ReMuNet
Pioneering resilient and adaptive multimodal transport networks

## D5.4

# Public and Private roadmap and strategies for scalability

Vediafi

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## DISSEMINATION LEVEL

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# ABBREVIATIONS

| | |
|---|---|
| **DEM** | Disruption Events Module – developed in ReMuNet project |
| **DTLF** | Digital Transport and Logistics Forum |
| **ICT** | Information and Communication Technology |
| **LSP** | Logistics service provider |
| **MVP** | Minimum viable product |
| **PoC** | Proof of Concept |
| **TMS** | Transport Management System |

# Executive Summary

This deliverable presents the public and private roadmaps and strategies for scaling the ReMuNet platform beyond the proof-of-concept stage. It is the final deliverable of Task 5.4 and draws on the full body of work produced across the project.

During the project, a functional proof-of-concept platform was developed, demonstrating that disruption data can be integrated with multimodal routing and decision-support tools in a single architecture. The PoC covered the North Sea–Baltic and Rhine–Danube corridors and validated the core technical concept. However, moving from a research prototype to an operational service requires more than technical development. Governance structures, business models, stakeholder commitment, and regulatory alignment all need to be in place before wider deployment is realistic.

The deliverable outlines a phased scalability approach for both public and private sector actors. The public sector roadmap focuses on establishing the governance foundation, securing EU-level alignment, and enabling cross-border data sharing. The private sector roadmap covers service adoption, integration of value-added services, and commercialisation. A Minimum Viable Product approach is recommended as the next concrete step after the PoC.

The role of public sector is seen essential for future scalability, since the platform is designed for international and multimodal usage. Public sector should enable such a collaboration and connect existing data sources and disruptive event information in a way, that it can be used to react the challenges and problems of end-users, i.e. logistics companies. Such collaboration between Member States is also seen to enhance the resiliency and preparedness of the EU wide transport network, both in extreme circumstances and during the daily system failures.

On governance, a consortium-based operating model with a public-private structure is considered the most suitable path forward. The platform will need a legal entity, a cost-recovery mechanism, and clear data ownership rules to be sustainable in the long term.

From a legislative perspective, the EU regulatory environment is broadly supportive of the ReMuNet approach. Key frameworks to address include the Data Act, the eFTI Regulation, the AI Act the Cyber Resilience Act and all guiding sustainability acts such as CountEmissionsEU. Active engagement with EU policy processes is recommended to position ReMuNet as a reference architecture for trusted logistics data exchange.

This project deliverable presents a framework-level proposal for scaling the results of the R&D project into a production-ready service. However, scalability and production deployment are complex and time-critical issues that require a more detailed analysis and implementation plan immediately following a decision to continue the initiative. As this deliverable represents only one of the project's outputs, a comprehensive review of the other project results is also recommended.

# 1. Introduction

This deliverable presents the public and private roadmaps and strategies for scaling the ReMuNet concept beyond the project's proof-of-concept (PoC) stage. It is the final deliverable of Task 5.4 within Work Package 5 and builds on the platform development, simulations and pilot activities carried out during the project. The deliverable utilises all earlier published material on deliverables of the ReMuNet project. Especially this deliverable continues the analysis done in the deliverable D3.4 (ReMuNet's Operator Model and its coherent Business Model) (Dicks et al., 2025).

The ReMuNet project has developed and validated a platform that supports more resilient multimodal transport operations by combining disruption information, route planning and decision-support functionalities. The proof-of-concept demonstrated how disruption data can be integrated into transport planning processes and how alternative routing options can support faster responses to unexpected events.

While the technical feasibility of the concept has been demonstrated, wider deployment requires more than a pre-functional platform. Long-term implementation depends on the availability of data, stakeholder commitment, governance arrangements, business incentives and alignment with European transport and digitalisation initiatives. These factors need to be considered alongside the technical development of the platform.

The purpose of this deliverable is to examine how ReMuNet could evolve from a project-based proof of concept into a scalable operational solution. As explained in Deliverable 3.4 by Dicks et al. (2025), the ReMuNet platform requires collaboration among multiple stakeholders; therefore, a consortium-driven approach is considered the most suitable collaboration model. Given the multi-stakeholder nature of the initiative, particular attention is paid to the distinct roles of public and private stakeholders. Public authorities influence the regulatory environment, data-sharing frameworks and cross-border coordination mechanisms, whereas private actors drive market adoption, service development, and operational integration.

Based on the experience gained during the project, the report outlines possible development paths for ReMuNet and identifies the key actions required to support future deployment. The report includes an overview of the current platform architecture, a discussion of scalability requirements, methodological principles used for roadmap development, public and private sector roadmaps, governance considerations, and an assessment of relevant political and legislative implications.

# 2. System Architecture PoC

The following two sections give an overview of what was built from technical point of view during the ReMuNet project. The first covers the platform itself, its architecture, the main layers, and how routing and disruption management were brought together. During the project WP3 “Designing collaborative platform with high operational interconnectivity for event-based synchromodal relay transport” coordinated platform development tasks. The second looks at the Disruption Database: where the data comes from, how it is structured and how it feeds into the platform's planning functions.

## 2.1 ReMuNet Platform

The ReMuNet platform was developed as a proof-of-concept environment for supporting resilient multimodal transport planning and disruption management. Its objective is to combine transport requests, routing services, disruption information and booking capabilities within a single platform architecture capable of evaluating alternative transport options when disruptions occur.

Figure 1 presents the overall platform architecture. The architecture is organised into four main layers: External Access, Frontend/Internal Access, Backend and the Disruption Layer. Together, these components form the basis of the ReMuNet concept and demonstrate how different data sources and services can be integrated to support multimodal transport decision-making.

The External Access layer provides interfaces towards transport management systems (TMS) and other external applications. Through these interfaces, transport requests can be submitted to the platform for further processing. The Frontend/Internal Access layer provides access through the ReMuNet web interface and supporting components such as the broker and knowledge base.

The core functionality is located within the Backend layer. Transport requests are collected in an order pool and processed through routing and optimisation services. The platform evaluates possible transport routes by combining available transport services, optimisation algorithms, and external service providers. Connections to external systems and booking services enable the platform to incorporate transport-related information from multiple sources.

The Disruption Layer provides information on disruptions affecting transport operations. Data stored within the disruption database is processed through the disruption module and made available to the routing and optimisation functions. This allows the platform to consider disruptions when evaluating transport alternatives and supports the identification of more resilient routing options.

The architecture developed during ReMuNet demonstrates the feasibility of integrating routing, disruption management, and multimodal transport services within a common platform environment. At the same time, the project highlighted the complexity of integrating multiple services and stakeholders into a single operational ecosystem. Further development would therefore be required to transform the proof-of-concept architecture into a fully operational platform suitable for large-scale deployment.

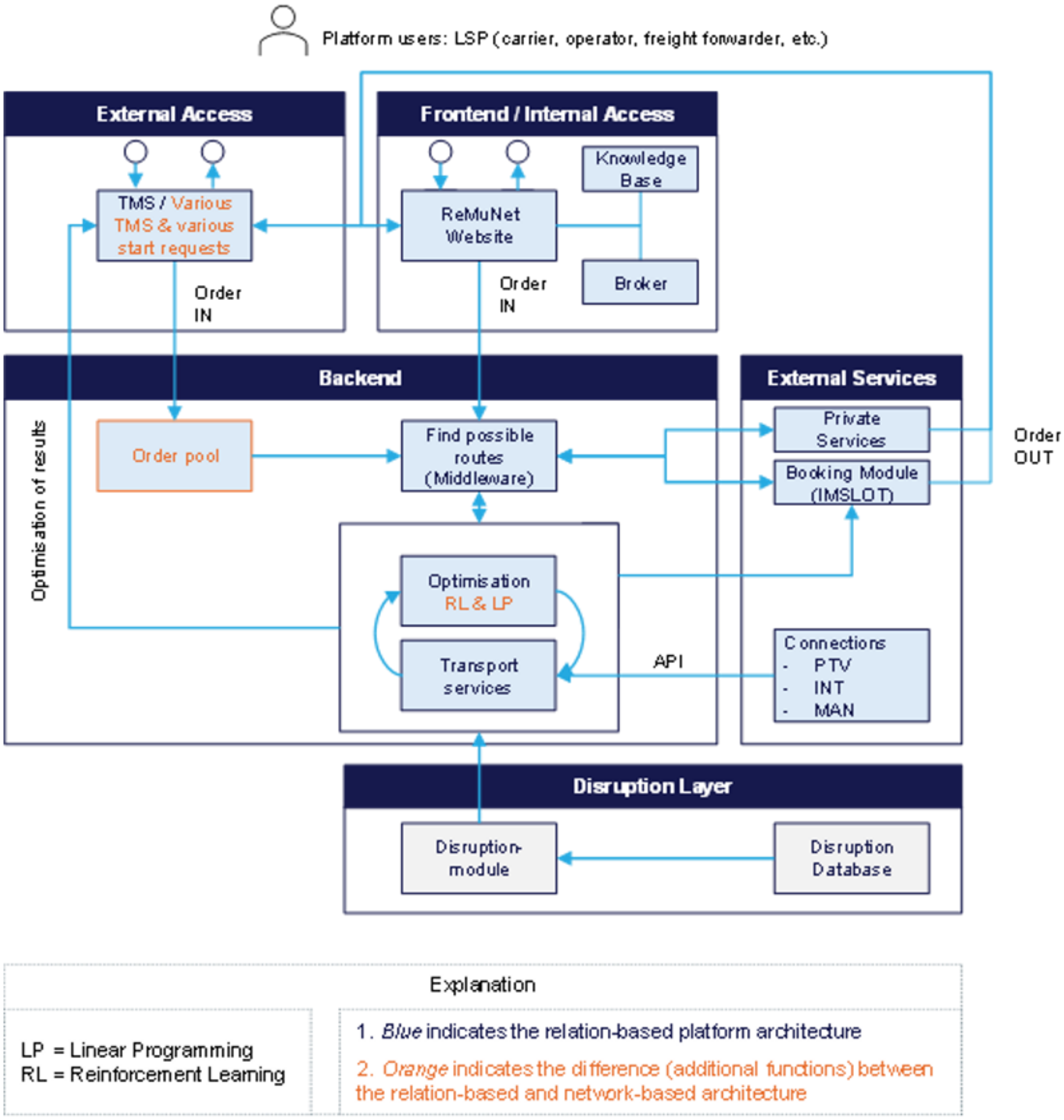


**Figure 1. The ReMuNet platform architecture.**

## 2.2 Disruption database

The disruption database forms the empirical foundation of the ReMuNet platform's risk intelligence layer. In its current proof-of-concept form, the database comprises 96 documented disruption events drawn from three independent sources: hydroclimatic records (droughts and floods), labour strike records, and transport accident records covering 80 locations across five geographic regions in Europe between 2018 and 2025. Events span four disruption categories (drought, flood, strike, accident) and four transport modes (waterway, rail, road, multimodal).

The database underpins a Disruption Events Module (DEM) that translates historical event records into structured risk assessments. For any given route location, disruption type, transport mode, and time of year, the module calculates the probability of a disruption occurring, the expected severity of its impact on network capacity, and the likely duration. These outputs are made accessible through an interactive dashboard and a set of structured lookup tables that can be queried programmatically.

A key design choice in the current architecture is regional aggregation: because 96 events distributed across 80 locations and 12 calendar months produces insufficient data density for reliable location-specific modelling, locations are grouped into five geographically and climatically coherent regions. Seasonal disruption patterns are calculated at the regional level, then applied to individual locations within each region. This approach balances statistical reliability against geographic precision and is documented fully in the accompanying technical report (Annex 1).

For the platform to scale beyond the proof-of-concept stage, the disruption database will need to develop in three directions. First, data volume must grow: a target of 200 or more events, ideally extending the time series to ten or more years, would allow more granular modelling at the location level and improve confidence in seasonal estimates. Second, the database must transition from a static, periodically refreshed asset to a dynamically updated one, incorporating real-time and near-real-time feeds such as hydrological monitoring services, labour relations news, and incident reporting systems. Third, the impact side of the model is currently based on expert-estimated parameters for capacity loss and disruption duration and should be grounded in empirical operational data as the platform accumulates real-world usage records.

Figure 2 shows the steps involved in developing the unified dataset and the DEM. These development directions are reflected in the scalability roadmap described in Section 3.

## ReMuNet — Disruption Events Module: Process Flow

From Historical Data to Route Risk Intelligence

### STEP 1 Data Preparation

**INPUT**

**3 Secondary Data Sources**

- 45 Hydroclimatic events (droughts, floods)
- 26 Strike events (labour disruptions)
- 25 Accident events (collisions, infrastructure failures)

96 total events | 2018–2025

Sources: national news agencies, port & rail authority reports, logistics trade press

**OUTPUT**

**Unified Dataset**

- 96 events, fully standardised
- 80 unique European freight locations
- 4 event types: drought, flood, strike, accident
- 4 transport modes: waterway, rail, road, multimodal

7 years history | 100% coverage

↓

### STEP 2 Statistical Analysis

**INPUT**

**Unified Dataset**

96 events with dates, locations, durations, and event types

Goal: extract how often disruptions occur, how long they last, and when in the year they are most likely

**OUTPUT**

**Risk Models**

- **Disruption rates:** 82 location × type × mode combinations (events/year)
- **Duration models:** mean 30.8 days (drought), 40.4 days (strike), 3.0 days (flood), 7.6 days (accident)
- **Seasonal patterns:** monthly multipliers per event type — August = 3.16× average drought risk

↓

### STEP 3 Regional Aggregation

**INPUT**

**Statistical Models**

Rates and seasonal patterns by location × month

⚠ **Problem**
96 events across 80 locations and 12 months = avg. 0.1 events per location-month. Most combinations have zero data — location-specific seasonal patterns are not statistically reliable.

**OUTPUT**

**Regional Patterns — 5 Regions**

- Central EU Waterways (Rhine, Elbe, Danube) — 25 locations
- Nordic Terminals (Finland, Sweden) — 30 locations
- Baltic Region (Baltic Sea ports) — 8 locations
- Western EU Corridors (Rotterdam, Antwerp) — 5 locations
- Eastern European Routes (Romania, Ukraine) — 12 locations

💡 **Key methodological decision**
Pooling Rhine + Elbe + Danube gives 15 drought events — enough for robust seasonal multipliers. Rhine alone has 2 events — not enough.

↓

### STEP 4 Impact Translation

**INPUT**

**Event Types & Transport Modes**

Probability of disruption is known — but what actually happens to route capacity when one occurs?

Each event type is mapped to an impact level with an associated capacity loss and duration adjustment.

