DIGITAL SOLUTIONS FOR MULTIMODAL FREIGHT TRANSPORT OPTIMISATION IN EUROPE: THE FOR-FREIGHT PLATFORM

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Executive Summary

The FOR-FREIGHT project, funded under the European Union's Horizon Europe programme (Grant Agreement No. 101069731), demonstrates how a new generation of digital technologies can reshape multimodal freight transport across Europe. By delivering a federated, service-oriented digital ecosystem, the platform interconnects ports, airports, terminals and logistics operators through AI-powered solvers, workflow-driven orchestration and trusted data-exchange mechanisms. In this way, FOR-FREIGHT moves beyond local optimisation tools and introduces a coherent digital layer that supports real-time, cross-modal coordination across the transport network.

A central innovation of the project is the introduction of Generalisable Solving Processes (SPs): abstract, reusable representations of logistics workflows that encapsulate tasks such as prediction, optimisation, planning and monitoring. These SPs serve as the conceptual blueprint for digitalising logistics processes. Through the FOR-FREIGHT Workflow Engine, the abstract process models are dynamically instantiated and bound to local systems, datasets and operational environments. This allows the same logical workflow—originally defined in one context—to be executed in a completely different setting, preserving the underlying sequence of tasks while adapting to local constraints. This paradigm transforms static process descriptions into living, executable digital workflows capable of harmonising heterogeneous data sources and responding dynamically to disruptions or changing operational conditions.

The FOR-FREIGHT Marketplace complements this orchestration layer by providing a unified catalogue of solvers and solving processes. Designed according to API-first principles, the marketplace ensures that every component can be invoked in a standardised way, with consistent interfaces and automatically generated user forms. This guarantees seamless integration within the platform and lowers the barrier for extending or reconfiguring workflows, supporting both developer productivity and ecosystem scalability.

The platform's technological maturity was demonstrated through three pilot deployments—Spain, Greece and Romania—each representing distinct multimodal corridors with unique operational requirements. In Spain, the platform was applied both to the port–hinterland corridor connecting Valencia with Madrid and to an innovative metro-based last-mile distribution model in the capital. Across these two environments, the integration of predictive solvers and digital-twin simulations enabled more accurate resource planning, tighter synchronisation of transport legs and more sustainable use of existing infrastructure. The results showed substantial reductions in greenhouse gas emissions, dramatic decreases in port container dwell times and a step-change in the efficiency of urban parcel distribution, where the use of the metro network demonstrated the feasibility of near-zero-emission last-mile logistics.

In Greece, the platform was validated along the time-critical multimodal corridor linking the Port of Piraeus with Athens International Airport. Here, the workflow engine orchestrated a chain of solvers for flight recommendation, warehouse capacity prediction, route optimisation, dwell-time estimation and real-time tracking. By turning a traditionally fragmented, manually coordinated process into a fully synchronised digital workflow, the platform significantly

reduced idle time at both the port and the airport, accelerated customs procedures and improved the reliability of urgent shipments. These operational gains translated into measurable increases in cargo handling capacity without requiring any physical infrastructure expansion.

The Romanian pilot focused on the inland waterway–rail corridor connecting Izmail in Ukraine with Galați in Romania. The platform demonstrated its ability to synchronise vessel arrivals, port operations and rail departures through AI-based ETA predictions, dwell-time modelling and resource planning. The conversion of static planning processes into dynamic, solver-driven workflows led to dramatic reductions in container idle time and overall transport duration, while also improving safety and accuracy throughout the corridor. By enhancing visibility and enabling proactive decision-making, the platform addressed longstanding inefficiencies in a complex cross-border logistics ecosystem.

Across all three deployments, FOR-FREIGHT delivered operational, environmental and economic benefits that illustrate the transformative potential of digitalisation in freight transport. The solver-based architecture enabled precise, data-driven planning, reducing delays, eliminating administrative errors and ensuring the reliable sequencing of intermodal operations. The integration of background data processing, predictive analytics and automated notifications supported faster decision cycles and improved coordination among stakeholders. In parallel, the demonstrated reductions in greenhouse gas emissions and idle time show that digital transformation is a powerful enabler of Europe's sustainability objectives, directly contributing to the modal shift and efficiency targets of the European Green Deal.

Beyond the tangible performance improvements, FOR-FREIGHT provides a strategic blueprint for Europe's future digital logistics architecture. By proving that abstract Solving Processes can be replicated across very different environments—from seaport-to-airport flows to inland waterway–rail corridors—the project establishes a model for scalable, transferable and interoperable digital workflows. This approach aligns with European initiatives on digital transport corridors, logistics data spaces and AI-enabled optimisation, offering a clear pathway toward an integrated digital layer for multimodal freight coordination across the continent.

Through its federated architecture, orchestrated solver chains and demonstration of real-world value, FOR-FREIGHT shows how fragmented logistics systems can evolve into intelligent, sustainable and interconnected ecosystems. By enabling the convergence of AI-driven optimisation, real-time data exchange and reusable workflow logic, the project sets the foundation for the next generation of multimodal freight operations in Europe and beyond.

1. Challenges in Multimodal Freight Transport

The European freight transport sector is undergoing a profound transformation driven by the need for greater efficiency, sustainability, and resilience. However, despite the clear benefits of multimodal logistics, the reality of operational execution remains fraught with complexity. The transition from unimodal optimisation to a fully synchronised multimodal network is currently hindered by a series of structural, technical, and organisational barriers. This chapter outlines the critical challenges that initiatives like FOR-FREIGHT seek to address.

One of the most persistent barriers to efficient multimodal transport is the fragmentation of the logistics chain. Currently, freight transport operates as a series of disjointed segments rather than a seamless continuum. Each mode of transport (maritime, rail, road, aviation) and each node (ports, airports, inland terminals) typically operates within its own "information silo," utilizing proprietary legacy systems that were designed to optimise local operations rather than facilitate cross-chain interoperability. This fragmentation means that data often remains trapped within the boundaries of a single organisation, preventing the holistic view required to optimise the entire logistics journey.

Closely linked to this structural fragmentation is the issue of inefficient coordination among the diverse stakeholders involved, including port authorities, terminal operators, freight forwarders, transport operators, and customs authorities. Coordination among these actors is often cumbersome, relying on manual communication channels such as phone and email rather than automated digital workflows. A significant root cause of this inefficiency is a lack of trust regarding data sovereignty. Stakeholders are frequently reluctant to share commercially sensitive operational data due to fears of losing competitive advantage or compromising security. This "trust gap" results in limited data sharing, leading to suboptimal planning and a reactive, rather than proactive, approach to logistics management.

This absence of trusted data sharing leads directly to a lack of real-time situational awareness across the supply chain. In many current operations, visibility is limited to specific segments of the journey, creating "black holes" where cargo status is unknown, particularly during transshipment between modes. This lack of end-to-end visibility prevents logistics managers from reacting promptly to disruptions such as traffic congestion, weather delays, or infrastructure bottlenecks. Without a unified, real-time view of cargo location and status, stakeholders cannot dynamically adjust routes or schedules, leading to cascading delays and the inability to provide accurate Estimated Time of Arrival (ETA) to final customers.

