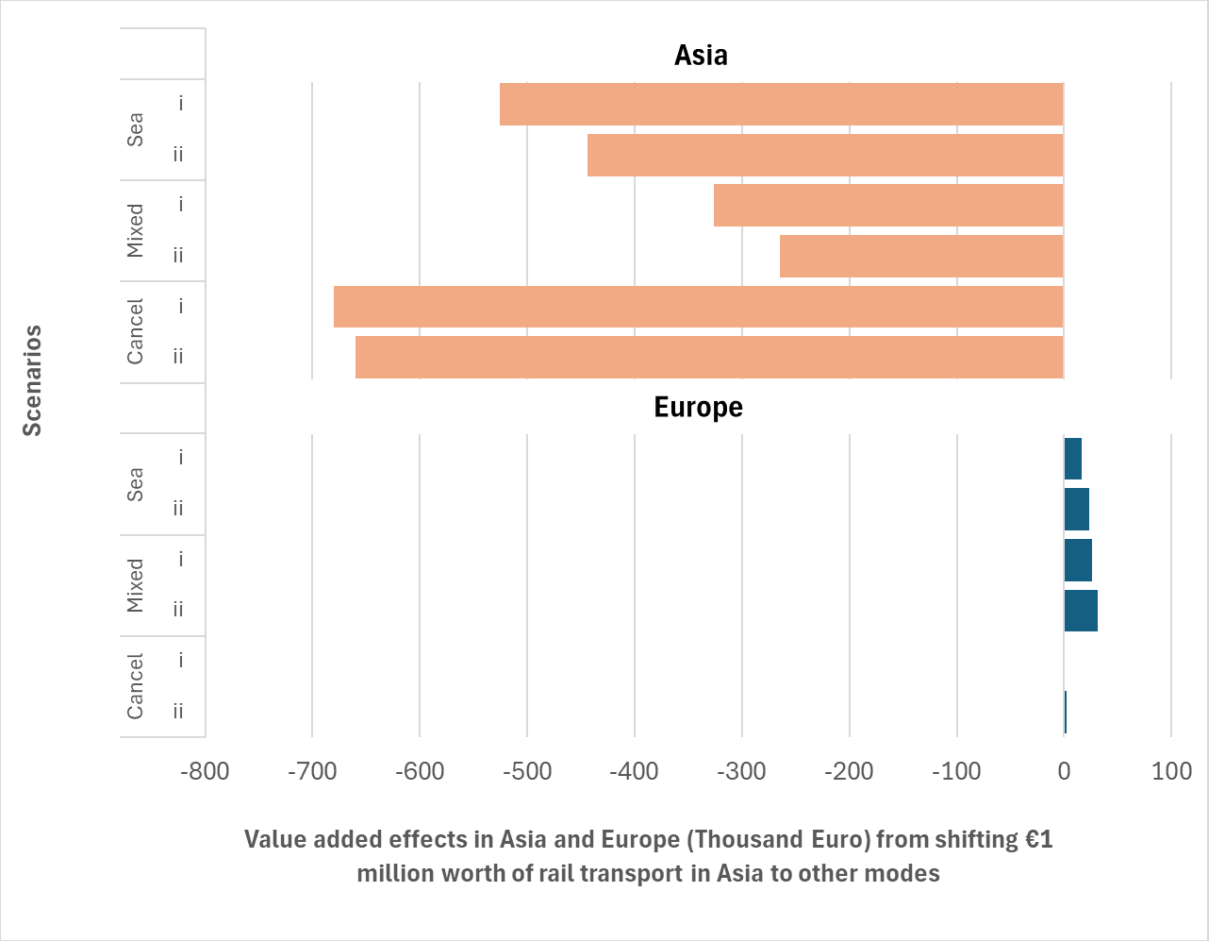


Figure 11: Net changes in value added when shifting €1 million worth of rail transport in Asia to other modes.