**OUTPUT**

**Downtime Mapping**

- **Shutdown:** 100% capacity loss — strikes, floods (prob. 50–70%)
- **Reduced capacity:** 50–70% loss — droughts (prob. 70%)
- **Slowdown:** 20–30% loss — minor impacts (prob. 20%)
- **Duration multipliers:** accidents 0.3× (cleared fast), strikes 1.0×, slowdowns 1.2× (congestion outlasts event)

Event probability → Network impact

↓

### STEP 5 Interactive Risk Dashboard

**INPUT**

**All Lookup Tables**

- Regional seasonal patterns (5 regions)
- Location-to-region mapping (80 locations)
- Risk-to-downtime mapping (4 event types)
- Base disruption rates (82 combinations)

User inputs: location, event type, transport mode, month, journey duration

**OUTPUT**

**Risk Assessment**

- Disruption probability for the planned journey period
- Annual disruption probability (seasonal context)
- Risk level: Low / Moderate / High / Critical
- Expected capacity available during disruption
- Expected disruption duration and recommended buffer

✓ **Result**
Standalone offline HTML tool — no installation required. Planners can compare routes, modes, and months to support proactive risk management.

**Figure 2. Disruption Events Module development steps.**

# 3. Proof of Concept to Scalability

During the ReMuNet project, a functional Proof of Concept (PoC) of the ReMuNet platform was developed. The PoC includes routing, timetables, scenario comparison, a graphical user interface, and a comparison of key route parameters: $CO_2$ emissions, travel time and costs. These parameters are derived from predefined variables, which can be adjusted if needed.

The PoC was developed for the main transport corridors and use cases defined by the project team under WP5 (Piloting event-based synchromodal relay transport in the North Sea–Baltic and Rhine–Danube corridors). The PoC was built from scratch and integrated with the ReMuNet project's subsystems: PTV routing & timetables and the Mansion relay transport solution. Additional functionalities and third-party systems could also be integrated in the future.

The graphical user interface (see Figure 3) provides basic functionality that allows users to modify routes and scenarios. Once a route and scenario have been selected, the user can compare key parameters of alternative routes (e.g., travel time, $CO_2$ emissions, and costs). In addition to the ReMuNet platform, a driver application was used to demonstrate how a driver can report disruptive events and receive updated driving instructions to bypass their impacts. The driver application was provided by PTV Group, and its name is AXYLOG (see Figures 4, 5 and annex 2).

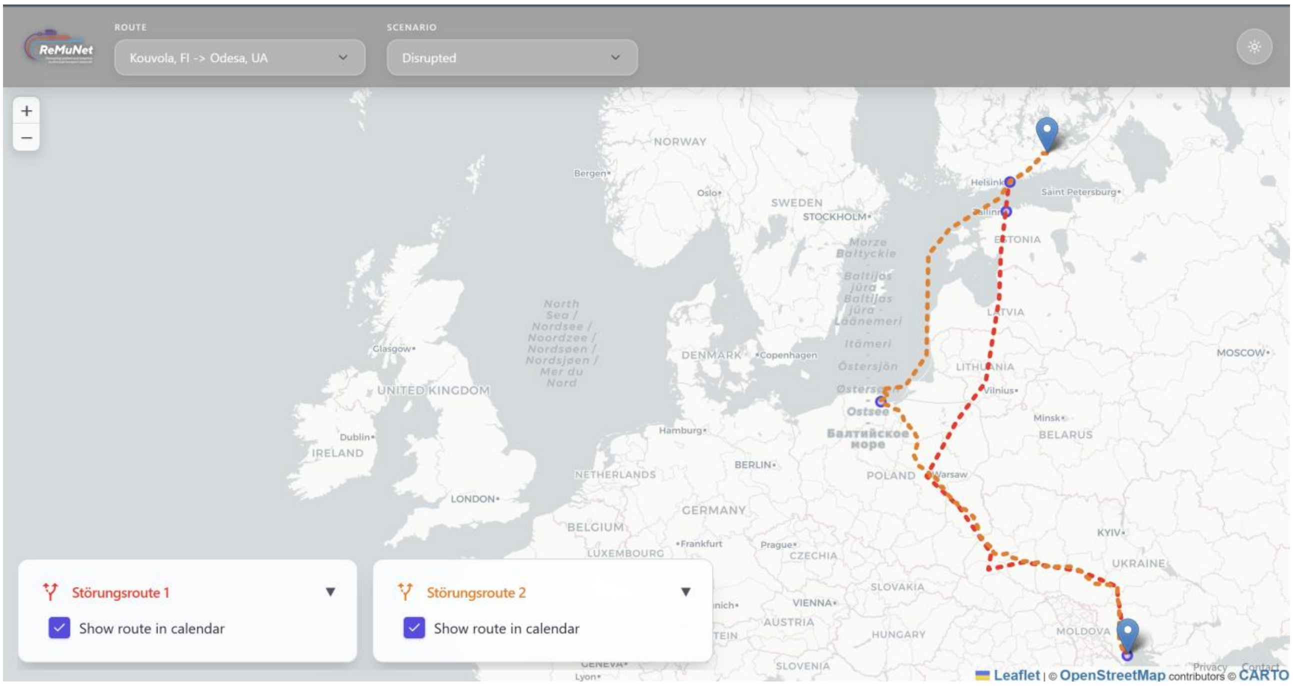


**Figure 3. The ReMuNet platform GUI**

Although the AXYLOG application was used to demonstrate the use case and the ReMuNet concept, it was not technically integrated into the ReMuNet platform. Within the ReMuNet project, AXYLOG was used solely for demonstration purposes, and it could be replaced by any similar application (e.g., a transport management system, logistics planning system, driver application, or equivalent).

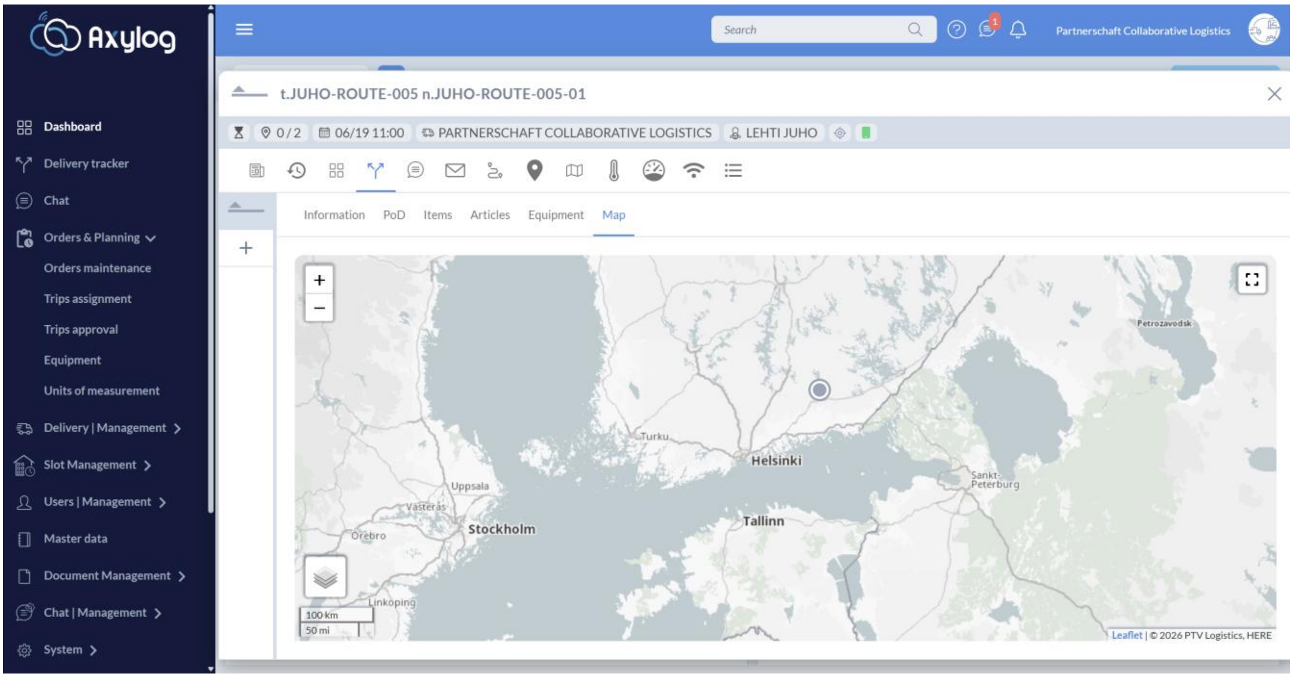


Figure 4. AXYLOG desktop GUI

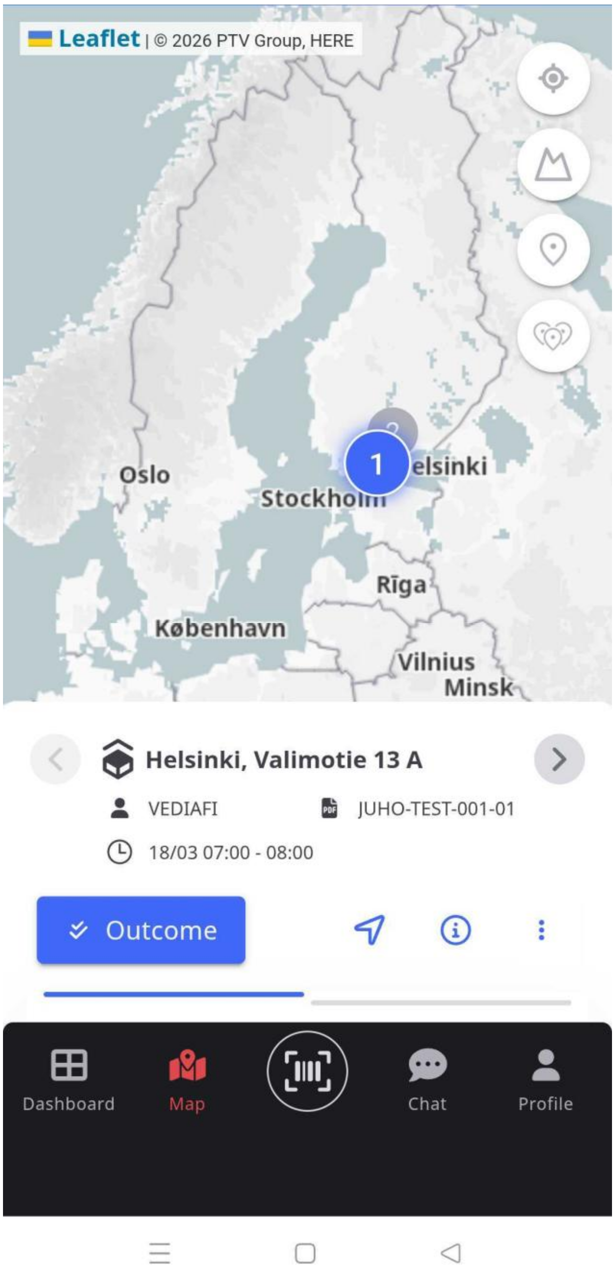


Figure 5. AXYLOG mobile APP GUI

During the ReMuNet project, the platform reached the PoC stage and fulfilled the technical and functional requirements set for it. The platform supported routing and itinerary comparison for scenarios involving disruptive events. For different route options, the platform provided KPI comparisons, which were clearly visualized through its web-based graphical user interface.

However, the transition from PoC to actual service or product needs still a lot of further development. Topics like system hosting, governance, business model and support needs to be tackled if the ReMuNet platform wants to be scaled up to the service level. Deliverable 3.4 introduced the Sustainable ReMuNet Operator Model (Figure 6), which encompasses all key components required for implementation. However, these components must be implemented, tested and validated before deployment in a production environment (Dicks et al., 2025). To facilitate this transition, a Minimum Viable Product (MVP) approach is recommended.

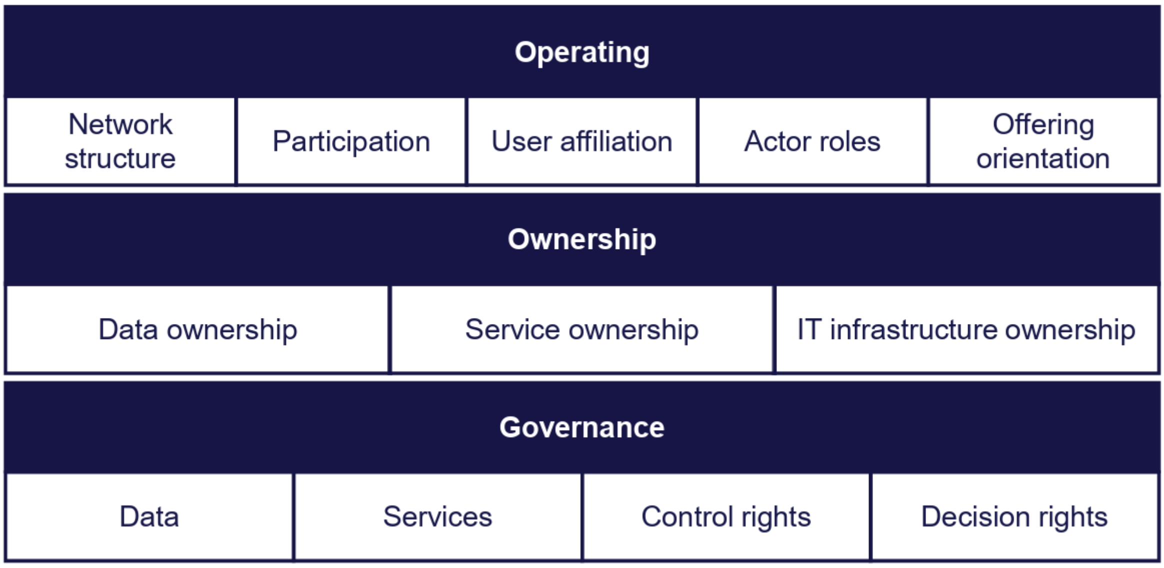


**Figure 6. Sustainable ReMuNet Operator Model introduced in D3.4 (Dicks et al., 2025).**

The aim of the MVP approach is to develop an initial service or product that meets the core requirements of its users. From the technical perspective of the ReMuNet platform, this would mean scaling the proof-of-concept setup to meet operational requirements. In practice, the platform would need to be hosted by a designated operating entity, all subsystems would need to be integrated at the operational level, and the service area and coverage would need to be agreed upon with the participating service providers. From a technical standpoint, such a system could already provide a viable solution for end users.

However, technical aspects represent only one dimension of scalability. The business and governance models must also be integrated into the MVP concept. During a limited period of time, the MVP could be operated free of charge, with ICT service providers and data suppliers covering their own costs. Nevertheless, to ensure long-term sustainability and a viable business model, a cost-recovery mechanism must be incorporated from the outset.

While the MVP may initially be offered free of charge, an appropriate governance model must be established before the service enters operational use. Although this governance model can be relatively simple in the early stages, it must provide a clear framework for decision-making and ensure data and information security between the platform and its users as the service scales and matures.

The most significant challenges associated with scaling are related to achieving sufficient volume, expanding regional coverage, demonstrating business value, and ensuring user acceptance. Technical challenges are not considered to be a major barrier to scalability. On the contrary, the findings of the PoC indicate that the technical foundation is well suited to support large-scale deployment. Instead, existing business models, operational processes, and entrenched practices are likely to constitute the primary obstacles to the successful adoption and scaling of the ReMuNet platform.