Beyond operational delays, these inefficiencies have severe environmental and economic implications. The pressure to reduce the carbon footprint of transport operations is intensifying under the European Green Deal, yet the lack of coordination in multimodal chains often results in inefficient resource utilisation, such as trucks running empty on return legs, longer-than-necessary waiting times at terminals, and suboptimal route selection. These inefficiencies drive up both operational costs and greenhouse gas (GHG) emissions. Furthermore, tight delivery time constraints in modern "just-in-time" supply chains exacerbate these issues, as operators may default to faster but more polluting modes (e.g., road-only transport) when multimodal options are perceived as unreliable or too complex to coordinate.

Additionally, there is a significant "digital divide" within the logistics ecosystem. While major hubs and large logistics operators may utilise advanced digital platforms, smaller actors, such as local trucking companies or smaller inland terminals, often lack the resources to adopt state-of-the-art technologies. This digitalisation gap creates weak links in the supply chain, where digital information flows are interrupted by manual processes. Consequently, the integration across different modes and actors remains limited, making it difficult to orchestrate complex multimodal operations that require the synchronised participation of actors with vastly different technological maturity levels.

Finally, even where digital tools exist, the absence of universally adopted standards for data exchange and operational processes acts as a major technical barrier. The logistics industry is characterised by a fragmented landscape where different systems use incompatible data formats, ontologies, and communication protocols. This lack of standardisation complicates the integration of disparate systems, increases the cost of IT solutions, and hinders the scalability of digital platforms. Without common standards, the automatic exchange of information between a port management system and a rail operator's scheduling tool, for example, becomes a costly custom integration project rather than a seamless plug-and-play operation.

2. The FOR-FREIGHT approach: Solvers, Generalisable solving processes, FOR-FREIGHT Marketplace and Workflow Engine

The FOR-FREIGHT platform is built upon a structured service taxonomy that distinguishes between four foundational concepts: **Solvers** and **Solving Processes (SPs)** define how logistics intelligence is modularized across multimodal transport environments; the **FOR-FREIGHT Marketplace** exposes those components to the outside world offering adaptable solutions for a diverse range of T&L operations. Last but not least, **the Workflow Engine** is the "brain" of the platform, defines how those solvers and SPs are orchestrated into end-to-end operational workflows and is also provided to the stakeholders for tailoring the acquired from the Marketplace SPs to their specific needs.

Solvers: Modular Decision-Support Services

Solvers constitute the smallest functional units within the FOR-FREIGHT ecosystem. Each solver encapsulates a specific analytical or operational capability—ranging from a lightweight API service to more sophisticated components that integrate AI/ML models, data stores, or optimisation algorithms. Their purpose is to address well-defined problems in the transport and logistics chain, such as ETA prediction, dwell-time estimation, route optimisation, capacity forecasting, or emissions calculation.

To ensure interoperability and seamless integration into larger workflows, all solvers adhere to a strict set of architectural principles. They expose standardised API endpoints, employ consistent input–output structures (JSON-based), and follow an API-first design approach. This ensures that solvers can be invoked programmatically, combined into composite workflows, and reused across pilots and operational contexts.

Once development reaches maturity, solvers are deployed within the platform's Kubernetes infrastructure using customised Helm charts. This automated deployment framework not only provisions the required compute resources but also configures ingress rules for secure, controlled access by authorised users. After deployment, solvers are registered in the platform's **Solver Marketplace**, completing their onboarding and enabling UI-driven invocation.

Solving Processes: Orchestrated, Multi-Step Digital Workflows

While solvers deliver discrete capabilities, **Solving Processes** represent their operational synthesis. An SP is a model-driven, multi-step workflow that combines several solvers—alongside external legacy systems or third-party applications where necessary—into a coherent end-to-end decision-support pipeline.

Solving Processes leverage the modularity of the underlying architecture to provide enriched outputs that no single solver could produce alone. By structuring the flow of data, connecting solver outputs to downstream solver inputs, and unifying disparate services under a single execution context, SPs deliver user-friendly, operationally meaningful solutions to complex logistics scenarios. They serve as the primary mechanism through which the platform realises generalisable, reusable digital workflows.

The FOR-FREIGHT Marketplace: A Federated Catalogue of Capabilities

The **FOR-FREIGHT Marketplace** serves as the authoritative registry for both solvers and solving processes. It enables the platform to dynamically generate user interfaces, automate the discovery of available services, and expose detailed metadata—including functional descriptions, intended use cases, endpoint specifications, and expected inputs/outputs.

Through this marketplace, solvers become discoverable, composable, and transparently integrated into the platform's operational environment. The marketplace forms the backbone of FOR-FREIGHT's federated architecture, ensuring that all components—regardless of origin or complexity—adhere to a unified integration model.

The Workflow Engine: Orchestrating End-to-End Solving Processes

At the core of the platform's orchestration capability lies the **Workflow Engine (WE)**, a key component enabling the creation, configuration, and execution of Solving Processes. Built upon and extended from the open-source Node-RED framework, the Workflow Engine offers a visual, flow-based development environment optimised for event-driven logistics applications.

Through the platform's graphical interface (Figure 1), users with the appropriate developer role can construct SPs by chaining solvers in sequential or parallel configurations. This environment enables developers to specify data flows, conditionally route outputs, and integrate multi-layered analytical steps into sophisticated, real-time decision-support pipelines.

Within FOR-FREIGHT, the Workflow Engine operationalises the concept of generalisable solving processes: once designed and deployed, an SP becomes immediately available to the broader platform—invocable via the standard user interface without any additional integration effort. This ensures rapid expansion of platform capabilities and supports the continuous evolution of domain-specific and cross-domain logistics workflows.