When transport sectors are adjusted by price per unit in the scenario analysis, we observe that, considering both direct and indirect effects, changes in the rail transport sector are associated with higher employment effects than for the sea transport sector. However, the air transport value chain generates even more employment than rail transport. This highlights the positive benefits of the rail transport sector for employment, while evidencing that possible disruptions in the rail freight transport sector are expected to result in net negative employment effects in Asia, with shipment cancellations have outright most negative effect on employment.

Finally for value added, changes in the rail transport sector have the highest impacts on value added amongst transport modes. Moreover, in the scenario analysis, when there is adjustment according to price per volume, it is clear that the rail transport sector in Europe and Asia have higher positive effects in value added than the sea transport sectors. This trend suggests that there will be net negative effects in value added with possible disruptions in the rail transport sector.

2.5.4 Conclusion

In the widescale disruption case, disruptions in the rail transport sector between Asia and Europe, modelled as different modal shifts and cancellations, generally result in higher net emissions, and reductions in employment and value added. These results highlight the long reaching effects of large-scale disruptions, which, due to globalised supply chains, can have environmental and economic impacts beyond the directly affected regions. While the approach used here is somewhat simplified to understand the potential wider impacts from freight disruptions, it nevertheless provides some

insight into the dependencies between sectors and regions. Overall, findings point to disruptions in rail transport having detrimental effects on value added, with "local" value added decreasing in all scenarios. Losses in efficiencies, modelled as higher costs, generally amplified positive economic effects, and curbed detrimental economic effects. This contrasts the environmental impacts, where lowered efficiency worsen environmental impacts in comparison to unchanged efficiency. Findings also show an inverse relationship between environment and economy; generally, scenarios with a lower impact on the environment show the worst effects on overall value added and the employment indicator, and *vice versa*. An important caveat to the findings, however, is that the data represents a snapshot of the economic system, and consequently, the analysis assumes all other economic relationships remain static. This means that the economy does not, for example, seek to establish alternative suppliers from non-disrupted regions.

Disruptions in the railway transportation route between Asia and Europe for the chosen indicators are dependent on the mitigation possibilities given. In most cases, emissions would likely increase in any alternative re-routing scenario - even if some of the shipments are cancelled, both on the Asian and the European part of the transportation route. However, for the Asian transportation systems, employment effects seem to be dependent on the alternative re-routing options, while European employment effects are slightly positive in all rerouting scenarios. Value added for European regions seem to increase somewhat in the re-routing scenarios, probably because the railway sector could be subsidised rather than generating value added while we can observe the reverse effect in Asia suggesting the railway sector could be generating high value added compared to other transportation solutions.

2.6 General Considerations

The analyses of the SARIL scenarios and the newly defined Global scenario presented in the previous sections provide a general assessment of system-wide environmental and economic impacts. While the numerical results from the scenarios are not directly comparable due to the differences in scope, they nevertheless illustrate the importance of the systems thinking. Additionally, the results do not provide a complete quantification of the impacts for these scenarios. This is because detailed data regarding the nature of the transport on these networks (e.g., share of passenger transport compared to freight transport, the nature of the goods being transport on given network segments, origin-destination) are necessary to calculate precise impacts and to distinguish between effects on passenger and freight transport, but generally not available for these studies.

General comments regarding the nature of these impacts, however, can be made. For example, in the consideration of trade-offs between resilience measures and sustainability, the effects of disruptions on the transport of particularly sensitive and critical goods should be considered; perishable items and medicines are two examples of such goods. In the face of a disruption, large quantities of such goods may potentially be needlessly destroyed if re-routing options are not found in time, or if emission-heavy rerouting options are ignored, representing both economic losses and environmental losses due to the embedded emissions in the production of these goods. Additionally, further social harm may also be incurred by the inability to transport such goods to the necessary areas.

Another aspect that is difficult to capture in this analysis is the temporal aspects of disruptions in transport; certain disruptions may have long-reaching effects that are difficult to predict and capture with the existing methods and available datasets. Major ripple effects arising from significant events with either (or both) far-reaching or long-lasting effects can significantly affect value chains, for example the blockage of imports of raw materials may hamper the operations of manufacturing industries, which in turn may cripple local economies.