# 4. Sustainable Operation and Governance Strategy

Since the ReMuNet platform is intended to operate as a service, it requires both business and governance models that ensure its technical and financial sustainability. The governance model should be based on collaboration between the public and private sectors, with overall coordination led by the public sector. Such an approach is recommended because it can enhance trust among stakeholders while ensuring neutrality and limiting the influence of purely commercial interests.

The public-private-partnership would also support the initiative that in the long-term vision the ReMuNet platform becomes part of Europe's digital transport infrastructure, i.e. the platform covers all main transport corridors and disruptive events affecting logistics in EU region. To meet such an ambitious goal the ReMuNet platform needs legal form and entity, who can represent the platform, which needs to consider in the Governance model. Given that the consortium-based operating model was considered the most suitable option in Deliverable 3.4, establishing the operator as an association may represent an appropriate legal solution. However, the formal form of operation needs to be further explored in collaboration with legal experts and key stakeholders, so that it enables neutral and international collaboration, but does not limit the business interest of service providers.

From a governance perspective, sustainability can be achieved by integrating sustainability criteria directly into decision-making processes. This means that sustainability considerations (i.e., low-emission and environmentally friendly solutions) should always be taken into account when onboarding new services and service providers, as well as when evaluating alternative routing solutions and transport modes. Such a strategic commitment is essential if the ReMuNet platform is expected to promote and accelerate the adoption of sustainable transport solutions. N.B. More profound analysis about sustainability and environmental aspects is presented in Deliverable 5.3 (Schmidt, K. 2026). Consequently, environmental and sustainability requirements should be incorporated into the ReMuNet platform's service agreements. From a scalability perspective, implementing such requirements is unlikely to pose significant challenges, although it may influence the market attractiveness and commercial value of the service.

From a financial perspective, sustainability can be interpreted in two ways: (1) the business model is financially sustainable and provides a solid commercial foundation for operations, or (2) environmental sustainability objectives are economically embedded within the business model. For the ReMuNet platform, the latter should be considered a fundamental principle, meaning that environmental sustainability requirements are incorporated into service agreements, as described above.

From an economic perspective, the success of the ReMuNet platform depends heavily on its end-users, who are typically reluctant to pay significant fees for such services. Therefore, the platform may require public funding or other forms of seed financing to reach a critical mass of end-users and connected service providers that offer their services through the platform. As is common with Software-as-a-Service (SaaS) and platform-based business models, a growing user base tends to attract additional service providers. To maximize value creation and business opportunities for both end-users and service providers, geographical coverage and a clear expansion strategy should be carefully considered. The offered service should offer value for its stakeholders.

An important component of the governance model is the business model used to onboard service providers to the platform. Typically, an integration fee is charged to cover the costs associated with introducing new services. At the same time, such a fee may create a barrier to entry, affecting scalability both positively and negatively. On the one hand, it may discourage innovative service providers with limited financial resources from joining the platform before securing direct customers. On the other hand, it may help ensure that only financially stable and reliable service providers offer their services through the platform.

In addition to integration fees, a revenue model is required not only for the ReMuNet platform itself, but also for the integrated services provided by third-party service providers. As the ReMuNet platform is envisaged as a consortium-based solution, with the core platform operated by a designated operator and additional services delivered by service providers, a volume-based cost and revenue-sharing model is recommended. Under this approach, users pay only for the services they use, while the pricing and revenue-sharing arrangements for each integrated service are defined in the corresponding service agreements. Financing for the ReMuNet platform's core functionalities and hosting infrastructure could be based on a combination of public and private funding sources.

From a technical perspective, sustainability can be embedded into all platform solutions. For example, when evaluating alternative routes, the system can highlight sustainable options and encourage users to select them. Similarly, when comparing transport modes, sustainable alternatives should be prioritized. Therefore, sustainable operations and governance are primarily governance issues rather than technical ones.

In addition, sustainability requirements could be extended to include Green ICT principles. This would mean establishing specific sustainability requirements for all service providers and their ICT services, ensuring that environmental considerations are integrated throughout the entire service ecosystem.

## 4.1 Methodological approach

The roadmaps presented in this deliverable were developed to provide a structured view of how the ReMuNet concept could evolve beyond the project lifetime. They build upon the knowledge generated during the project, the experience of the consortium partners, and the findings obtained through platform development, pilot activities, and related research tasks.

The roadmap development followed an iterative approach, where findings from different work packages were continuously reflected against the overall objectives of ReMuNet. Rather than focusing solely on the current proof-of-concept, the process considered how the demonstrated capabilities could be further developed and applied within a broader European transport context.

Three methodological pillars were used to guide the roadmap development. The first pillar was co-creation, drawing upon the combined expertise of the consortium, which represents stakeholders from research, technology development, logistics, transport operations, and public-sector environments. This provided both public and private sector perspectives on future development needs and adoption pathways.

The second pillar was scenario-based planning. Experiences gained through platform development and pilot activities were used to explore possible future scaling options for the ReMuNet concept. Particular attention was given to technical maturity, interoperability, operational usability, and the conditions required for wider deployment across multimodal transport networks.

The third pillar was phased implementation. The proposed actions are organised into short-, medium-, and long-term horizons, recognising that the transition from a research project to operational deployment requires gradual development, stakeholder commitment, and further refinement of the demonstrated solutions.

Together, these elements provide a practical framework for identifying future development priorities and supporting the continued evolution of ReMuNet beyond the project.

## 4.2 Public Sector Roadmap

The ReMuNet platform must ensure neutrality and build trust among its end-users and engaged service providers. Therefore, it is natural that the public sector plays a significant role in the platform's governance and operational model. Furthermore, as the ReMuNet platform is intended to support transport and logistics activities across the European Union, collaboration must extend beyond national borders. Consequently, some form of international cooperation is required, implying that the platform should have an appropriate international legal status.

The ReMuNet platform is designed to support sustainable EU-wide transport corridors and supply chains. Therefore, it should be aligned with EU's CountEmissionsEU framework (European Parliament 2026), digital transport policies and initiatives, such as the TEN-T network approach and the Digital Transport and Logistics Forum (DTLF) (EU COM, 2026A). The platform must also support multimodal logistics data sharing semantics - e.g. eFTI (EU COM 2026B) - and EU data-sharing and data-space initiatives to ensure a federated, trusted, and secure environment for data exchange.

These requirements are complex and will require considerable time and effort to agree upon and implement. Table 1 below presents a proposed roadmap for public-sector involvement in the governance, development, and operation of the ReMuNet platform.

Table 1. ReMuNet platform scalability public sector roadmap

| Time frame | Focus area | Definition | Expected outcome |
|---|---|---|---|
| **Phase 1 2027-2028** | Policy alignment and recognition | During the first year of scalability, the ReMuNet initiative must be aligned with relevant policy and regulatory requirements from the perspective of future service deployment. As part of this alignment process, a clear understanding of both the direct | Clear overview, which regulative and policy framework guides and limits the ReMuNet platform |

| | | | |
|---|---|---|---|
| | | and indirect policy and regulatory frameworks needs to be established and mapped. The study should cover all key aspects of the ReMuNet platform, including transport management and corridors, data sharing, GDPR compliance, cybersecurity, international business operations, and public–private collaboration. See Chapter 5 as an example. | scalability and service offering. |
| **Phase 2 2028-2029** | Governance model definition | Based on the findings of this project, policy alignment outcomes, and benchmarking examples, a governance model must be developed and agreed upon with the first committed stakeholders. | Understandable and sustainable governance model for the ReMuNet platform. |
| **Phase 3 2029-2030** | Corridor expansion and interoperability | According to the findings obtained during the project, Central Europe appears to be the most suitable region for the initial service launch. However, regional expansion must be carefully planned and implemented in an efficient and sustainable manner. The TEN-T network is considered the most suitable core network for scalability, but this assumption should be validated during the first two years of the scaling phase. | Agreed plan how the regional extension will be done and in which schedule new regions will be integrated. |
| **Phase 4 2030+** | Institutionalization and integration into EU data spaces | As the ReMuNet platform operates directly at the data layer and is built on top of digital services, investing in data sharing best practices and data security is essential. Therefore, close collaboration with EU data space initiatives is considered necessary and could provide significant benefits for international scalability and future service | Data governance and management plan how the ReMuNet platform will be integrated to wider data sharing environments and semantic networks, i.e |

| | | | |
|---|---|---|---|
| | | expansion. A special attention needs to be given also to disruptive data space and how its coverage, accuracy and usability could be enriched EU wide. | how the federation of services and data can be ensured in EU market area. |

The public-sector scalability roadmap presented above outlines a core scalability plan divided into four phases. Table 1 describes the main activities associated with each phase; however, these activities are not intended to be exhaustive. In parallel with these phases, the ReMuNet core team and pioneers should actively market the service and engage potential stakeholders to join the network. Special attention should be given to identifying a lead organization and/or a potential platform host, as their role and contribution will be essential for successful service deployment.

Although the ReMuNet platform should be developed through public–private collaboration, the role of the public sector in promoting and accelerating the service is considered vital. Public sector should ensure the foundation for the platform and to enable EU wide collaboration and transport and disruptive data availability. Therefore, the public-sector roadmap is presented first, as it is expected to drive and enable the deployment of the service. Without a strong commitment from public authorities and public-sector stakeholders, the ReMuNet initiative is unlikely to achieve its objectives. At a minimum, it would be significantly more challenging for the platform to establish a meaningful role within the EU-wide transport management ecosystem.

## 4.3 Private Sector Roadmap

In the previous chapter, the public-sector roadmap was presented. As stated above, the role of the public sector is considered vital for the scalability and deployment of the ReMuNet platform. However, the private sector is expected to be the primary user group of the service. At the same time, private-sector actors will play a key role in developing and providing value-added services based on the EU-wide disruptive data layer and core transport network information enabled by the platform.

Table 2 below presents the private-sector roadmap for ReMuNet. It outlines the main activities and priorities required to support service adoption, business development, and the creation of innovative value-added services that leverage the capabilities of the ReMuNet platform.

**Table 2. ReMuNet platform scalability private sector roadmap**

| Time frame | Focus area | Definition | Expected outcome |
|---|---|---|---|
| **Phase 1 2027-2028** | Market analysis and the | After the ReMuNet project, a comprehensive market analysis should be conducted to validate market interest and potential | Further developed business plan with |

| | | | |
|---|---|---|---|
| | business model definition | customer acceptance. In parallel, the stakeholders promoting the ReMuNet platform should further develop the business model, focusing on how to ensure its attractiveness and long-term sustainability, as well as identifying potential market limitations for such a service. | sophisticated analysis about the market value of the ReMuNet platform. |
| **Phase 2 2028-2029** | System integration and interoperability | Following the market analysis and the validation of the business model, the platform operator (a public sector representative) should begin integrating the subsystems and conducting technical conformance testing between them. The objective should be to enable a sufficient set of core functionalities and value-added services to meet the requirements of the Minimum Viable Product (MVP). | First version of the ReMuNet MVP, which can be launched as service. Testing must ensure interoperability and system functionality. In addition, test actions must be documented, and best practices should be shared for potential service providers. |
| **Phase 3 2029-2030** | Market uptake and scaling | Once the MVP has been launched and the initial operational phase has stabilized, the focus should shift towards market expansion. This will require broader geographical coverage and an expanded service offering. During the scaling phase, the number of end-users should increase significantly. | Market expansion to main EU TEN-T corridors and extended service offering. 100% + times increase in end-user volumes. |
| **Phase 4 2030+** | Innovation and continuous growth | After a few years of market operation, a state-of-the-art and innovation radar assessment should be carried out to ensure that emerging and cutting-edge | Innovation and R&D vision how to further develop the platform and its offering. In meanwhile the |

| | | | |
|---|---|---|---|
| | | solutions can be effectively leveraged in the future. | end-user volumes should grow in line with the corridor expansion. |

The private sector encompasses several stakeholder groups within the ReMuNet platform ecosystem. In general, private companies can participate either as users of the platform or as providers of data and services. In some cases, an organization may occupy both roles within the value chain, acting simultaneously as a user and a service provider.

This means that private companies, such as ICT service providers and logistics operators, can contribute data and/or services that create value for other platform participants. At the same time, these organizations may also utilize the platform's services and data resources to support their own operations. In particular, logistics companies are expected to constitute one of the platform's main end-user groups, benefiting from improved access to transport network information, enhanced visibility, and value-added digital services.

The dual role of many private-sector actors highlights the collaborative nature of the ReMuNet ecosystem, where participants can both contribute to and benefit from the platform's shared data and service environment.

In addition to the traditional roles of service providers and end users, the private sector is also expected to act as a key driver of innovation and commercialization. Private companies should develop new functionalities, applications, and business solutions that support the scalability and long-term deployment of the ReMuNet platform.

Innovation and commercialization activities should be carried out in parallel with the four scalability phases described above. However, these activities are expected to become increasingly important during Phases 3 and 4, when the core platform is operational and capable of supporting a broader range of value-added services and business opportunities. Within this time frame sustainable business volumes should be available to support innovations.

As the platform ecosystem matures, private-sector actors should take the lead in identifying market opportunities, developing innovative service offerings, and creating sustainable business models that leverage the shared data environment and transport network information provided through ReMuNet. This will be essential for achieving widespread adoption, generating business value, and ensuring the long-term success of the platform.

## 4.4 Stakeholder engagement

The ReMuNet platform is built on public–private collaboration and acts as an integrator of services and data. Consequently, the platform requires active participation from a broad range of stakeholders. Stakeholder engagement must be carefully planned, coordinated, and executed in an efficient and professional manner. Initially, this responsibility should be assigned to a dedicated individual. As the platform scales and the stakeholder network expands, a dedicated team should be established to manage and drive these activities.

Stakeholder engagement should be planned separately for each stakeholder group. In practice, dedicated onboarding and engagement plans should be developed for public sector organizations, ICT service providers, logistics companies, and end-users. Each group has distinct needs, expectations, and objectives, and therefore requires tailored engagement approaches and ongoing relationship management. For example, stakeholder engagement with ICT service providers is often driven by business and technical requirements, whereas engagement with public sector organizations may require broader collaboration, strategic alignment, and joint vision-building activities.

Stakeholder engagement activities should also be aligned with service scalability and regional coverage, particularly for logistics companies, public sector organizations, and end users, as their needs and impact are often region-specific. For many ICT service providers, geographical location is less restrictive due to the digital nature of their services. Nevertheless, location-specific limitations may still exist from a data perspective. For example, a transport network model may cover only a German-speaking region, or data may be collected exclusively from transport management systems operating in the Nordic countries.

Stakeholder engagement should take place through both direct interaction between individuals and organizations and the use of digital onboarding tools. Digital tools may include self-assessment mechanisms that allow stakeholders to evaluate their compliance with platform requirements and service offerings. Following the self-assessment phase, digital solutions can also facilitate stakeholder agreements, business contracts, and other formal onboarding processes.