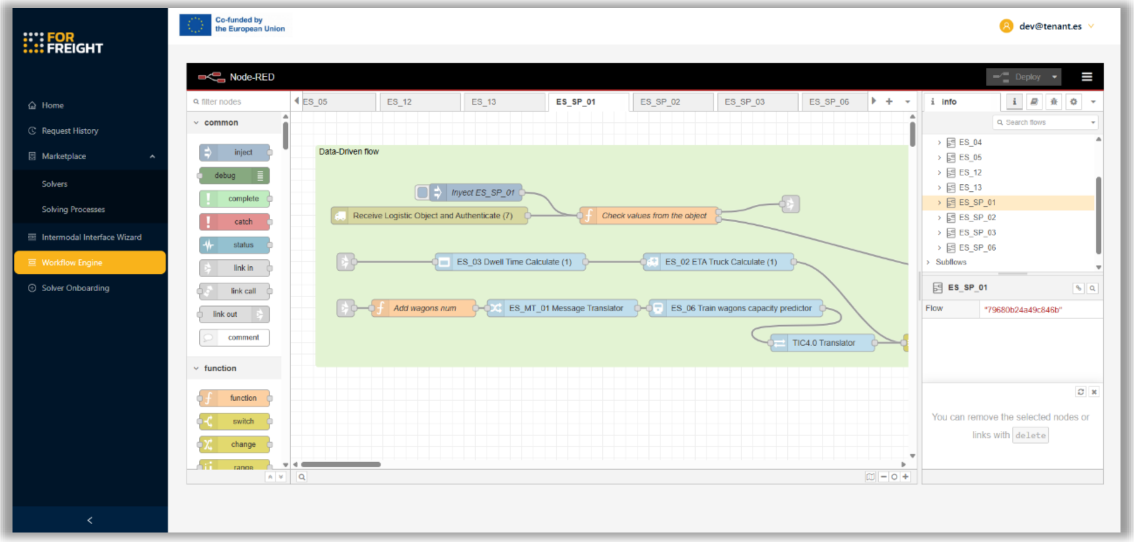

Figure 1 FOR-FREIGHT Platform: Workflow Engine UI

Once a Solving Process (SP) is designed and deployed via the Workflow Engine, it becomes a first-class, platform-wide capability. Newly created SPs are automatically exposed through both the Intermodal Interface Wizard and the Solving Process Marketplace, enabling users to invoke them using the standard graphical workflow - selecting a process, providing the required inputs, and executing it - without any additional integration effort. This seamless transition from development to operational use illustrates the architectural principle behind FOR-FREIGHT: every new workflow defined by a developer becomes an immediately reusable digital asset for the entire ecosystem. In doing so, the Workflow Engine continually expands the platform's functional repertoire, enabling partners to operationalize custom pipelines and progressively enrich the shared catalogue of multimodal optimisation services.

3. Use Case Scenarios and Pilot User Stories

The technological maturity of the FOR-FREIGHT architecture is demonstrated most clearly through the implementation and validation of SPs in the project's three pilot deployments. Each pilot represented a distinct operational environment - port-to-hinterland coordination in Spain, seaport-to-airport synchronisation in Greece, and inland waterway–rail integration in Romania - providing a rigorous testbed for assessing the adaptability, robustness, and transferability of the platform's components. Collectively, these deployments demonstrated how solver-driven intelligence, orchestrated through the Workflow Engine, can transform fragmented multimodal operations into integrated, data-driven logistics ecosystems.

In Spain, FOR-FREIGHT was applied along two interconnected logistics systems: the critical freight corridor linking the Port of Valencia with the Madrid hinterland, and an innovative urban last-mile distribution model based on the Metro de Madrid network. Across both contexts, a comprehensive suite of AI-driven solvers - covering vessel and truck ETA prediction, container dwell-time modelling, multimodal route optimisation, digital-twin–based capacity forecasting, real-time container and roller-cage tracking, demand prediction, workforce planning, and blockchain-enabled document management—was orchestrated into coherent solving processes. Through a combination of real-world trials and large-scale digital-twin simulations, the Spanish deployment demonstrated how FOR-FREIGHT enables end-to-end optimisation, provides continuous real-time visibility across transport legs, and supports trusted coordination among stakeholders operating along long-haul freight corridors and dense urban distribution networks.

The Greek pilot focused on the strategically important corridor linking the Port of Piraeus to Athens International Airport—an environment in which the reliable and sustainable transfer of high-value goods between maritime and air transport is essential. Three solving processes were implemented, integrating solvers for ETA prediction, cargo dwell-time estimation, warehouse capacity evaluation, flight recommendation, route optimisation, CO_2-emission estimation, and real-time vehicle tracking. Orchestrated through the Workflow Engine, these components ensured the precise sequencing of solver executions and the smooth flow of data between them. The resulting workflows dynamically adapted to live information from on-board units and sensor networks deployed along the corridor, supporting real-time operational decisions. The Greek deployment thus demonstrated how FOR-FREIGHT creates a unified digital continuum across transport modes, transforming disparate data streams into synchronised, actionable intelligence for international freight handling.

The Romanian use case examined the multimodal freight corridor linking Izmail (Ukraine) with Galați (Romania), a complex environment where inland waterway transport, port operations, and rail logistics must operate in tight coordination. Three AI-driven solving processes were deployed, integrating real-time container tracking, vessel and train ETA prediction, cargo dwell-time estimation, port resource forecasting, and multi-criteria rail route optimisation. The Workflow Engine orchestrated these components into a coherent predictive pipeline, ensuring consistent sequencing of analytical steps and continuous data mediation across modes. By providing a unified operational picture from vessel departure to onward rail movement, the Romanian pilot validated the platform's ability to create a seamless digital continuum across waterways, ports, and rail logistics—turning previously isolated data sources into a synchronised, predictive decision-support framework for sustainable multimodal transport.

The Spanish UC: Port of Valencia Logistics Chain

The Spanish Use Case consists of two complementary scenarios:

Scenario 1 focuses on Multimodal transport chain from the Port of Valencia to the Madrid hinterland, supported by ETA prediction, Digital Twin simulations, route optimisation, and real-time tracking. Scenario 2's focus is on innovative Metro de Madrid last-mile logistics model, integrating rail-based parcel distribution with route optimisation, demand prediction, and new operational business models.

For illustrative purposes and to explain how the FOR-FREIGHT solving process operates, this section focuses on Scenario 1, demonstrating how the solving processes guide the end-to-end transport of a container from vessel arrival at the Port of Valencia to its final delivery point in Madrid.