3. Conclusion

To definitively address green and resilient transport systems, a holistic approach encompassing all parts of the transport sector and across all stakeholder roles is necessary. In this task, we build on the findings previously performed in Task 3.3 using a life cycle approach to capture both direct and indirect environmental and economic impacts. This approach is particularly important to evaluate resilience measures with physical manifestations, such as infrastructure or mode shifts (in contrast to organisational or behavioural changes). Most green mitigation measures of this nature involve an up-front environmental and economic investment, which must be weighed against the overall added resilience and potential other utility provided by the measure.

In the Regional Scenario, the flood wall and network redundancy both have considerable investment costs and embedded emissions in comparison to the savings these measures provide in the form of lower indirect costs from reduced fuel use and transport delays in comparison to the disruption scenario. However, in consideration of these measures, infrastructure owners should consider that adding a new segment in the network may have additional co-benefits in non-disruption situations, while the flood wall is a measure that does not have any further function or co-benefits beyond preventing road closures in the event of a flood.

The impacts from the National Scenario were discussed qualitatively rather than quantitatively; nevertheless, the results point to a situation where the mitigation methods may not be entirely free from detrimental side effects, despite reducing the effects of the forest fire disruption on the transport system. Establishing a firebreak or installing a forest mass management program may result in further ecosystem fragmentation or land use changes, or may be invasive to the existing ecosystems, while additionally inducing emissions from e.g., machinery. These effects are highly sensitive to the nature of the area in which the measure is applied. However, management using native varieties that are more resistant to fire, avoiding monoculture, provides greater resilience to the infrastructure and leads to a decrease in the carbon footprint.

For the European scenario, an electric truck and mode shift scenarios were considered. The analysis shows that while a life cycle perspective does not necessarily change the overall conclusions from the scenarios, it can considerably increase the absolute emissions observed. In the case of the electric vehicle mitigation scenario, the life cycle approach to calculating emissions reduces the scale of the benefit observed due to the inclusion of well-to-tank, or upstream, emissions from both fossil fuels and electricity, as well as the production emissions for the vehicles, which is higher for battery powered vehicles in comparison to traditional internal combustion engine vehicles.

Finally, a hypothetical scenario was investigated where rail shipments from Asia are blocked from reaching Europe, as a Global scenario. This scenario presumes mode shifts from Asia, and potential changes in emissions and economic impacts that arise as a result. In this widescale disruption scenario, the impacts of disrupted rail transport in Asia have effects both domestically in Asia and in Europe due to increasingly globalised value chains. While the aggregated, macroscale nature of the underlying data make it difficult to pinpoint exact causes for the observed trends, we can nevertheless see inverse relationships between economic and environmental impacts; a scenario where shipments are cancelled may directly result in a lower environmental impacts in the economy than other scenarios, but also lead to a higher loss of employment and value added than scenarios with higher environmental effects, all else being equal.

Each of the scenarios evaluated in SARIL required a different approach due to geographical scale, the nature of the system and disruption, and the types of the stakeholders affected. This highlights the

challenges in developing a generalised and holistic decision-making framework for evaluating green resilience. Direct impacts may be relatively local to the disrupted area, but indirect impacts can be both far-reaching, long-lasting and complicated to anticipate, making it difficult to truly understand the consequences of the disruption itself, and of any potential resilience measures. At relatively local levels, bottom-up approaches such as LCA and life cycle costing, or cost-benefit analyses may be appropriate, while for larger, multi-national disruptions and global supply chains, top-down approaches such as EEIO may be better suited. Common for all these approaches, however, is the need for the appropriate data specific to the region in question to make accurate analyses in evaluating potential effects. Independent of the methods used, however, the findings indicate that in many cases, policymakers must weigh the importance of maintaining transport services in the face of disruptions against environmental impacts and investment costs.

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