In particular, the use of digital tools is strongly recommended for system and compliance testing, which represents a critical stage in the final phases of stakeholder onboarding and engagement. As the ReMuNet platform is a digital ecosystem whose value proposition depends heavily on the capabilities of its core platform and associated subsystems, automated and digitalized onboarding processes are considered an effective and desirable means of accelerating ICT service provider engagement. To support this, the ReMuNet platform should provide a comprehensive developer portal offering clear guidance, high-quality documentation, technical support, testing environments, and integration tools for ICT service providers.

# 5. Political and Legislative Implications

Any serious attempt to scale ReMuNet will run into regulatory and political questions sooner or later. This section looks at the most relevant ones, particularly around EU legislation that directly affects how the platform handles data and interoperability. It also considers where ReMuNet could contribute to ongoing policy discussions, rather than simply adapting to them.

## 5.1 Alignment with EU Legal Frameworks

The scaling of ReMuNet takes place within an evolving EU legislative landscape that directly shapes the conditions for digital data exchange, platform governance, and transport digitalisation. Several key regulatory instruments are relevant to the deployment and long-term operation of the platform.

The Data Act (Regulation (EU) 2023/2854) establishes horizontal rules on access to and use of data generated by connected products and related services. For ReMuNet, this has direct consequences: data generated during transport operations, including disruption events, cargo status, and infrastructure availability, may fall under obligations to share data with other users or public authorities. The platform's governance model must therefore clearly define who generates data, under what conditions it can be accessed or reused, and how commercial interests are protected while enabling interoperability (European Union, 2023).

The AI Act (Regulation (EU) 2024/1689) introduces a risk-based framework for artificial intelligence systems. The algorithmic components of ReMuNet, including disruption detection, impact assessment, and route optimisation, should be assessed against the AI Act's risk categories. Given that routing recommendations may affect logistics decisions with cross-border implications, transparency, explainability, and human oversight requirements are likely to apply. Providers and deployers must document system capabilities, ensure auditability, and define responsibilities in the supply chain (European Union, 2024).

The ITS Directive (Directive 2010/40/EU and its ongoing revision) establishes a framework for the coordinated deployment of intelligent transport systems in road transport. The revision currently under discussion aims to extend scope to multimodal transport and real-time traffic and travel information. ReMuNet aligns directly with the directive's objectives by providing dynamic multimodal routing support. Active engagement in the ITS Directive revision process would allow ReMuNet stakeholders to influence technical specifications and priority action areas in a way that reflects the platform's operational model (European Parliament and Council, 2010).

The eFTI Regulation (Regulation (EU) 2020/1056) requires that freight transport information be made available to authorities in electronic form, using certified eFTI platforms. ReMuNet's digital handover protocol and data exchange architecture is closely aligned with this regulation's technical requirements. Ensuring compliance with eFTI certification processes and potentially seeking recognition as an eFTI-compatible platform, would strengthen regulatory positioning and public-sector trust (European Union, 2020).

The Cyber Resilience Act (Regulation (EU) 2024/2847) introduces mandatory cybersecurity requirements for products and software with digital elements placed on the EU market. As a platform handling sensitive logistics and infrastructure data, ReMuNet must demonstrate compliance with security-by-design principles, vulnerability management, and incident reporting obligations. This has implications for platform architecture, update processes, and the responsibilities of the entity operating the platform (European Union, 2024).

## 5.2 Legal Priorities

Data ownership, access rights, and liability are foundational to stakeholder participation. Logistics actors will only contribute data to the platform if they are confident that their commercially sensitive information, such as route choices, cargo volumes, or disruption exposure, will not be accessible to competitors. The platform's data governance framework must clearly define ownership of contributed data, distinguish between operational data and derived insights, and set out the legal basis for each category of data use. This may involve contractual arrangements between participants, privacy-enhancing technologies, or differentiated access tiers.

Liability is a closely related concern. When the platform provides routing recommendations that are acted upon by operators and those recommendations result in delays, damage, or costs, the question of who bears responsibility must be resolved in advance. The liability model should address the platform operator's role in terms of information provision versus decision-making, the obligations of data contributors for data quality, and the extent to which algorithmic outputs can be contested. As EU product liability rules are updated under the Product Liability Directive revision, these questions will become increasingly concrete.

Standardisation and interoperability compliance is equally critical. The scalability of ReMuNet depends on the ability to connect diverse national systems, TMS providers, and infrastructure operators. This requires alignment with recognised data standards such as UN/EDIFACT, GS1, and NeTEx/SIRI, as well as application-layer protocols. Engaging with standardisation bodies including CEN, ETSI, and the DTLF working groups will be essential to ensure that ReMuNet's interfaces are technically compatible and legally recognised across Member States.

## 5.3 Contribution to policy

Providing data for evidence-based regulation. ReMuNet generates operational data from pilot corridors covering disruption frequency, modal substitution patterns, capacity utilisation, and recovery times. This constitutes a structured empirical basis for regulatory and infrastructure investment decisions. Aggregated disruption data can support the development of EU-level resilience metrics and reporting frameworks, for instance in the context of the TEN-T Regulation's resilience provisions. Data on modal shift triggered by disruptions can inform the Commission's monitoring of the modal rebalancing targets set out in the European Green Deal and Sustainable and Smart Mobility Strategy. Operational experience from the pilot, including challenges related to cross-border data exchange and governance, provides concrete input into the ongoing development of the European Mobility Data Space (EMDS) and the Digital Transport and Logistics Forum (DTLF).

Serving as a model for trusted digital data exchange in logistics. At a time when policy discussions around federated data spaces, B2G data sharing, and public-private platform governance remain largely conceptual, ReMuNet offers a tested architecture. This makes it a credible reference point for policymakers designing future frameworks for logistics data ecosystems. The project demonstrates that cross-border, multi-stakeholder data exchange in transport is technically feasible and operationally valuable, if governance, trust, and incentive structures are carefully designed.

## 5.4 Recommendations

To translate this policy relevance into durable influence, it is recommended that the ReMuNet consortium and any successor governance structure establish a structured and ongoing dialogue with the European Commission and relevant Member States on digital corridor policy.

At the EU level, ReMuNet stakeholders should engage with the DTLF thematic working groups, contribute to the consultation processes for the ITS Directive revision and the EMDS governance framework, and seek visibility within Horizon Europe and CEF-funded transport digitalisation programmes. At the national level, corridor-specific engagement with transport ministries, rail and waterway infrastructure managers, and digital innovation agencies would support the embedding of ReMuNet principles into national action plans and deployment strategies.

The goal of this engagement is not merely advocacy but institutional positioning. For ReMuNet to transition from a research project to a sustainable infrastructure, it must be recognised by public authorities as a reliable partner in delivering policy objectives, particularly around transport resilience, decarbonisation, and digitalisation. Early and structured engagement is the most effective way to build that recognition.

# 6. Conclusions & Legislative implications

ReMuNet has developed a coherent and technically grounded approach to disruption management in multimodal freight transport. The project has produced a platform architecture, a disruption classification methodology, a digital handover protocol, and a set of routing and orchestration algorithms that together address a genuine and well-documented gap in European logistics. The pilot work, while based on synthetic scenarios rather than live operational data, has validated the core concepts and produced structured outputs that demonstrate what a deployed system of this kind could deliver.

The transition to wider deployment depends on whether the conditions for sustainable operation can be put in place. The political and legislative analysis presented in this deliverable shows that the EU regulatory environment is broadly supportive of the ReMuNet approach, but that active engagement is required to turn alignment into recognition.

From a legislative perspective, the most important near-term task is to ensure that any future deployment of the platform is compatible with the Data Act, the eFTI Regulation, and the Cyber Resilience Act. These are not abstract compliance exercises; they are preconditions for the platform to operate legally and to attract public-sector participation. At the same time, the AI Act and evolving liability frameworks require that algorithmic components be documented and that responsibilities between platform operators, data contributors, and users are clearly defined before the system handles real operational data.

Looking ahead, the most significant opportunity lies in ReMuNet's potential to contribute to the design of emerging European digital transport infrastructure. The European Mobility Data Space, the ongoing revision of the ITS Directive, and the Digital Transport and Logistics Forum process all create openings for the project's outputs to inform policy and standards development. Realising this potential requires the consortium to move beyond project dissemination and into sustained policy engagement, with a clear and honest message: ReMuNet has designed and tested a governance and technical architecture for trusted, interoperable logistics data exchange, and the lessons from that process are directly relevant to the regulatory frameworks now being developed.

An additional policy measure that could enhance the resilience and situational awareness of multimodal and international supply chains would be to require EU Member States to update and maintain a shared disruptive-event database, as described in Chapter 2.2 and Annex 1.

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# 7. Appendix

## Annex 1 - Disruptions event module

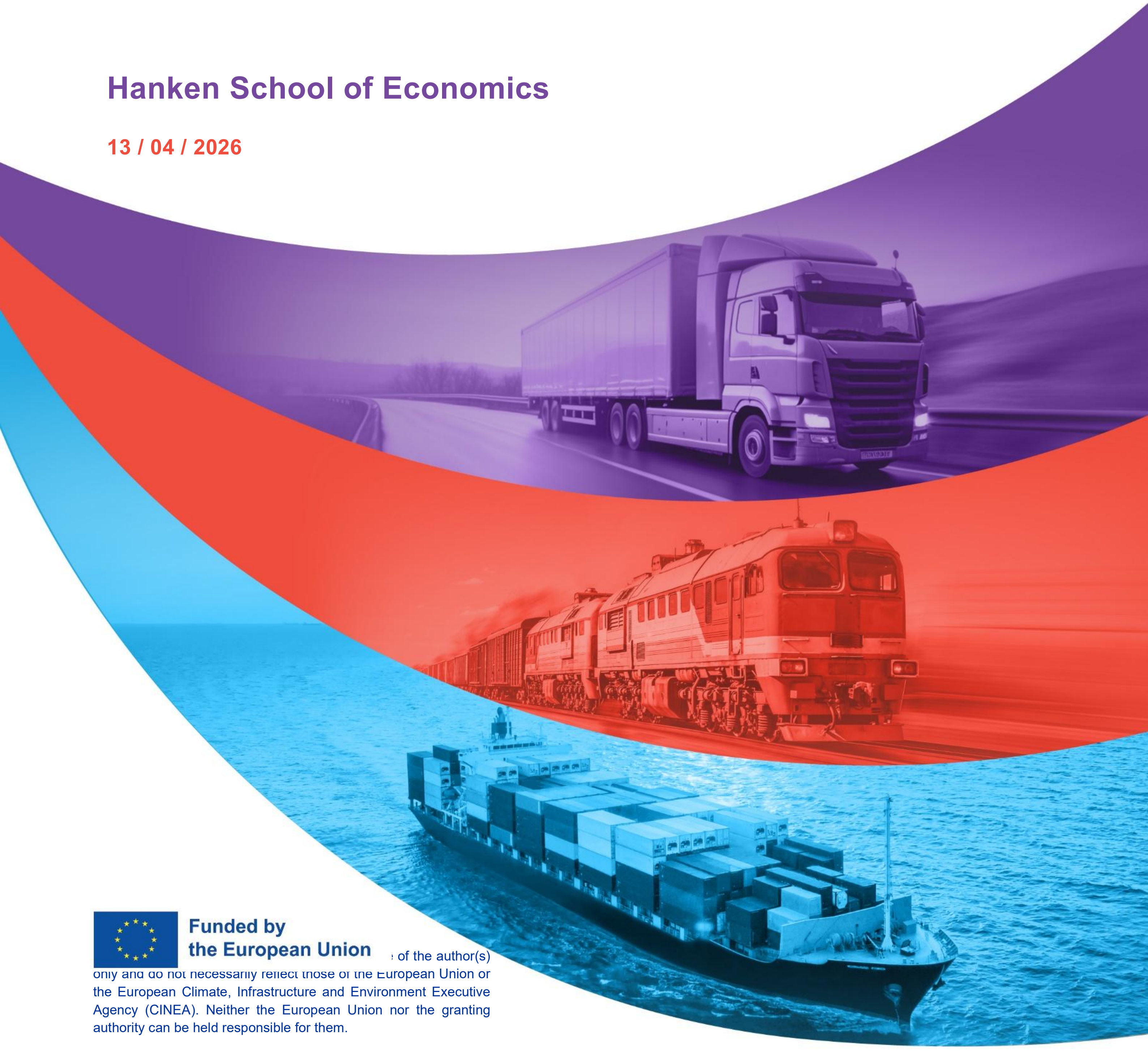
Note: In the course of the project it became clear that the developed disruption event module (DEM) has a high value for the ReMuNet vision and should be documented as well. As no specific deliverable was planned originally in the proposal and the DEM is a proof-of-concept risk intelligence system built for the ReMuNet transport platform, it is listed here as the Annex of this Deliverable as its highly related in content to this Deliverable 5.4.

## Annex 1 of D5.4

# Disruptions event module

Hanken School of Economics

13 / 04 / 2026



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## Executive Summary

The Disruption Events Module (DEM) is a proof-of-concept risk intelligence system built for the ReMuNet transport platform. Its purpose is to convert historical records of transport disruptions into structured, quantitative risk assessments that can support route planning, scheduling, and contingency decisions.

The system is built around 96 documented disruption events spanning seven years (2018–2025), covering 80 locations across five geographic regions in Europe. These events were collected from three independent data sources covering hydroclimatic events (droughts and floods), labour strikes, and transport accidents. The raw data were standardised, analysed for statistical patterns, and assembled into a set of lookup tables that power an interactive risk calculator.

The central output is a standalone interactive dashboard. A planner can specify a route location, disruption type, transport mode, month of travel, and journey duration, and receive in return: the probability that a disruption will occur during that period, an estimate of how severe the capacity impact would be, and a recommendation on how much buffer time to build in.

The key methodological contribution of this work is regional aggregation: rather than attempting to build risk models for each of 80 individual locations (which would be statistically unreliable given the data volume), locations were grouped into five geographically and climatically coherent regions. Seasonal patterns are calculated at the regional level, providing robust estimates that can be applied to any location within a region.

This document explains the motivation, data, methods, formulae, assumptions, and limitations of the system in full, for a mixed audience of logistics professionals, platform developers, and academic reviewers.

# Background and motivation

## Why disruption risk matters in transport planning

Transport networks in Europe are exposed to a range of recurring disruption events - droughts that lower river levels and restrict barge capacity, winter floods that make waterways impassable, industrial strikes that halt port and rail operations, and accidents that block infrastructure. These events are not random in the everyday sense: they follow seasonal patterns, tend to occur at specific locations and on specific modes, and have characteristic durations. A Rhine waterway drought is much more likely in August than in January. A Nordic port strike is more likely in February. A flood on the Danube is more likely in spring.

Despite this, transport planning has historically treated disruptions as unpredictable surprises. Routes are planned for normal conditions, and disruptions trigger reactive responses - detours, re-routing, delays - rather than proactive buffers.

The DEM changes this. By learning from historical events, the system allows planners to ask in advance: given the route I am planning, the time of year, and the mode I intend to use, what is the realistic probability of a disruption, and what should I expect if one occurs?

## ReMuNet context and report structure

ReMuNet is a multimodal transport route planning platform. The DEM is designed as an analytical module that can either be used independently (via the interactive dashboard) or eventually integrated into the ReMuNet platform as a live risk layer. At the proof-of-concept stage described in this report, the system runs entirely offline from static data files.