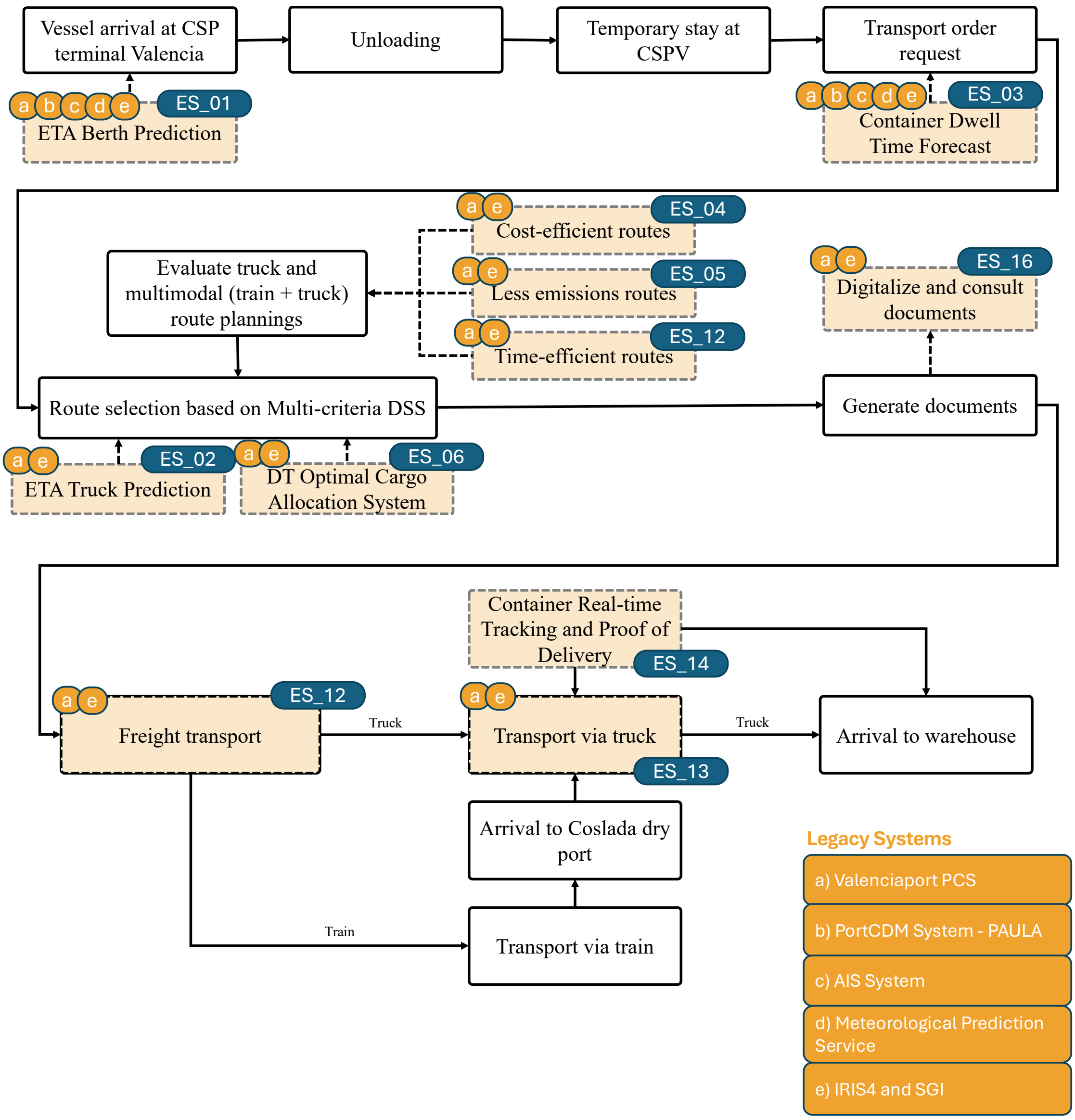

Figure 2 Process flow and legacy systems of the Spanish Final Trial - Scenario 1

Step 1: ETA-Informed Time Planning Forecast (SP6)

The process begins with the use of ETA-related solvers: ETA Berth Predictor, ETA Truck Predictor, and Container Dwell Time Estimator. These tools provide precise forecasts on vessel berthing times, truck arrival times, and expected dwell times at the terminal. This predictive visibility allows port operators, terminal planners and inland transport providers to prepare resources in advance, optimise shift allocation and minimise bottlenecks in planning the first leg of the transport chain.

Step 2: Digital Twin Optimal Cargo Allocation System and ETA-Informed Planning in Truck and Train Routes (SP1)

Stakeholders could use the Digital Twin to simulate operational conditions and determine the optimal allocation of cargo between trucks and trains departing from the port. By integrating accurate ETA predictions and truck/train configurations, the system helps operators decide how many trains or trucks are needed, when they should depart, and how resources should be deployed to minimise delays.

Step 3: Optimal E2E Multimodal Planning System (SP2)

Once capacity and timing are defined, the user triggers the Optimal E2E Multimodal Planning System (SP2) to identify the best route from the Port of Valencia to Madrid. The solver compares truck-only and multimodal (train + truck) options based on time, cost, and GHG emissions.

Step 4: Optimal Dynamic E2E Multimodal Planning System (SP3)

During transport, real-time updates are enabled through SP3, which dynamically recalculates the optimal route based on the container's actual position and surrounding conditions. Based on the current position, SP3 modifies the recommended route accordingly and provides an updated set of times, costs and emissions.

Step 5: Stakeholder Collaboration Platform for Intermodality (SP5)

Finally, the Stakeholder Collaboration Platform supports the digitalisation of all transport-related documents, such as DUT, COARRI or ITD. This platform automates document exchange, ensures secure communication between actors, and centralises operational data. By replacing manual processes and fragmented communication channels, this step provides transparency, traceability and coordinated intermodal operations among port operators, carriers, terminals and related logistics stakeholders.

The Greek UC: Port to Airport Urgent Cargo Flow

This scenario demonstrates how the FOR-FREIGHT platform coordinates an urgent shipment of spare parts from the port of Piraeus to Amsterdam via Athens International Airport (AIA), involving a freight forwarder (COSCO) and an airport cargo handler (Goldair Handling).

Step 1: Flight Recommendation (SP2)

A freight forwarder at COSCO initiates the process on the platform to find a feasible flight. The Flight Recommendation solver analyses the required delivery window, cargo readiness time, and real-time schedules. It calculates the total time needed for warehouse processing, road transit, and airport handling, then returns a list of suitable flights from AIA that meet all deadlines. The forwarder selects the optimal flight and proceeds with the booking.

Step 2: Automated Notification (SP1)

Once the flight is confirmed, COSCO enters the details into the platform. The system automatically triggers a notification to the export supervisor at Goldair Handling's cargo terminal. This notification contains all critical information: cargo ID, specifications, the truck's estimated time of arrival (ETA), and aircraft details. This advance visibility allows the airport team to pre-allocate storage space, book screening slots, and schedule staff accordingly, eliminating manual coordination via phone and email.

Step 3: Real-Time Tracking and Dynamic ETA (SP3)

COSCO dispatches the truck, which is equipped with a real-time tracker. The forwarder selects a delivery priority (e.g., Fastest Route). The FOR-FREIGHT platform computes the optimal route from Piraeus to AIA and displays the truck's live position on a map. As the truck travels, its ETA is dynamically updated based on live traffic data. If a delay is detected, the system automatically alerts the airport cargo handler, allowing them to adjust their resource planning in real time.

This end-to-end, digitally orchestrated process ensures that all stakeholders have a shared, real-time view of the operation, enabling proactive decision-making and guaranteeing the on-time arrival of critical, high-value goods.

By integrating predictive analytics, real-time tracking, and automated communication, the platform transformed a fragmented, manual process into a synchronised, data-driven workflow, shown in Figure 3.

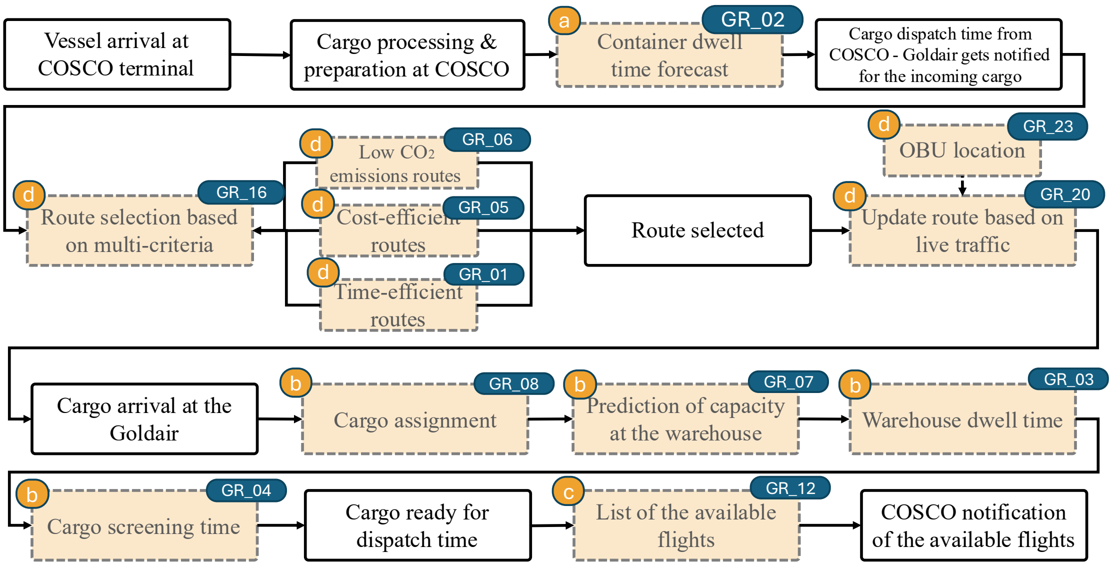

Figure 3 Greek UC data driven workflow

The Romanian UC: Smart Multimodal Logistics on the Danube Corridor

The Romanian Use Case focuses on the inland waterway and rail transport corridor linking the Ukrainian Port of Izmail to the Romanian Port of Galați and further toward the national railway network. The chain relies on precise ETA prediction for vessels and trains, accurate modelling of cargo dwell times, resource planning for port and rail operations and optimal rail route selection toward inland destinations. Three solving processes (RO_SP_01, RO_SP_02 and RO_SP_03) work together to support the end-to-end planning and execution of container handling, from vessel departure in Ukraine to the onward movement of the freight by rail in Romania.

For illustrative purposes, and to explain how the FOR-FREIGHT solving process operates, this section focuses on the Romanian multimodal scenario, demonstrating how the solving processes guide the transport of a container from Izmail to Galati and subsequently toward inland rail destinations.

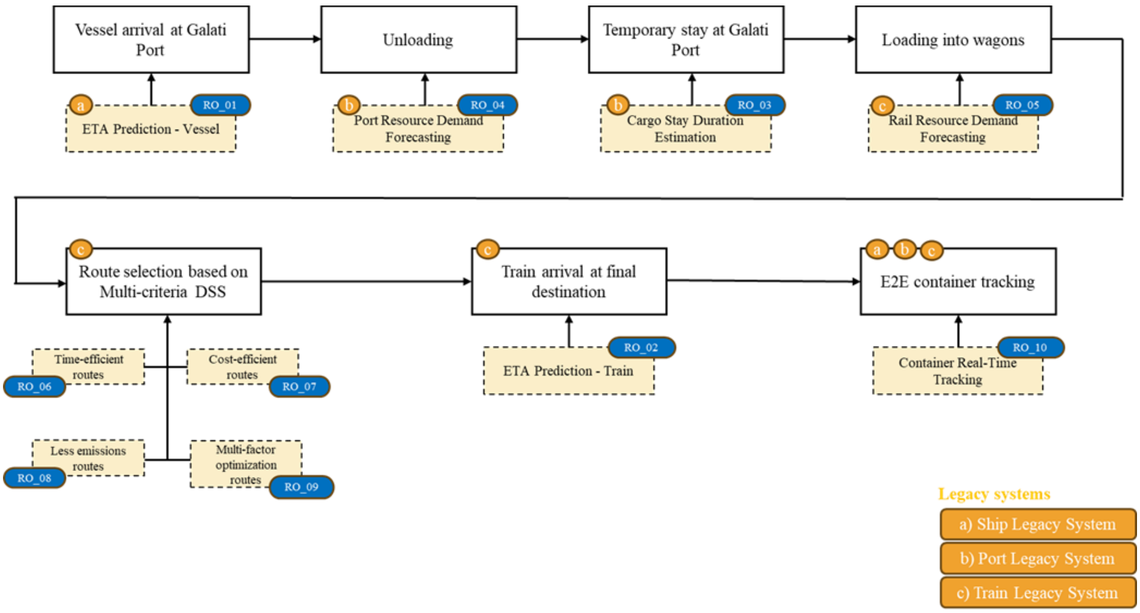

Figure 4 Process flow and legacy systems of the Romanian use-case

Step 1: ETA-Informed Multimodal Synchronisation (RO_SP_01)

The process begins with RO_SP_01, which integrates vessel ETA prediction, container dwell-time estimation and real-time container tracking. As the vessel departs Izmail, the solving process generates a unified timeline that anticipates the vessel's arrival at the Port of Galati, the expected container handling duration and the onward train departure ETA.

This upfront visibility allows port operators, terminal stakeholders and rail coordinators to synchronise operations between the waterborne and rail legs of the transport chain, reducing uncertainty and preparing for the incoming workload before the vessel reaches Romanian waters.

Step 2: Port and Rail Resource Planning (RO_SP_02)

Once the vessel's arrival window and estimated dwell time are known, RO_SP_02 is activated to anticipate operational needs within the Port of Galati. The solving process combines predictions from the vessel ETA module, unloading duration estimations and rail capacity forecasting to determine the required levels of port labour, equipment availability and rail resources.

By aligning these resource predictions with upcoming vessel arrivals, RO_SP_02 helps minimise idle time, prevents congestion and ensures that unloading teams, cranes and rail slots are allocated efficiently across shifts.

Step 3: Optimal Rail Route Recommendation (RO_SP_03)

After the container is processed and ready for its inland journey, RO_SP_03 identifies the best rail route toward its final Romanian destination. The solving process evaluates routing alternatives across single or multiple rail connections, considering time efficiency, transport cost and CO_2 emissions.

Users can compare routes optimised for minimum time, minimum cost, minimum emissions or a balanced multi-objective option. This supports informed decision-making on how the container should continue its journey from Galați, enhancing both operational efficiency and sustainability objectives along the rail corridor.

Step 4: Integrated Operational Continuum Across the Corridor

Throughout the logistics chain, the Workflow Engine ensures the seamless orchestration of RO_SP_01, RO_SP_02 and RO_SP_03. The solving processes exchange data through automated pipelines, allowing each step to respond dynamically to updates such as navigation delays, port congestion or rail schedule changes. The system continuously recalculates timelines, resource needs and route options, providing a coherent operational picture from vessel departure to rail delivery.