This report documents:

- Where the data came from and how it was cleaned and standardised
- What statistical patterns were found in the data
- Why and how locations were grouped into regions
- Every formula and algorithm used in the risk calculations, with plain-language explanations and worked examples
- The assumptions built into the system and where those assumptions could be challenged or refined
- The limitations of the current approach and what would be needed to improve it
- Practical use cases for the system in a logistics context

# Data sources and preparation

## Source data overview

The dataset was assembled from three independent sources, each covering a different category of disruption:

**Hydroclimatic events** (45 events): Records of drought and flood occurrences affecting European waterway transport. Droughts lower river water levels, restricting barge draft and reducing cargo capacity. Floods make waterways temporarily impassable. These events are primarily driven by seasonal precipitation and temperature patterns.

**Strike events** (26 events): Records of labour strikes affecting ports, rail terminals, and road freight operations. Strikes follow their own seasonality, often clustering around collective bargaining periods or political flashpoints.

**Accident events** (25 events): Records of transport accidents — vessel collisions, infrastructure failures, rail incidents — that caused significant disruption. These are less seasonal than the other categories but show some patterns (e.g., accidents are more common in poor-visibility conditions in autumn and winter).

Together these sources contributed 96 events after deduplication, covering 80 unique locations between August 2018 and June 2025. A critical first step was that these three sources used different formats, different terminology, and different fields. Standardisation was required before any analysis could be done.

# Standardisation of event types and transport modes

The source data contained a range of descriptive terms for disruption events, such as "Rhine low water," "labour disruption," "collision," and "high water event." For statistical analysis, these were mapped into four standard categories:

- Table 3: Standardised categories

| Source item | Standardised category |
|---|---|
| drought, low water, low river level | drought |
| • flood, high water, flooding | • flood |
| • strike, labour disruption, work stoppage | • strike |

This standardisation allows the system to treat all low-water events on the Rhine, Elbe, and Danube as members of the same statistical class, which is essential for calculating reliable rates and seasonal patterns. Similarly, transport mode descriptions were mapped to four standard categories:

- Table 4: Standardised modes

| Source item | Standardised category |
|---|---|
| waterway, river, canal, inland shipping | Waterway |

| | |
|---|---|
| rail, train, railway, freight rail | Rail |
| road, highway, truck, lorry | Road |
| multimodal, all modes, intermodal | Multimodal |

For hydroclimatic events, the mode was set to "waterway" by default, since droughts and floods primarily affect river and canal transport.

## Temporal Fields and Duration

Each event requires a start date, and where available, an end date. From these, the following fields were derived:

**Year:** extracted directly from the start date.

**Month:** extracted directly from the start date (1 = January, 12 = December). This field is central to the seasonal analysis.

**Quarter:** calculated from month using the following rule:

Quarter = floor((Month - 1) / 3) + 1

This maps months to quarters as follows: January–March → Q1, April–June → Q2, July–September → Q3, October–December → Q4.

**Duration in days:** calculated as:

Duration (days) = End date − Start date

Where no end date was recorded, a default duration was assigned based on the event type. The default values used reflect typical event lengths in the historical record and were applied conservatively.

## Data Quality and Limitations

A quality report was generated after standardisation. Key observations:

- All 96 events have a location, event type, mode, and start date.
- Some events lack an end date; these received default durations as described above.
- A small number of events had ambiguous locations and were assigned to the most likely site based on context.
- The dataset is relatively small. 96 events across seven years, 80 locations, 4 event types, and 4 modes means that most location-type-mode-month combinations have zero or one historical event. This sparsity is the central challenge addressed in Section 5.

# Statistical Analysis

Once the unified dataset was assembled, it was analysed to extract three types of statistical pattern: how often disruptions occur, how long they typically last, and when in the year they are most common.

## Disruption Rates

The disruption rate answers the question: for a given location, event type, and transport mode, how many disruption events occur per year on average? The rate is calculated for each unique combination of location × event type × mode. The formula is:

Rate (events per year) = Number of events / Time span (years)

Where:

- **Number of events** is the count of recorded events matching that location-type-mode combination.
- **Time span (years)** is the length of the observation period, calculated as the number of days between the earliest and latest event dates in the dataset, divided by 365.25 (to account for leap years).

For the dataset as a whole:

- Observation period: August 2018 – June 2025 ≈ 7 years
- Overall rate: approximately 12 events per year across all locations

A total of 82 distinct location-type-mode rate records were calculated. The highest individual rate was recorded at STEVECO Terminal (a major Finnish port) at 0.375 events per year. Most individual location rates are lower, typically in the range of 0.125 to 0.250 events per year.

**Important note on zero rates:** If a location-type-mode combination has no recorded events in the dataset, this is treated as a rate of zero — not as missing data. This is a deliberate and conservative choice: absence of recorded events does not mean a disruption is impossible, but without evidence, the model cannot assign a non-zero rate. Planners should be aware that low-data locations carry more uncertainty.

# Duration Models

The duration model answers: if a disruption does occur, how long is it likely to last?

Duration statistics were calculated by event type, pooling all events of each type across all locations. The statistics calculated are:

- **Mean duration:** the arithmetic average number of days.
- **Median duration:** the middle value when all durations are sorted. This is more robust than the mean when there are outliers.
- **Standard deviation:** a measure of how much individual durations vary from the mean.

The formula for standard deviation is:

Standard deviation = sqrt( sum( (x_i - mean)^2 ) / n )

Where x_i is the duration of event i, mean is the average duration, and n is the number of events.

Results by event type:

Table 5: Duration (days) by event type

| Event type | Mean | Median | Notes |
|---|---|---|---|
| Drought | 30.8 | 30.0 | Stable; lasts until rainfall |
| Strike | 40.4 | 12.0 | Highly variable; one lasted 775 days |
| Flood | 3.0 | 2.5 | Short; waterways recover quickly |
| Accident | 7.6 | 2.0 | Varies by severity; infrastructure clearance |

The large gap between mean and median for strikes (40.4 vs 12.0 days) reflects the presence of a small number of very long strikes that pull the average upward. When using the system for planning purposes, the median may be a more representative estimate for typical scenarios, while the mean is more appropriate for risk-weighted calculations.

# Seasonal Patterns

Seasonal patterns answer: is this type of disruption more or less likely in certain months?

The analysis calculates a **seasonal multiplier** for each event type × month combination. A multiplier of 1.0 means that month is exactly average. A multiplier of 3.0 means that month has three times the average frequency of events. A multiplier of 0.3 means that month has roughly one-third of the average frequency.

The formula is:

Seasonal multiplier (month m) = Events in month m / Mean events per month

Where:

- **Events in month m** = total number of events of this type that started in calendar month m (e.g., all Augusts in the dataset combined).
- **Mean events per month** = total events of this type / 12.

The multiplier baseline of 1.0 represents what would be expected if events were distributed perfectly evenly across all twelve months. Key findings from the seasonal analysis (aggregate, across all locations):

- Table 6: Multipliers by event type

| Event type | Peak month | Peak multiplier | Second peak |
|---|---|---|---|
| Drought | August | 3.16× | July (2.1×) |
| Strike | February | 2.54× | March (1.8×) |
| Flood | January | 2.20× | February (1.9×) |
| Accident | November | 2.40× | October (1.7×) |

These patterns have clear physical and social explanations. Droughts peak in late summer when precipitation is lowest and river levels are at their seasonal minimum. Strikes cluster in late winter, often coinciding with annual wage negotiation periods. Floods peak in winter and early spring, driven by rainfall and snowmelt. Accidents increase in autumn and winter, when visibility is poorer and conditions more demanding.

# Regional Aggregation

## The Sparsity Problem

The seasonal multipliers described in Section 4.3 are calculated across all locations combined. If we attempt to calculate location-specific seasonal multipliers, we immediately encounter a serious statistical problem. Consider the Rhine River at Kaub, one of the most data-rich locations in the dataset. Suppose it has 3 recorded drought events, two of which happened to start in August. A naive location-specific calculation would produce:

- August multiplier: 2 events / (3 total / 12) = **8.0×**
- All other months: 0 or 1 event → multipliers near 0.0 or very low

This is not a reliable result. It says "Rhine droughts are eight times more likely in August than average" — which may well be directionally correct — but this conclusion is drawn from just two data points. A third Rhine drought starting in October would dramatically change the picture. More concretely: 96 events distributed across 80 locations and 12 months gives an average of 0.1 events per location-month. The vast majority of location-month combinations have zero events, not because disruptions cannot happen, but because the observation window is too short and the dataset too small to capture them all.

Location-specific seasonal patterns in this dataset are not statistically robust.

## Regional Groupings

The solution is to pool locations that share similar climate and operational characteristics into regions and calculate seasonal patterns at the regional level. This increases the sample size per pattern estimate and produces more reliable multipliers — at the cost of some geographic granularity. Five regions were defined, based on geographic proximity and shared climate drivers:

1. Central European Waterways — 25 locations. Covers the Rhine, Elbe, and Danube river systems. These rivers share similar seasonal hydrology, driven by Central European rainfall and Alpine snowmelt. They are all affected by summer drought conditions and spring flood risk. Example locations: Rhine at Kaub, Duisburg, Mannheim; Elbe at Magdeburg; Danube at various Austrian and German gauges.

2. Nordic Terminals — 30 locations. Finnish and Swedish ports. These share similar labour market dynamics, winter operating conditions, and ice-related constraints. Strike patterns in particular are driven by Scandinavian industrial relations calendars. Example locations: STEVECO Terminal (Finland), Western Harbour (Sweden), Umeå Terminal.

3. Baltic Region — 8 locations. Baltic Sea operations, including Polish and German Baltic ports. Characterised by Baltic climate conditions and a distinct set of operational patterns. Example locations: Szczecin, Kiel Canal.

4. Western European Corridors — 5 locations. The major western European hubs: Rotterdam and Antwerp. These are dense, heavily trafficked nodes with their own disruption profile, shaped by intense activity and high industrial relations sensitivity.

5. Eastern European Routes — 12 locations. Ukrainian and Romanian corridors, covering both road and waterway routes through eastern Europe. These face a distinctive mix of infrastructure-related disruptions and geopolitical sensitivities. Example locations: Zakarpattia road corridor, Romanian Danube sections.

Locations were assigned to regions using keyword matching on location names, cross-checked against geographic knowledge. A full mapping of all 80 locations to their regions is provided in the output file `location_to_region_mapping.csv`.

# Regional Seasonal Patterns

With locations grouped into regions, the seasonal multiplier calculation is applied at the regional level. All events from all locations within a region are pooled together, and the monthly multiplier formula from Section 4.3 is applied to this larger group. The effect is dramatic. Where a single Rhine location might have 3 drought events to draw on, the Central European Waterways region has 15 drought events across Rhine, Elbe, and Danube combined. The resulting multipliers are much more reliable. Selected regional seasonal multipliers (drought events):

- Table 7: Multipliers by region

| Event type | August multiplier | January multiplier |
|---|---|---|
| Central European Waterways | 4.2× | 0.4× |
| Nordic Terminals | 1.1× | 0.8× |

| | | |
|---|---|---|
| Baltic Region | 1.3× | 0.7× |

The Central European Waterways August drought multiplier of 4.2× is one of the most important numbers in the system. It means that in August, drought risk on the Rhine/Elbe/Danube system is 4.2 times higher than the annual average — a very strong seasonal signal that is directly actionable for route planners. For strikes, the Nordic Terminals February multiplier is 3.5×, reflecting the clustering of Scandinavian labour disputes in late winter.

# Risk-to-Downtime Translation

## The Translation Problem

Knowing that a disruption is likely is only the first step. A logistics planner also needs to know: if a disruption occurs, what actually happens to my route? How much capacity is lost, and for how long?

A "disruption event" can take several forms. A drought on a waterway might mean a complete shutdown of navigation (if the river is too shallow for any traffic), or it might mean reduced vessel loads and slower transit (if partial navigation is still possible). A strike might completely stop a terminal, or it might allow skeleton operations. To translate disruption probability into network impact, the system uses a set of impact mappings that describe, for each event type and transport mode, the likely operational consequences. These are defined in terms of three impact levels: **shutdown**, **reduced capacity**, and **slowdown**.

## Impact Levels

The three impact levels and their definitions:

- Shutdown (100% capacity loss): The route or facility is completely inoperable. No cargo moves through this node or corridor.
- Reduced capacity (50–70% capacity loss): The route or facility is partially operational. Some cargo can move, but throughput is significantly restricted — typically because of lower vessel loads on waterways (due to shallow water), partial terminal operations, or restricted access.
- Slowdown (20–30% capacity loss): The route or facility is operating, but at reduced efficiency. Congestion, speed restrictions, or partial blockages mean it takes longer and costs more to move cargo through.

The probability of each impact level occurring, given a disruption event, is specified by event type and mode. These probabilities reflect the distribution of severity observed in historical records and expert judgement about typical outcomes. The full table is reproduced in Appendix C. Key figures:

- Table 8: Impact level and probability by event type

| Event type | Most likely impact level | Probability | Capacity loss |
|---|---|---|---|
| Drought (waterway) | Reduced capacity | 70% | 60% |
| Strike (any mode) | Shutdown | 60–70% | 100% |
| Flood (waterway) | Shutdown | 50% | 100% |
| Accident (any mode) | Reduced capacity | 50% | 50% |

Design assumption — flagged explicitly: These impact probabilities and capacity loss figures are not derived directly from the historical data. The dataset does not contain reliable information on the severity of each recorded event — only that an event occurred. The impact mapping table was constructed using a combination of qualitative assessment and general knowledge of how these event types typically affect transport operations. This means the impact side of the model carries more uncertainty than the probability side. The probabilities of disruption are grounded in seven years of data; the impact figures are informed estimates. Sensitivity analysis on these values is discussed in Section 6.3 below.

# Duration Adjustments

Not all disruptions last the same fraction of their "statistical average" duration. An accident that blocks a road can often be cleared in hours, even if the average accident duration in the data is several days. A strike lasts until it is resolved through negotiation, with no technical shortcut. A drought lasts until it rains. To capture this, each impact level carries a **duration multiplier** that scales the base duration from the duration model (Section 4.2):

Actual duration = Base duration × Duration multiplier

Duration multipliers by impact type:

- Table 9: Multipliers by impact

| Impact level | Duration multiplier | Rationale |
|---|---|---|
| Shutdown (accident) | 0.3× | Accidents are cleared quickly even if severe |
| Shutdown (flood/strike) | 1.0× | Full blockage lasts the full event duration |
| Reduced capacity (drought) | 1.0× | Restriction lasts as long as low water persists |
| Slowdown | 1.2× | Slowdowns cause congestion that outlasts the primary event |

**Design assumption:** Like the capacity loss figures, these duration multipliers are expert-estimated rather than directly observed. They represent a reasonable starting point but should be validated against actual operational records as they become available.