This orchestrated configuration validates how the FOR-FREIGHT platform enables an end-to-end digital continuum across the Romanian multimodal corridor, turning fragmented data sources into coordinated decision-support tools for daily freight operations.

4. Key Results and performance highlights

Spain: Port of Valencia logistics chain & urban metro distribution

The Spanish Use Case validation was divided into two distinct scenarios: optimising the port-to-hinterland flow from the Port of Valencia (Scenario 1) and piloting a novel metro-based last-mile delivery system in Madrid (Scenario 2). Both scenarios leveraged the FOR-FREIGHT platform to integrate legacy systems with advanced predictive solvers, achieving significant operational and environmental gains.

Scenario 1: Port of Valencia to Madrid Hinterland

This scenario focused on the multimodal transport of containerised cargo from the Port of Valencia to the Madrid region. The validation incorporated a comprehensive suite of solvers, including ETA prediction for vessels and trucks (ES_01, ES_02), container dwell time estimation (ES_03), and a Digital Twin for capacity planning (ES_06). By processing real-time data from daily transport operations and sensorised trucks, the platform successfully optimised the decision-making process between road-only and multimodal (rail+road) transport.

Operational results from the final trials demonstrated a 47.79% reduction in GHG emissions when utilising the multimodal route suggested by the platform compared to the road-only baseline. This massive reduction validates the platform's ability to operationalise sustainability goals. Efficiency was improved through predictive intelligence; the use of accurate ETA berthing predictions and dwell time forecasts allowed for better synchronisation of port resources. Specifically, the average container dwell time at the port was reduced by 80.52% (from ~9.6 days to ~1.9 days) thanks to the just-in-time planning enabled by the Digital Twin simulations. Furthermore, the time required to set up end-to-end multimodal transport was reduced by 22.20%, streamlining the administrative and planning burden on logistics operators. Finally, the integration of the Blockchain-enabled Stakeholder Collaboration Platform (ES_16) achieved 100% digitalisation of transport orders, replacing fragmented physical documentation with a unified digital workflow.

Scenario 2: Metro de Madrid last-mile delivery

The second scenario validated a disruptive logistics model: utilising the Metro de Madrid network for parcel distribution to reduce urban congestion. This pilot required precise orchestration between DHL's logistics network and the public transport infrastructure, managed by FOR-FREIGHT's demand prediction (ES_08), workforce planning (ES_09), and real-time tracking (ES_15) solvers.

The results confirmed the viability and high impact of this model. The trials achieved an 85.65% reduction in CO_2 emissions compared to standard van-based delivery, proving the potential of "zero-emission" urban logistics. Operational efficiency gains were equally impressive; the optimised loading and routing strategies led to a 61.73% reduction in the number of delivery vehicles required for the same parcel volume. Consequently, the operational cost per parcel dropped by 45.78%, making the model economically attractive. Service reliability also improved significantly, with a 49.5% reduction in missed deliveries, attributed to the better coordination between metro schedules and locker availability facilitated by the platform.

Greece: Port to airport urgent cargo flow

Validation in the Greek use case focused on the critical, time-sensitive logistics corridor connecting the Port of Piraeus with Athens International Airport (AIA). The trials demonstrated that the FOR-FREIGHT platform can successfully orchestrate complex, multi-stakeholder operations to significantly enhance efficiency, reliability, and predictability for high-value air-sea cargo.

The results, depicted in Table 1 measured against established operational baselines, show substantial improvements across key performance indicators.

Table 1 Greek UC Key Performance Indicators

KPI	Baseline	Achieved Result	Improvement
Cargo Idle time at port	1-3 working days	1.59 days	25.7% reduction
Cargo idle time at airport	4-6 hours	3.86 hours	29.5% reduction
Customs clearance time	3.5 hours	1.18 hours	66% Reduction
Personnel handling time	1.75	1.25	40% Reduction
Annual cargo handling capacity	40,000 tonnes/year	46,289 tonnes/year (projected)	15.7% increase
Mishandling & delay-causing errors	40 incidents/year	0 incidents recorded	100% reduction (during trial)

Performance analysis & operational impact

Synchronized operational flow: The 25.7% reduction in port idle time and 29.5% reduction in airport idle time confirms the value of the "chained" prediction models. By accurately forecasting the "Ready-to-Fly" time, the freight forwarder could schedule truck pickups precisely when the cargo was cleared, rather than padding the schedule with excessive buffer time.

Resource optimization & capacity growth: The trial data revealed that personnel required 40% less time to handle a shipment because resources were pre-allocated based on accurate ETAs rather than reacting to truck arrivals. This was largely driven by the automated arrival notification process (SP1), which pushed high-precision ETAs directly to the airport handlers hours in advance, allowing for the precise reservation of unloading docks and screening staff guided by the warehouse capacity predictor. This efficiency gain directly translates to scalability; the pilot projects a 15.7% increase in the airport hub's annual cargo handling capacity without requiring physical infrastructure expansion.

Technical reliability: Beyond logistics metrics, the platform demonstrated exceptional technical robustness. Across all trials, the solvers achieved 100% service availability and 100% API success rates, proving that the system is stable enough for mission-critical commercial operations. The system's robustness was further validated by the real-time route optimizer, which successfully processed live traffic data to dynamically adjust routes without service interruption, ensuring transparency even during traffic congestion events.

Romania: Smart multimodal logistics on the Danube corridor

The Romanian use case addressed the optimisation of a complex intermodal corridor linking the inland waterways of the Danube to the European railway network via the Port of Galați. This pilot focused on improving transhipment efficiency, reducing bottlenecks at the port-rail interface, and enhancing visibility across a cross-border supply chain often plagued by uncertainties. The trial deployed a full suite of solvers, including ETA prediction for vessels and trains, cargo stay duration estimation, resource demand forecasting, and multi-criteria route optimisation.

Operational performance and efficiency

The most significant achievement in the Romanian trial was a 60.7% reduction in end-to-end transport time. By integrating AI-based ETA predictions with real-time tracking, the platform replaced static, historical averages with dynamic planning. This allowed for tighter synchronisation between vessel arrivals and train departures. Consequently, the container idle time at the port was reduced by 88.6% (from a baseline of ~30 days to ~3.4 days), and the ITU dwell time decreased by 87.7%. These drastic reductions highlight the platform's ability to eliminate the "black holes" of visibility that typically cause cargo to stagnate at transhipment nodes.

Safety, accuracy, and resource management

The platform also proved instrumental in mitigating operational risks. The baseline KPI for routing errors and accidents was approximately 15%; however, during the trials, the system recorded 0 routing errors or accidents. This was achieved through continuous, real-time container tracking which provided immediate alerts on deviations, ensuring cargo remained on the correct path. Furthermore, the loading and unloading times at terminals were improved by 21.86%, as the resource demand forecasting solvers allowed terminal operators to allocate cranes and crews in advance of vessel arrivals, smoothing out peaks in demand.

Environmental impact

Sustainability was a core component of the routing strategy. The trial utilised solvers to optimize train selection based on CO_2 emissions and fuel consumption. By prioritising electrified rail routes and optimising train loads based on solver recommendations, the trial supported a transition toward greener transport options. Additionally, the trial demonstrated the feasibility of reducing the environmental impact of refrigerated transport, achieving a 45.13% reduction in potential emissions from F-gases by integrating data on newer, lower-GWP refrigerants into the decision-making framework. Finally, the project successfully digitalised the communication infrastructure between port and rail authorities, moving from manual phone/email coordination to a unified digital platform, thereby increasing transparency and trust among stakeholders.

5. Business Value & Exploitation Paths

The FOR-FREIGHT platform introduces a new generation of digital capabilities for multimodal logistics, delivering concrete business value across operational, financial, and sustainability dimensions. By integrating predictive analytics, solver-driven optimisation, and seamless data exchange across traditionally fragmented systems, the platform enables each category of logistics stakeholder to unlock benefits that were previously unattainable due to siloed processes and limited interoperability.

For **port and terminal operators**, FOR-FREIGHT provides a transformative shift from reactive coordination to anticipatory, data-driven planning. Predictive solvers for ETA estimation, container dwell time, and resource allocation allow operators to optimise gate operations, crane and warehouse utilisation, and truck appointment systems. These capabilities directly translate into increased throughput and higher cargo handling capacity without requiring physical expansion. With improved visibility into truck arrivals and terminal activity, congestion is reduced and operational bottlenecks can be proactively mitigated. In this way, the platform strengthens terminals' ability to operate efficiently under fluctuating demand and evolving supply-chain pressures.

Freight forwarders gain substantial value through improved reliability, transparency, and service differentiation. Real-time tracking combined with accurate, continuously updated ETAs enables forwarders to provide their customers with dependable delivery commitments and fewer exceptions. The multi-criteria optimisation solvers help identify the best combination of modes, routes, and schedules—balancing cost, transit time, and environmental impact. This empowers forwarders to reduce avoidable delays, optimise their operational expenditure, and enhance competitiveness in tendering processes. As sustainability becomes a key criterion in logistics procurement, the ability to quantify and select low-emission routing options also supports forwarders in meeting growing ESG requirements and customer expectations.

For **logistics and shipping companies**, the platform functions as a unifying operational layer that delivers end-to-end visibility across multimodal chains. Instead of navigating multiple disconnected systems and communication channels, operators gain a single digital environment where events, alerts, and operational status updates converge. This consolidation improves resilience, as dynamic re-routing and disruption management solvers allow quick adaptation to incidents such as traffic congestion, delays at ports, or last-minute schedule changes. Furthermore, the digitisation of documentation—supported by a collaborative communication interface—reduces administrative workload and minimises human errors during handovers between actors. These benefits collectively increase service reliability, compress lead times, and strengthen performance in contract-driven operations.

Overall, the business value of FOR-FREIGHT lies in its ability to convert fragmented, manually coordinated chains into synchronised, intelligent logistics ecosystems. Its solver-based architecture and generalisable solving processes position the platform for wide exploitation in core logistics sectors and beyond, offering operators the tools to enhance efficiency, reduce costs, and support the transition toward greener and more resilient transport networks.

6. Lessons Learned & Recommendations

The deployment and validation of the FOR-FREIGHT platform across three diverse European corridors, Spain, Greece, and Romania, have generated a wealth of operational and technical insights. By testing 37 distinct solvers in real-world environments, ranging from maritime hubs to urban last-mile networks, the project has identified critical success factors and persistent barriers for the digitalisation of multimodal logistics. This chapter synthesises these findings into actionable lessons and recommendations, focusing on technical deployment, stakeholder engagement, and the architecture of future digital platforms.

6.1 Lessons from Technical Deployment

The technical validation confirmed that modular, service-oriented architectures are the most effective path to scalability, yet significant challenges remain regarding latency and transferability.

Modular Design and API-First Integration are Prerequisites for Scale: The trials demonstrated that solvers designed with modular architectures and standardised interfaces (API-first) achieved the highest levels of interoperability and adaptability. Solvers that utilised simple, standard data formats like JSON and CSV for data exchange were integrated significantly faster than those relying on proprietary or complex schemas. This "loose coupling" allowed for the rapid replacement or upgrading of individual components without disrupting the broader ecosystem, a critical feature for heterogeneous logistics networks.

Future deployments should mandate an "API-first" approach for all components, enforcing strict adherence to open standards (e.g., OpenAPI) and common data models from day one to minimise integration friction.

Mitigating Latency in Compute-Heavy AI Models: A key technical challenge identified was the high latency in compute-heavy solvers, particularly those running complex AI algorithms for ETA prediction or real-time optimisation. In some instances, synchronous execution of these models blocked operational workflows, creating unacceptable delays for real-time decision-making.

To support real-time operations, heavy AI models must be optimised using strategies such as model pruning, quantisation, and asynchronous execution. Architecture designs should offload intensive computations to background processes, ensuring that the user interface and core workflow engine remain responsive.

Overcoming Barriers to Transferability: While many solvers proved highly transferable, Machine Learning models trained on strictly local historical data (e.g., specific port congestion patterns or local rail timetables) struggled to perform accurately when moved to new sites without retraining. Similarly, solutions with hard hardware dependencies (e.g., specific crane automation protocols) required bespoke, site-specific adaptation.

The "plug-and-play" deployment of AI in logistics is a myth unless accompanied by automated pipelines. Future platforms should include automated data ingestion and retraining pipelines (MLOps) as part of the standard deployment package, allowing models to rapidly "learn" the local context of a new site using local data.

6.2 Lessons from End-User Engagement

The FOR-FREIGHT experience underscored that successful digital transformation depends as much on change management as it does on technology. Continuous engagement was the single most important factor in driving adoption.

Co-Design Builds Trust and Ownership: The most successful trials occurred where end-users were treated not as passive customers but as active co-designers. In the Greek and Spanish use cases, deep-dive workshops and iterative "lean start-up" validation cycles allowed technical partners to align solver functionality with actual daily pain points. This participatory approach transformed skepticism into ownership, as operators saw their specific feedback implemented in subsequent software releases.

Digital initiatives must move beyond a "deliver and train" model to a "co-create and iterate" model. Stakeholder engagement plans should include structured feedback loops at every development phase, ensuring that the technology evolves in lockstep with operational reality.

Navigating the Data Sharing Trust Gap: A persistent barrier to engagement was the reluctance of commercial stakeholders to share sensitive operational data. The project overcame this by starting with non-sensitive datasets to demonstrate value before requesting deeper integration.

To build trust, platforms should implement granular data sovereignty controls, allowing owners to define exactly who sees what. Furthermore, engagement strategies should focus on demonstrating the "mutual benefit" of sharing - showing clearly how a terminal operator’s data helps a haulier, and vice versa, creating a reciprocal value ecosystem.