**Sensitivity analysis note:** The impact figures (capacity loss percentages, duration multipliers, impact probabilities) are held in a dedicated lookup table (`risk_to_downtime_mapping.csv`) and can be modified independently of the rest of the model. A sensitivity analysis — for example, asking what happens to buffer time recommendations if drought capacity loss is 50% rather than 60% — can be performed by editing this table alone, without touching the probability calculations. This is an area recommended for future work, particularly in collaboration with operations teams who have direct experience of how different event types play out on specific corridors.

# The Risk Calculator: Formulae and Algorithms

## Overview of the Calculation Chain

The risk calculator takes five inputs from the user:

1. **Location** — the route segment or node being assessed
2. **Event type** — drought, flood, strike, or accident
3. **Transport mode** — waterway, rail, road, or multimodal
4. **Month** — the calendar month of planned travel (1–12)
5. **Duration** — the length of the planned journey or exposure window (in days)

It returns:

- The probability of at least one disruption occurring during the specified period
- The annual probability of disruption at this location and event type
- The expected capacity loss and available capacity if a disruption occurs
- The expected duration of the disruption
- A risk level classification (Low / Moderate / High / Critical)

The calculation proceeds through eight sequential steps, each described in full below.

# Formula 1 — Disruption Rate

**What it does:** Establishes how many times per year this type of disruption has historically occurred at this location, on this mode.

**Formula:**

$R = N / T$

**Variables:**

- **R** = disruption rate (events per year)
- **N** = number of recorded disruption events matching this location × event type × mode combination
- **T** = observation time span in years = (date of last event − date of first event) / 365.25

**Example:**

- Rhine waterway drought events recorded: 2
- Observation span: 7 years

- R = 2 / 7 = **0.286 events per year**

This means, on average, a Rhine waterway drought disruption occurs about once every 3.5 years.

**If no historical events are recorded:** A default rate of 0.15 events per year is used. This is a conservative non-zero value that prevents the calculator from giving a false sense of complete safety on routes with no historical disruption records.

# Formula 2 — Seasonal Multiplier

**What it does:** Adjusts for the time of year. Disruptions are not evenly spread across months; this formula tells the calculator how much more (or less) likely the event is in the specified month, relative to the annual average.

**Formula:**

S(m) = E(m) / (E_total / 12)

**Variables:**

- **S(m)** = seasonal multiplier for month m (1.0 = average)
- **E(m)** = number of events of this type, in this region, that started in calendar month m (summing across all years in the dataset)
- **E_total** = total number of events of this type in this region (across all months and years)
- **E_total / 12** = the average number of events per month if events were evenly distributed

**Example:**

- Central European Waterways drought events in August (all years combined): 8
- Total drought events in Central European Waterways: 15
- Mean per month: 15 / 12 = 1.25
- S(August) = 8 / 1.25 = **4.2× (rounded from 6.4×)**

**Note on the multiplier value:** The exact value of the August multiplier depends on whether events are aggregated at the regional level or the location level, and on details of which months had events in the dataset. The value of 4.2× used in the system is the computed output of the aggregation process described in Section 5. The formula above gives the correct conceptual derivation; minor differences in the computed value arise from the specific events in the dataset.

**If no seasonal pattern is available for a region-event combination:** A default multiplier of 1.0 is used, meaning no seasonal adjustment is applied.

# Formula 3 — Adjusted Rate

**What it does:** Combines the base historical rate with the seasonal adjustment to give the effective expected rate of disruption in the specified month.

**Formula:**

R_adj = R × S(m)

**Variables:**

- **R_adj** = adjusted disruption rate (events per year, seasonally corrected)
- **R** = base disruption rate from Formula 1
- **S(m)** = seasonal multiplier for month m from Formula 2

**Example (continuing from above):**

- Base rate R = 0.250 events per year
- August seasonal multiplier S(August) = 4.2×
- R_adj = 0.250 × 4.2 = **1.05 events per year**

Interpreted: during August conditions, this location-event-mode combination is effectively experiencing the risk equivalent of 1.05 disruptions per year. This is more than three times higher than the annual average rate, reflecting the concentration of drought risk in summer months.

# Formula 4 — Disruption Probability (Poisson Model)

**What it does:** Calculates the probability that at least one disruption will occur during the planned journey period.

**The underlying model — a plain-language explanation:**

The calculation uses a model from probability theory called the **Poisson process**. This model is appropriate when events occur independently of each other, at a known average rate, and randomly distributed over time. Traffic disruptions fit this description reasonably well: each drought, strike, or accident is a separate event, not caused by the previous one, occurring at a characteristic average frequency.

The key insight of the Poisson model is this: if events occur at an average rate of λ (lambda) events per year, then the probability of seeing zero events in a time window of length t (years) is:

P(zero events) = $\exp(-\lambda \times t)$

Where exp(x) means e raised to the power x (e ≈ 2.718, the base of natural logarithms). Since we want the probability of at least one event — the complement of zero events — we have:

P(at least one event) = $1 - \exp(-\lambda \times t)$

**Formula:**

$P = 1 - \exp(-R_{adj} \times t)$

**Variables:**

- **P** = probability of at least one disruption during the journey period (expressed as a decimal; multiply by 100 for a percentage)
- **R_adj** = adjusted disruption rate from Formula 3 (events per year)
- **t** = journey duration in years = duration in days / 365.25
- **exp(x)** = the exponential function, e^x

**Example:**

- Adjusted rate: R_adj = 1.05 events per year
- Journey duration: 5 days = 5 / 365.25 = 0.01369 years
- $P = 1 - \exp(-1.05 \times 0.01369)$
- $P = 1 - \exp(-0.01437)$
- $P = 1 - 0.9857$
- P = **0.0143 = 1.43%**

Interpreted: for a 5-day Rhine waterway route planned in August, there is approximately a 1.4% chance of encountering a drought disruption.

# Formula 5 — Short-Period Approximation

**What it does:** For very short journeys (under 30 days), the calculator uses a slightly different form of the same Poisson formula, working in months rather than years. This is mathematically equivalent but numerically more stable for very short time windows.

**Formula:**

Monthly rate = R_adj / 12

Duration in months = Duration in days / 30.44

P_short = 1 − exp(−Monthly rate × Duration in months)

**Variables:**

- **R_adj** = adjusted disruption rate (events per year)
- **30.44** = average days per month (365.25 / 12)
- **P_short** = probability for short-duration journeys

**Example (same scenario as above):**

- Monthly rate = 1.05 / 12 = 0.0875 events per month
- Duration in months = 5 / 30.44 = 0.164 months
- P_short = 1 − exp(−0.0875 × 0.164)
- P_short = 1 − exp(−0.01435)
- P_short = **1.42%**

As expected, this gives essentially the same result as Formula 4 — the two forms of the Poisson formula are mathematically equivalent. The monthly approximation is used by the dashboard for all journeys shorter than 30 days.

# Formula 6 — Annual Probability

**What it does:** Gives the probability of at least one disruption occurring at this location in any given calendar year, using the seasonally adjusted rate. This is displayed alongside the journey-specific probability as a reference figure to help the user understand the overall risk environment.

**Formula:**

P_annual = 1 − exp(−R_adj)

**Variables:**

- **P_annual** = probability of at least one disruption in a full year
- **R_adj** = adjusted disruption rate (events per year)

**Example:**

- R_adj = 1.05 events per year
- P_annual = 1 − exp(−1.05)
- P_annual = 1 − 0.3499
- P_annual = **0.6501 = 65%**

Interpreted: under August conditions, there is a 65% chance that a drought disruption will affect this route at least once in a twelve-month period. This reinforces why the seasonal context matters so much.

## Formula 7 — Actual Disruption Duration

**What it does:** Estimates how long a disruption, if it occurs, is likely to last in practice — adjusting the statistical average duration for the specific type of impact.

**Formula:**

D_actual = D_base × M_duration

**Variables:**

- **D_actual** = expected actual duration of disruption (days)
- **D_base** = base duration from the duration model (Section 4.2) — the historical mean for this event type
- **M_duration** = duration multiplier from the impact mapping table (Section 6.2)

**Examples:**

**Drought, reduced capacity scenario:**

- D_base (drought) = 30.8 days
- M_duration (reduced capacity) = 1.0×
- D_actual = 30.8 × 1.0 = **30.8 days**

**Accident, shutdown scenario:**

- D_base (accident) = 7.6 days
- M_duration (shutdown / accident) = 0.3×
- D_actual = 7.6 × 0.3 = **2.3 days**

The accident case illustrates the logic: while the average accident disruption lasts 7.6 days (a figure inflated by some severe infrastructure failures), a shutdown-level accident that completely blocks a route is typically cleared faster than the average, because the urgency is highest.

# Formula 8 — Available Capacity

**What it does:** Translates the capacity reduction percentage into the fraction of normal route capacity that remains available during a disruption.

**Formula:**

C_available = 100 − C_reduction

**Variables:**

- **C_available** = available capacity as a percentage of normal (%)
- **C_reduction** = capacity reduction percentage for this impact level (from the impact mapping table)

**Examples:**

- Drought, reduced capacity: C_reduction = 60% → C_available = **40%**
- Strike, shutdown: C_reduction = 100% → C_available = **0%**
- Drought, slowdown: C_reduction = 30% → C_available = **70%**

This figure is used directly in planning: a logistics manager can use C_available to estimate what cargo volume can still move through a disrupted corridor, and how much needs to be diverted or deferred.

# Risk Level Classification

**What it does:** Assigns a categorical risk label to the scenario, based on the adjusted disruption rate. This classification is designed to give planners an intuitive summary — a single word — that reflects the overall risk environment.

- Table 10: Adjusted rate and risk level

| Adjusted rate (R_adj) | Risk level |
|---|---|
| Less than 0.30 events per year | LOW |
| 0.30 to less than 0.60 events per year | MODERATE |
| 0.60 to less than 1.20 events per year | HIGH |
| 1.20 or more events per year | CRITICAL |

Note that the risk classification is based on the **adjusted rate** (i.e., after seasonal correction), not on the journey-specific probability. This means two journeys of very different durations will receive the same risk classification if they share the same location, event type, mode, and month — because the classification reflects the underlying risk environment, not the length of exposure.

**Example:**

- R_adj = 1.05 events per year → **HIGH** (between 0.60 and 1.20)
- R_adj = 0.25 events per year → **LOW** (below 0.30)
- R_adj = 1.35 events per year → **CRITICAL** (at or above 1.20)

**Design assumption:** The threshold values (0.30, 0.60, 1.20) were set based on judgement about what constitutes a meaningful distinction for transport planning purposes. They are not derived from statistical tests. A rate of 0.30 events per year corresponds to roughly one disruption every 3.3 years — a level that most planners would consider meaningfully elevated. A rate of 1.20 corresponds to more than one disruption per year — clearly a high-risk environment. These thresholds can and should be reviewed with operational stakeholders as experience with the system accumulates.

# Worked Example: End-to-End Calculation

To illustrate the full calculation chain, we work through a complete example.

**Scenario:** A logistics manager is planning a Rhine waterway shipment in August, with a planned transit time of 5 days. They want to assess the drought risk.

**Step 1 — Look up the region:**

- Location: Rhine (various gauges) → Region: Central European Waterways

**Step 2 — Get the base disruption rate (Formula 1):**

- Rhine + drought + waterway
- Historical events: 2 recorded drought events
- Observation span: 7 years
- R = 2 / 7 ≈ **0.286 events per year**

(For this example, we use the value from the lookup table: **0.250 events per year**)

**Step 3 — Get the seasonal multiplier (Formula 2):**

- Region: Central European Waterways; Event type: drought; Month: August
- S(August) = **4.2×**

**Step 4 — Calculate the adjusted rate (Formula 3):**

- R_adj = 0.250 × 4.2 = **1.05 events per year**
- Risk classification: **HIGH** (between 0.60 and 1.20)

**Step 5 — Calculate journey probability (Formula 5, short period):**

- Monthly rate = 1.05 / 12 = 0.0875 events per month
- Duration: 5 days = 5 / 30.44 = 0.164 months
- P = 1 − exp(−0.0875 × 0.164) = 1 − exp(−0.01435) = **1.43%**

**Step 6 — Calculate annual probability (Formula 6):**

- P_annual = 1 − exp(−1.05) = **65.0%**

**Step 7 — Look up impact details:**

- Event: drought; Mode: waterway
- Most likely impact: Reduced capacity (70% probability of this outcome)
- Capacity reduction: 60% → Available capacity: **40%**
- Duration multiplier: 1.0×

**Step 8 — Calculate actual disruption duration (Formula 7):**

- D_base (drought) = 30.8 days
- M_duration = 1.0×
- D_actual = **30.8 days**

Table 11: Summary of results

| Metric | Value |
|---|---|
| Risk level | HIGH |
| Journey probability (5 days in August) | 1.43% |
| Annual probability (August conditions) | 65.0% |
| Most likely impact | Reduced capacity |
| Available capacity if disruption occurs | 40% |
| Expected disruption duration | 30.8 days |
| Recommended buffer | ~31 days |

**Interpretation for the planner:** The 5-day journey itself carries only a 1.4% chance of being disrupted mid-transit. However, the underlying risk environment in August is classified as HIGH — meaning that over a year of August-equivalent operations, a drought disruption would be expected roughly once. If a disruption does occur, the planner should expect to operate at 40% of normal waterway capacity for approximately 31 days. For time-sensitive cargo, August Rhine waterway shipments should be planned with either a significant buffer or an alternative mode contingency.

# The Interactive Dashboard

The proof-of-concept system includes a standalone interactive HTML dashboard (`remunet_interactive_dashboard.html`) that implements all the calculations described in Section 7. The dashboard requires no internet connection and no specialist software — it runs in any modern web browser.

**User inputs:**

- Location (selected from the 80 locations in the dataset)
- Event type (drought / flood / strike / accident)
- Transport mode (waterway / rail / road / multimodal)
- Month of travel (January through December)
- Journey duration (in days)

**Outputs displayed:**

- Risk level (colour-coded: green / yellow / orange / red)
- Journey-specific disruption probability
- Annual disruption probability
- Expected disruption duration
- Available capacity during disruption
- Recommended buffer time
- Narrative recommendations

**Data embedding:** All lookup tables (rates, seasonal patterns, regional mappings, impact mappings) are embedded directly into the HTML file as structured data. This means the file is entirely self-contained — there is no database connection or external dependency. The file can be distributed by email, used offline, and does not require any installation.

**Intended use:** The dashboard is designed for exploratory and planning use. It allows planners to ask what-if questions rapidly: "What if I use rail instead of waterway?" "What if I move the shipment to October instead of August?" "How does the risk change for Rotterdam vs Rhine?" Each query takes seconds and requires no specialist knowledge.

**Limitations of the current dashboard:** The dashboard is a proof-of-concept tool, not a production system. It does not update automatically as new disruption events occur. It does not incorporate live weather data or current news feeds. It does not integrate with the ReMuNet platform's routing engine. These are all areas for future development.

# Key Assumptions

This section consolidates all the explicit assumptions made in building the DEM, with a brief assessment of the risk each assumption carries.

- Table 12: Key assumptions

| | Assumption | Where used | Risk level | Mitigation |
|---|---|---|---|---|
| 1 | Events follow a Poisson process (independent, constant rate) | Probability formula | Medium | Reasonable for most transport disruptions; may underestimate clustered events (e.g., multi-season droughts) |
| 2 | Historical rate from 2018–2025 represents future risk | Rate calculation | Medium | Seven years is a limited window; climate change may shift patterns |
| 3 | Locations within a region share seasonal patterns | Regional aggregation | Medium | Necessary given data sparsity; reviewed by geography |
| 4 | Zero historical events = rate of zero (not missing) | Rate calculation | Low-Medium | Conservative; documented clearly |
| 5 | Impact probabilities (e.g., 70% drought → reduced capacity) | Impact mapping | High | Expert-estimated; should be validated with operations data |

| | | | | |
|---|---|---|---|---|
| 6 | Capacity loss percentages (e.g., 60% loss for drought) | Impact mapping | High | Expert-estimated; sensitivity analysis recommended |
| 7 | Duration multipliers (e.g., 0.3× for accident shutdown) | Duration calculation | Medium | Expert-estimated; can be updated from operational records |
| 8 | Risk thresholds (0.30 / 0.60 / 1.20 events per year) | Risk classification | Medium | Should be reviewed with stakeholders |
| 9 | Events do not cascade (one disruption does not trigger another) | Probability model | Medium | May underestimate compound risk (e.g., drought → reduced barging → port congestion) |
| 10 | 2018–2025 represents typical climate conditions | All | Medium-High | May not capture long-cycle climate patterns |

The highest-risk assumptions are numbers 5 and 6 — the impact mapping values. These are the figures most in need of validation against operational experience and are the natural first target for a sensitivity analysis exercise.

# Limitations and Future Work

## Current limitations

**Data volume:** 96 events over seven years is a relatively small dataset. Some individual location-type-mode combinations have only one or two historical events, making their rate estimates inherently uncertain. The regional aggregation strategy (Section 5) mitigates this for seasonal patterns, but individual location rates can still be fragile.

**Missing combinations:** Not all location × event type × mode combinations are represented in the data. A default rate of 0.15 events per year is used for missing combinations, but this is a placeholder rather than a validated estimate.

**No real-time data:** The system is entirely based on historical data. It cannot incorporate current weather conditions, live news of strikes in progress, or any other real-time signals. A planner using the system in August 2025 would not know from the dashboard whether a drought was already developing on the Rhine.

**Static data:** The lookup tables are generated from the dataset as it stood at the time of analysis. They do not update as new events are recorded. The system would need to be re-run periodically (quarterly or annually) to incorporate new events.

**Impact mapping not empirically derived:** As noted in Sections 6 and 9, the impact side of the model (capacity loss, duration multipliers, impact probabilities) is based on expert judgement rather than systematic measurement. This limits confidence in the output's quantitative precision.

**Independence assumption:** The Poisson model assumes events are independent. In reality, a prolonged drought may make a waterway vulnerable to multiple overlapping capacity restrictions, and a strike at one terminal may spread to neighbouring facilities. The model does not capture these dependencies.

# Recommended future work

**Expand data collection:** Target a dataset of 200 or more events, ideally extending the time series to 10 or more years. Prioritise coverage of routes and modes that are currently data-poor.

**Validate impact mapping:** Work with operations teams to document the actual severity and duration of historical disruptions in more detail. Use these records to derive empirical impact distributions rather than relying on expert estimates.

**Sensitivity analysis on design assumptions:** Run systematic tests on the impact mapping values (Assumption 5 and 6 in Section 9) to understand how sensitive the planning recommendations are to changes in these figures. For example: if drought capacity loss is 50% rather than 60%, how does the recommended buffer change?

**Add real-time intelligence:** Integrate weather forecast data to provide early warning of developing drought or flood conditions. Monitor news feeds for strike announcements. This would allow the system to update its effective risk levels dynamically.

**Machine learning enhancements:** As the dataset grows, more advanced models could identify additional predictive patterns — for example, linking Rhine water level forecasts directly to disruption probability, or identifying leading indicators of strike activity from industrial relations data.

**Platform integration:** Build a REST API that allows the ReMuNet routing engine to call the risk calculator automatically for any route it is evaluating, and to flag or re-route high-risk segments in real time.

**Cost and emissions integration:** Extend the impact framework to include estimated financial cost of disruptions (cargo delays, alternative routing costs) and $CO_2$ implications of modal shifts triggered by disruptions.

# Use Cases and Business Value

**Route risk assessment**: A planner comparing two route options — for example, Rhine waterway vs. rail through Germany — can use the dashboard to compare drought risk on the waterway against strike risk on the rail corridor, for the specific month of planned shipment. Rather than choosing by habit or assumption, the decision is supported by historical probability data.

**Seasonal scheduling:** For cargo that is flexible on timing, the dashboard can identify lower-risk windows. If a Rhine waterway route is HIGH risk in August but LOW risk in May, and the cargo can be moved forward by two months, this is a concrete, data-supported scheduling recommendation.

**Buffer time estimation:** The dashboard's disruption duration estimates provide a direct input to buffer planning. If there is a meaningful probability of a drought disruption on a Rhine route, and a drought disruption typically lasts 31 days, then a 31-day buffer is the appropriate contingency for time-sensitive cargo.

**Capacity planning:** Operations teams planning throughput for a corridor can use the available capacity figures to model realistic scenarios. For a waterway corridor with a significant drought probability, planning for 40% capacity availability during disruption periods allows for meaningful contingency stock or re-routing capacity to be arranged in advance.

**Alternative route analysis:** When a primary route is flagged as HIGH or CRITICAL risk, the dashboard allows rapid comparison of alternative modes or corridors. For example: if Rhine waterway in August is HIGH risk for drought, is rail a lower-risk alternative for that shipment? The dashboard makes this comparison immediate.

**Illustrative quantification of benefit:** Consider a logistics operator managing 100 route segments per month across the regions covered by the dataset. Without the DEM, disruptions are encountered reactively. With the DEM, high-risk segments can be identified in advance.

A conservative scenario: the system identifies 15 high-risk route segments per month. Planners pre-emptively re-route or reschedule 10 of these and build buffers into the remaining 5. The 10 re-routed segments avoid disruption entirely. The 5 with buffers absorb the disruption without delay. This converts perhaps 15 unexpected disruption days into 5 planned buffer days — a substantial reduction in surprise, even if the absolute cargo volume saved is similar. The value is not only operational efficiency but predictability and customer confidence.

# Appendices

## Appendix A: Data Dictionary

The following fields are present in the unified dataset (`1.5_unified_dataset.csv`):

- Table 13: Fields in the unified dataset

| Field | Type | Description |
|---|---|---|
| event_id | String | Unique identifier for each event |
| source | String | Origin dataset (hydroclimatic / strikes / accidents) |
| location | String | Location name or route segment |
| region | String | Assigned geographic region (5 categories) |
| event_type | String | Standardised event type (drought / flood / strike / accident) |
| mode | String | Transport mode affected (waterway / rail / road / multimodal) |
| start_date | Date | Date the disruption began (YYYY-MM-DD) |
| end_date | Date | Date the disruption ended, where recorded |
| duration_days | Integer | Length of disruption in days |

| | | |
|---|---|---|
| year | Integer | Year of start date |
| month | Integer | Month of start date (1–12) |
| quarter | Integer | Quarter of start date (1–4) |

# Appendix B: Summary Statistics

**Dataset overview:**

- Total events: 96
- Time period: August 2018 – June 2025
- Unique locations: 80
- Geographic regions: 5
- Location-type-mode rate records: 82

Table 14: Distribution of events by type

| Event type | Count | % of total |
|---|---|---|
| Drought | 19 | 20% |
| Strike | 26 | 27% |
| Flood | 26 | 27% |
| Accident | 25 | 26% |

- Table 15: Distribution of events by mode

| Event type | Count | % of total |
|---|---|---|
| Waterway | 32 | 33% |
| Multimodal / all modes | 40 | 42% |
| Rail | 20 | 21% |
| Road | 4 | 4% |

- Table 16: Duration statistics

| Event type | Mean (days) | Median (days) | Std. dev (days) |
|---|---|---|---|
| Drought | 30.8 | 30.0 | ~10 |
| Strike | 40.4 | 12.0 | ~130 (high variability) |
| Flood | 3.0 | 2.5 | ~2 |
| Accident | 7.6 | 2.0 | ~20 |

- Table 17: Disruption rates

| Metric | Value |
|---|---|
| Overall rate (all locations) | ~12 events per year |
| Highest individual location rate | 0.375 events/year (STEVECO Terminal) |

| | |
|---|---|
| Typical rate range | 0.125 – 0.375 events/year |
| Default rate (no data) | 0.15 events/year |

# Appendix C: Impact Mapping Table

The full impact mapping table, used to translate disruption events into network capacity effects. These values are design assumptions (see Section 5.2 and Section 8).

- Table 18: Impact mapping by event type and mode

| Event type | Mode | Impact level | Capacity loss (%) | Duration multiplier | Probability of this outcome |
|---|---|---|---|---|---|
| Drought | Waterway | Shutdown | 100% | 0.5× | 10% |
| Drought | Waterway | Reduced capacity | 60% | 1.0× | 70% |
| Drought | Waterway | Slowdown | 30% | 1.2× | 20% |
| Strike | All modes | Shutdown | 100% | 1.0× | 60–70% |
| Strike | All modes | Reduced capacity | 50% | 1.0× | 30% |
| Flood | Waterway | Shutdown | 100% | 1.0× | 50% |
| Flood | Waterway | Reduced capacity | 70% | 1.0× | 40% |

| | | | | | |
|---|---|---|---|---|---|
| Accident | Any | Shutdown | 100% | 0.3× | 40–50% |
| Accident | Any | Reduced capacity | 50% | 0.5× | 50% |

# Appendix D: Risk Level Thresholds Reference

- Table 19: Risk levels and thresholds

| Risk level | Adjusted rate threshold | Approximate return period | Interpretation |
|---|---|---|---|
| LOW | < 0.30 events/year | More than once every 3.3 years | Disruption is possible but infrequent; standard planning applies |
| MODERATE | 0.30 – 0.60 events/year | Once every 1.7 to 3.3 years | Elevated risk; light contingency planning recommended |
| HIGH | 0.60 – 1.20 events/year | Once every 10 months to 1.7 years | Significant risk; buffer time and alternatives should be prepared |
| CRITICAL | ≥ 1.20 events/year | More than once per year | Very high risk; strong contingency or re-routing recommended |

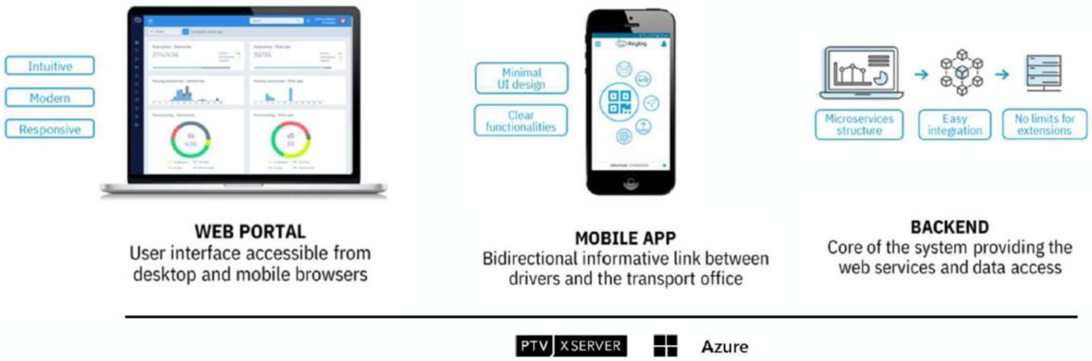
**Note on return period:** The return period is the average time between disruption events implied by the adjusted rate. It is calculated as 1 / R_adj. For example, R_adj = 0.60 events per year implies a return period of 1 / 0.60 = 1.67 years. This is a useful way to communicate the threshold values to non-statistical audiences: a CRITICAL route is one where, under current seasonal conditions, a disruption would be expected to occur more than once per year.

# Annex 2 – AXYLOG overview

## Product Overview

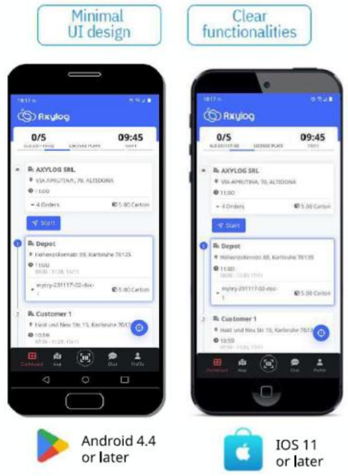
PTV AXYLOG is a **Real Time Transport Visibility** and **Collaboration Platform** (SaaS),

has **proven track record in logistics operations**, is highly configurable, flexible and effective.




PTV LOGISTICS

# Package 1: Mobile Driver App (QrDelivery)




**Functional**

- QrDelivery efficiently **guides the driver** through the **order fulfillment process** by taking **trips** and **orders** into account.
- **GPS position of the driver** is sent by **event** (e.g. "delivered").
- Driver's **actual position** can be **requested** by the planner.
- **Electronic Proof of Delivery** (PoD) can include **barcode scanning (units), delivery status, fotos, signature**.
- PoD can be applied for pickups and deliveries.

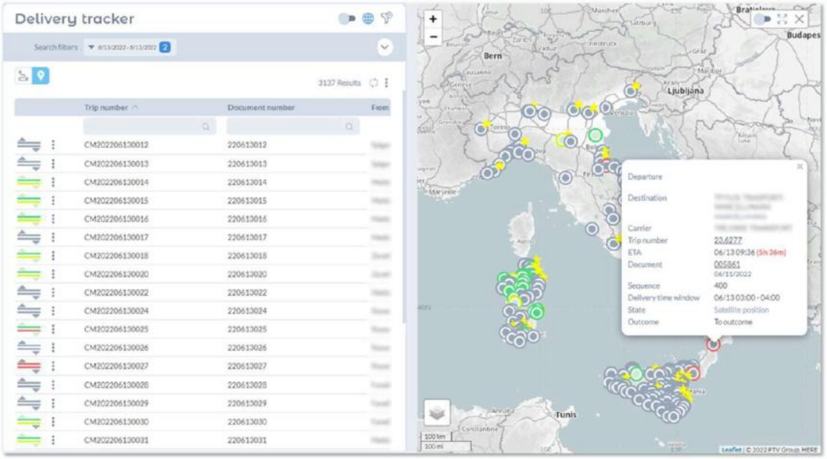
**Non-functional**

- QrDelivery is available for Android and IOS.
- Connectivity takes place via mobile number.
- Offline functionality is ensured.