Focus on Tangible Business Value: Engagement waned when discussions became overly technical but surged when the conversation shifted to business outcomes. Stakeholders were most motivated when presented with clear metrics: reduced idle time, lower fuel costs, or eliminated administrative errors.

Technical complexity should be abstracted away. User engagement must focus relentlessly on the "Value Proposition", quantifying the time and cost savings delivered by the solution rather than the sophistication of the underlying algorithms.

6.3 Recommendations for Future Digital Logistics Platforms

Looking beyond FOR-FREIGHT, the following recommendations provide a blueprint for the next generation of European digital logistics platforms.

Standardise to Conquer Information Silos: The fragmentation of the logistics sector remains the primary obstacle to efficiency. Future platforms must act as "connective tissue," bridging legacy silos through harmonised data models.

Future platforms should adopt a "federated" approach, utilizing shared community platforms and standard data models (e.g., UN/CEFACT, FEDeRATED) to integrate legacy systems without requiring their replacement. This lowers the barrier to entry for SMEs and less-digitalised actors.

Prioritise Developer Experience for Ecosystem Growth: The speed of innovation in logistics depends on how easily third-party developers can build upon existing platforms. The validation phase highlighted that complex onboarding slows down ecosystem growth.

Platforms should invest in a robust Developer Portal, interactive API documentation, and sandbox environments. Reducing the "time-to-integration" from weeks to hours will catalyse a vibrant market of third-party apps and services.

Embed Resilience and Compliance by Design: In an era of supply chain disruptions, digital platforms must be resilience-engines, not just optimisation-engines.

Future platforms should embed compliance and resilience features, such as blockchain-based audit trails and predictive disruption alerts, into the core architecture. Automation of regulatory reporting (e.g., eFTI compliance) should be a standard feature, reducing administrative burdens and increasing the platform's stickiness.

From Static Tools to Dynamic Ecosystems: Finally, the static view of logistics optimisation must be replaced by dynamic, self-learning ecosystems.

Future platforms should transition from static "tools" to dynamic "ecosystems" where Solving Processes are treated as reusable digital assets. By enabling the cross-border sharing of successful workflow templates (e.g., a "Port-Rail Synchronization" process), Europe can accelerate the replication of best practices across its entire logistics network.

7. Sustainability and Policy Relevance

The validation of the FOR-FREIGHT platform and its solvers offers a tangible blueprint for transforming the European logistics sector into a model of efficiency and environmental stewardship. By proving that digital transformation directly drives decarbonisation and resource optimisation, the project establishes a validated pathway for reducing the ecological footprint of freight operations while enhancing their economic resilience.

Aligning with the European Green Deal's target to reduce transport emissions by 90% by 2050, FOR-FREIGHT provides the digital infrastructure needed to shift cargo to sustainable modes and optimise transport efficiency. The project supports three core policy pillars:

First, it facilitates Modal Shift by making multimodal transport as reliable as road haulage. In the Valencia-Madrid corridor, the Train/Truck Capacity Predictor (ES_06) empowered planners to prioritise rail options, supporting the EU's goal to double rail freight traffic. Second, it enhances Operational Efficiency for "zero-emission logistics" in urban centres. The Spanish metro-based last-mile pilot utilised existing public infrastructure to remove vans from streets, aligning with EU urban mobility frameworks. Third, it leverages Digitalisation as an Enabler, operationalising the "Common European Mobility Data Space" vision by proving that secure data exchange unlocks system-wide sustainability gains.

Additionally, FOR-FREIGHT demonstrated measurable reductions in carbon emissions and waste in operational environments. Intelligent logistics led to significant decarbonisation across the trials. The metro-based last-mile scenario achieved an impressive 85.65% reduction in CO_2 emissions compared to standard delivery, proving that data-driven models can nearly eliminate urban carbon footprints. Similarly, the long-haul corridor from Valencia to the DHL warehouse saw a 47.79% reduction in GHG emissions through route optimisation and modal shift tools. Predictive solvers further empowered operators to proactively make "green routing" decisions. Digital tools also drastically improved asset utilisation. In the last-mile scenario, demand prediction and Digital Twin simulations enabled a 261% increase in load factors, meaning 61.73% fewer vehicles were needed for the same volume of goods. Additionally, accurate ETA predictions enabled just-in-time operations, reducing cargo idle times by over 25% in Greece and container dwell times by up to 87.7% in Romania, thereby minimising energy wasted by idling equipment.

Beyond carbon metrics, the FOR-FREIGHT approach delivers broad socio-environmental benefits. By shifting freight to metro networks and optimising routes, the project offered a path to reduced urban congestion, leading to less traffic, noise, and safer streets. Service reliability also improved, with a significant reduction in mishandling errors in the Greek trial, reducing wasteful re-deliveries. Finally, the digitalisation of documentation via blockchain improved working conditions by reducing administrative burdens and planning stress for logistics staff.

In conclusion, FOR-FREIGHT validates a technological pathway for the European logistics sector to meet sustainability obligations, ensuring economic growth in freight transport is effectively decoupled from environmental impact.

8. Conclusion and vision beyond the project

The FOR-FREIGHT project has successfully demonstrated a new paradigm for the digitalisation and optimisation of multimodal freight transport in Europe. By combining interoperable components for data exchange, orchestration, and analytics, the project proved that fragmented transport processes can be transformed into a cohesive digital ecosystem. Central to this achievement is the concept of generalizable Solving Processes - abstract, model-driven representations of logistics workflows that can be instantiated, adapted, and executed across different contexts.

Rather than creating isolated optimisation tools, FOR-FREIGHT introduced an architectural model where Solving Processes are defined once but deployable anywhere. Each SP encapsulates a logical sequence of tasks (prediction, recommendation, optimisation, monitoring) that can be dynamically mapped to local infrastructures, legacy systems, and company-specific data sources. Through the Workflow Engine, these abstract SPs are translated into executable workflows that support real-time information exchange and adaptive decision-making, ensuring operational continuity across ports, airports, and urban logistics networks.

This ability to abstract and dynamically bind digital workflows to heterogeneous environments constitutes one of the project's most significant technological advances. It enables cross-domain scalability - where the same process logic can optimise vessel scheduling in a maritime hub, vehicle dispatch in a logistics centre, or last-mile delivery in an urban network—without redevelopment effort. By promoting standardised interfaces and event-driven orchestration, FOR-FREIGHT has laid the foundation for a new generation of interoperable, self-adaptive logistics systems capable of responding to changing demand, disruptions, or sustainability constraints in real time.

Beyond the project, this vision extends toward the creation of a pan-European digital layer for multimodal freight coordination, where generalisable Solving Processes act as reusable digital assets connecting public and private transport infrastructures. This concept aligns with broader European initiatives on digital transport corridors, logistics data spaces, and AI-supported optimisation. It positions FOR-FREIGHT as a blueprint for future intelligent freight ecosystems, where abstract workflow logic, localised data, and AI-driven optimisation converge to achieve a fully digitised, resource-efficient, and sustainable transport network.

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