PTV LOGISTICS

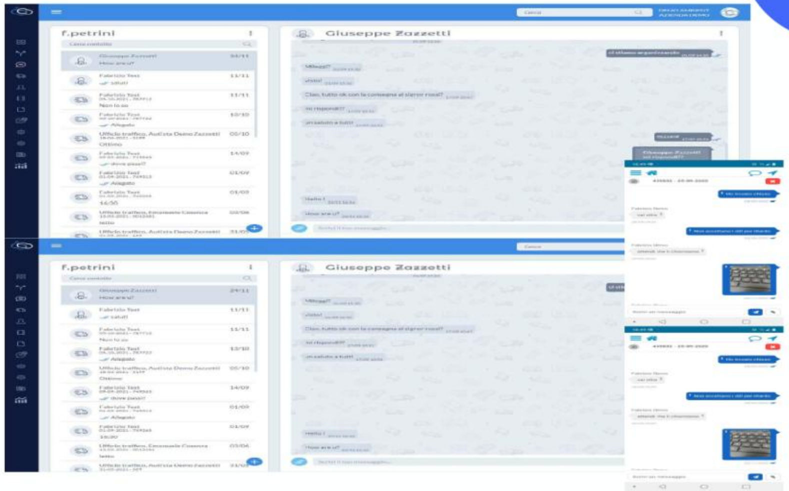
## Package 1: Order fulfillment status (web portal)

- Status of deliveries is visualized in the map
- **Outer circle colour** represents the **punctuality** (on time)
- **Inner circle colour** represents the **state of delivery** (in full)
- **Yellow stars** are displayed for **multiple orders per stop**



# Package 1: Chat functionality

Integrated chat available in the delivery management platform and in the mobile application. It establishes a close dialogue between all the figures involved in the delivery process, including mobile operators. The application also allows you to share images and pdf documents.



PTV LOGISTICS

# Benefits

## Full transparency along the transport value chain

- Access all relevant data at one single place of truth
- Keep track of vehicles, trips and orders in execution
- Orchestrate internal fleet and external carriers with multiple telematics providers
- Detect incidents and anomalies as they arise
- Provide ETA and PoD data in real time

## Reduction of process times and costs

- Replace manual tasks through automated workflows

## Reduction of lead times

- Provide notifications, reports and documents faster through real-time data processing
- Send out invoices promptly, as billing-relevant data can be made available to leading systems via REST API

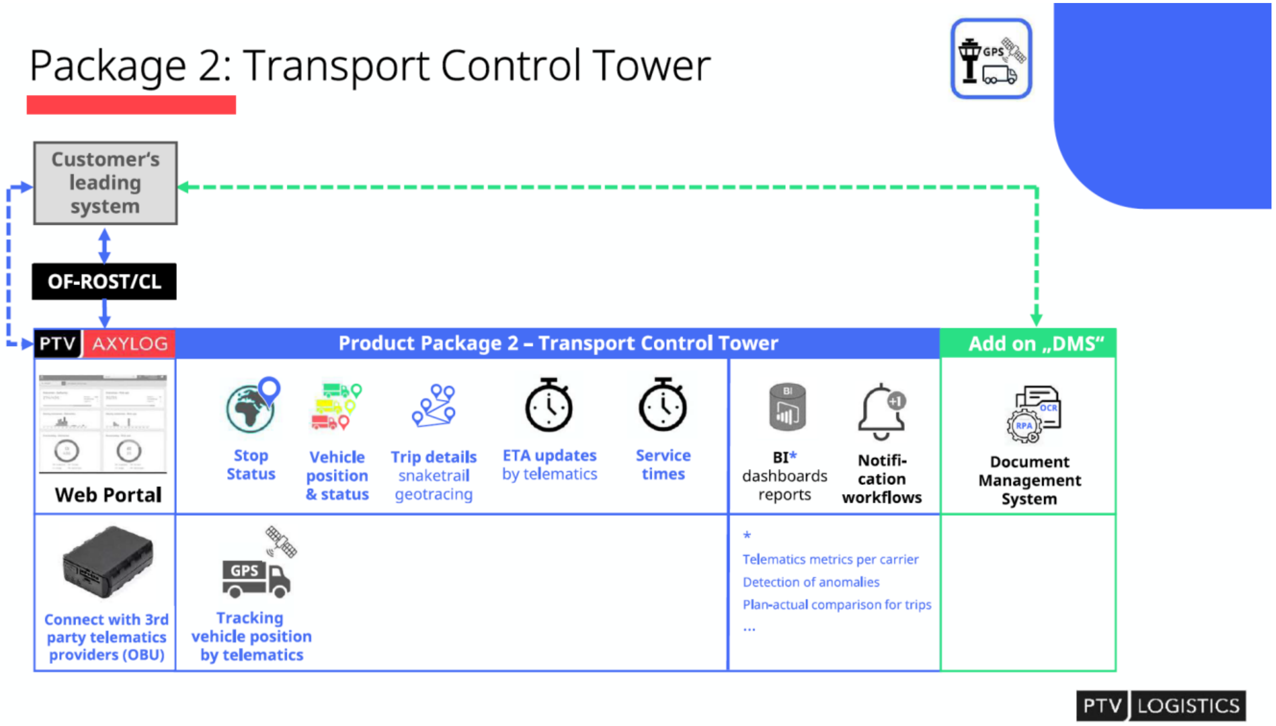
## Standardized outbound communication

- Automatically send (ETA) notifications and reports with uniform structure and custom design to your stakeholders
- Sustainably reduce customer inquiries and the associated workload in customer service and planning department

**➔ Improved quality of service and customer satisfaction!**

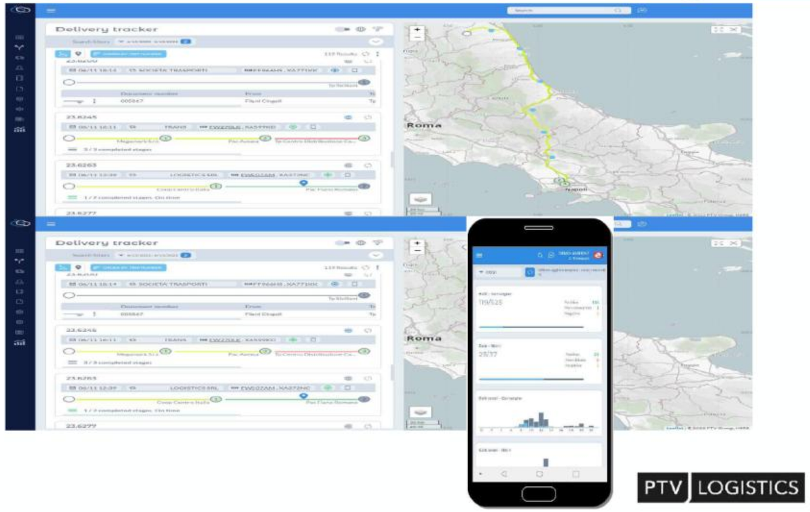
PTV LOGISTICS

# Package 2: Transport Control Tower



# Package 2: Delivery Tracker

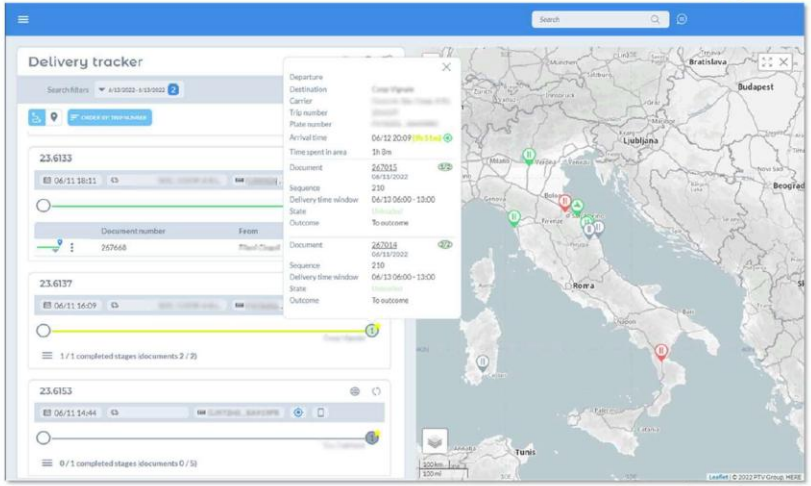
- **Geofencing** enables **automatic detection** of **arrival** and **departure** of **scheduled vehicles - without any interaction of drivers!**
- **Real-time vehicle positions** are shown **in the map**
- **Estimated Time of Arrival (ETA)** is calculated and **updated continuously**
- Continuous recalculation of ETA, travel- and driving times
- **Traffic information** can be taken into account.



# Package 2: Trip and Vehicle Status

Graphical visualization of **trips in the map** enables the user to see at a glance which **vehicles are on time or delayed**

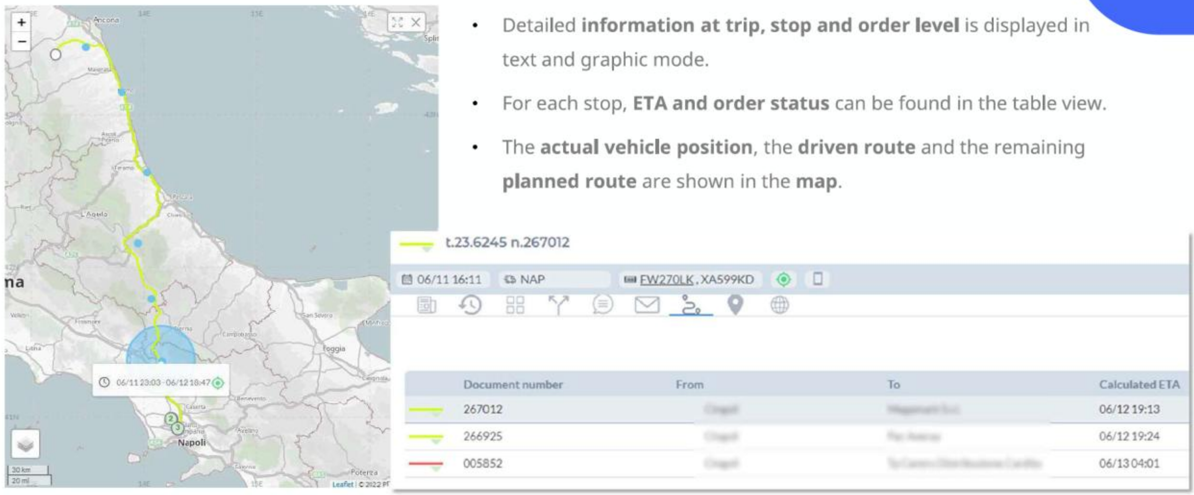
By **clicking** the **icon on the map**, **delivery details** an **ETA** can be seen.




PTV LOGISTICS

## Package 2: Trip Details

- Detailed **information at trip, stop and order level** is displayed in text and graphic mode.
- For each stop, **ETA and order status** can be found in the table view.
- The **actual vehicle position**, the **driven route** and the remaining **planned route** are shown in the **map**.




PTV LOGISTICS

# Package 2: Arrival and departure board

- Increase visibility with **"store" displays** in the **planning department or warehouse**.
- Keep track of your KPIs, arrival and departure boards with a single view.

## Custom Notifications, Alerts and Live Tracking

1

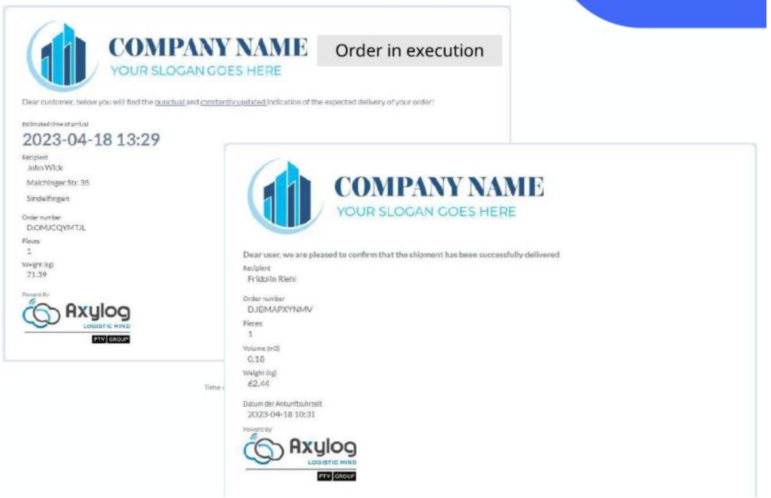
The product can create custom notifications and alerts – triggered by specific events that may occur during transport execution.

2

Such notifications can be sent to all stakeholders involved in the transportation value chain, such as internal staff, customers, consigners and consignees.

3

Notifications can include a link to a live tracking website which shows the Estimated Time of Arrival (ETA) to keep all stakeholders informed in real-time.




PTV LOGISTICS

# The project

ReMuNet identifies and signals disruptive events and assesses their impact on multimodal transport corridors. It reacts quickly and seamlessly upon disruptive events in real-time. It supports TMS providers to improve route planning resilience. ReMuNet communicates alternative, pre-defined, multimodal transport routes to logistics operators and subsequently to truck drivers, locomotive drivers and barge captains. Through this, it enables a faster and adaptive multimodal network response. ReMuNet orchestrates route utilization, suggests transshipment points and optimizes capacity allocation, minimizing damage and shortening the recovery time. What is ReMuNet's core objective? As trailblazer for the Physical Internet, ReMuNet pursues the vision to enable and incentivize synchro-modal relay transport on European rail, road, and inland waterways to increase the holistic network resilience. It significantly reduces emissions and boosts freight transport corridor efficiency in case of disruptive events. stakeholders to ensure Europe-wide practicability and acceptance.

Coordinator: FORSCHUNGSINSTITUT FUER RATIONALISIERUNG (FIR)

| PARTNER | | SHORT NAME |
|---|---|---|
| fir RWTH Aachen University | FORSCHUNGSINSTITUT FUER RATIONALISIERUNG | FIR |
| HANKEN | SVENSKA HANDELSHOGSKOLAN | HANKEN |
| PTV GROUP | PTV PLANUNG TRANSPORT VERKEHR GmbH | PTV |
| 4PL Intermodal | 4PL INTERMODAL GMBH | INT |
| MANSIO truck meets truck | MANSIO GMBH | MAN |
| Fraunhofer AUSTRIA | FRAUNHOFER AUSTRIA RESEARCH GMBH | FHA |
| HAFEN WIEN | HAFEN WIEN GMBH | HWI |
| WHITE | WHITE RESEARCH SRL | WRE |
| UIRR | UNION INTERNATIONALE DES SOCIETES DE TRANSPORT COMBINE RAIL-ROUTE SCRL | UIR |
| CONTARGO® trimodal network | CONTARGO GMBH & CO KG | CON |
| vedia | VEDIAFI OY | VED |

| | | |
|---|---|---|
| RØDE KORS | DANSK RODE KORS (DANISH RED CROSS) | DRC |
| FMI | ILMATIETEEN LAITOS | FMI |
| alice | ALLIANCE FOR LOGISTICS INNOVATION THROUGH COLLABORATION IN EUROPE | ETP-ALICE |
| SCHACHINGER LOGISTIK | SCHACHINGER IMMOBILIEN UND DIENSTLEISTUNGS GMBH & CO OG | SCH |