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ATLAS–ALMA ARCHITECTURE FOR THE INTELLIGENT OPERATION OF MULTIMODAL FREIGHT TRANSPORT NETWORKS: CONCEPTUAL MODEL AND IMPLEMENTATION FRAMEWORK

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Abstract - The paper proposes a conceptual and operational framework for the integration of artificial intelligence in the management of multimodal freight transport through the ATLAS–ALMA architecture. The study starts from a structural limitation of current logistics systems, namely the fragmentation of operational decisions between road, rail and inland waterway transport, fragmentation that reduces visibility, limits adaptive rerouting and diminishes the efficiency of modal shift. The methodology integrates multimodal network modeling, agent-based representation of the logistics unit, multi-objective optimization and dynamic redirection based on the network state in real time. In this architecture, ATLAS functions as a network-level orchestration layer, and ALMA as an adaptive agent associated with each transport request. The decision-making process is formalized through an optimization function that correlates economic, operational and environmental criteria. The results, formulated as estimates and targets derived from pilot scenarios, indicate improvements in end-to-end visibility, ETA accuracy, document digitisation and terminal utilisation, while reducing downtime, logistics costs and CO_2 emissions. The comparative analysis of routes suggests that multimodal solutions coordinated by the proposed algorithm are particularly advantageous for long-distance industrial flows, where the environmental benefits of modal shift become more pronounced. Under these conditions, the ATLAS–ALMA architecture provides a solid methodological basis for the digital and sustainable transformation of multimodal freight transport operations.

Keywords: Artificial intelligence, Multimodal transport, Digital twin, Smart logistics, Multi-objective optimization, eFTI, Operational resilience.

1. Introduction

The digital transformation of logistics cannot be reduced to the simple computerization of documents or the isolated automation of operations. In multimodal freight transport, the central issue is the coordination of a heterogeneous network, in which road, rail and river modes operate under distinct constraints of capacity, time, cost, operational risk and environmental impact. In this framework, artificial intelligence becomes relevant when it is integrated into a mechanism capable of observing the state of the network, anticipating its evolution and formulating decisions adapted to each logistics unit, e.g.: [1], [2].

Recent literature shows that artificial intelligence it is used in transport logistics for prediction, decision support and resource optimization, with a direct effect on economic and environmental performance, e.g.: [1]. In parallel, research on digital twins shows that the operational value of these infrastructures derives from their ability to support efficient, transparent and timely decisions by synchronizing field data with the digital model of the system, e.g.: [2]. These directions are particularly relevant in multimodal networks, where performance depends on the coordination of

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transfers between modes, the availability of terminals and the ability to react to disruptions.

In the proposed architecture, the system is structured around two complementary digital components: ATLAS and ALMA. ATLAS (Advanced Transport & Logistic Artificial Intelligence Software) stands for the central multimodal network orchestration platform, responsible for integrating operational data, updating the digital infrastructure model and coordinating decisions at system level. In addition, ALMA (Adaptive Logistics Management Agent) designates the digital agent associated with each logistics unit, having the role of interpreting the transport demand, generating and evaluating candidate routes and initiating the reservation of capacity according to cost, time, emissions and operational risk. From a functional perspective, the relationship between the two components is clear: ATLAS operates at the network level, and ALMA at the level of the logistics unit, which allows the integration between global coordination and local decision in an intelligent multimodal transport operating model.

The system is built on the logic of a double optimization: global optimization at the network level and local optimization at the level of each logistics unit, based on real-time operational data, slot reservation and automatic redirection according to restrictions, congestion or specific risks, such as low water levels on the Danube.

Conceptually, the novelty of the solution lies in changing the unit of analysis. Instead of the decision being centered on the vehicle or transport service, the logistics unit becomes a digital entity with its own parameters of origin, destination, deadline, priority, maximum accepted cost and emission estimate. In this formulation, the goods are no longer treated passively, but as the object of an ongoing decision on routing and capacity allocation. The paper explicitly describes this approach by integrating a Network Digital Twin, a network health estimation layer, AI/ML-based predictive services, and a capacity and slot orchestrator.

The relevance of such a solution is amplified by the European regulatory context. Regulation (EU) 2020/1056 on electronic freight transport information establishes a legal framework allowing economic operators to transmit information relating to the transport of goods by road, rail, inland waterways and air to the competent authorities in electronic format, e.g.: [3]. This legal basis is important because optimization and prediction algorithms cannot operate robustly in the absence of standardized and interoperable data flows. At the same time, the new European framework for harmonising the calculation of emissions in transport uses EN ISO 14083:2023 as a reference methodology for quantifying greenhouse gas emissions from transport services, e.g.: [4].

Thus, the digital and methodological infrastructure begin to converge, which makes it possible to introduce sustainability directly into the objective function of the algorithm.

Therefore, the use of artificial intelligence in the ATLAS–ALMA architecture should not be interpreted as a technological complement, but as the mechanism by which multimodal transport can become predictive, adaptive and measurable. The proposed system aims to connect operational data, network modeling, and routing decisions into a single framework capable of reducing information fragmentation, increasing resilience, and supporting the modal transition to logistics options with a smaller climate footprint.

2. The Dimension of Sustainability Resulting from the Implementation of the AI Algorithm

The sustainability dimension of the system does not derive from the simple digitization of processes, but from the way in which the AI algorithm restructures the logistics decision. In the proposed configuration, the optimization engine in ATLAS compares transport modes, assesses operational risks and simultaneously optimizes cost, time and emissions, which explicitly introduces the environmental component into the route selection mechanism. Recent literature considers this integration one of the major directions of AI in logistics, as it correlates operational performance with economic, social and environmental sustainability, e.g.: [1], [5].

The first consequence of sustainability is to facilitate modal shift. The project starts from the well-known hierarchy of costs and emissions per tonne-kilometre, in which road transport is more emission-intensive than rail, and options on rivers and sea can become even more energy efficient, depending on operational conditions. In the proposed system, the algorithm does not automatically select the shortest road route, but chooses the node and modal combination with the best compromise between cost, time, emissions and risk. The paper explicitly indicates that, on pilot routes, by modal shift, a reduction in emissions per logistics unit of the order of 40–50% is required for origin-destination relations longer than 800–1000 km.

The second consequence is the reduction of indirect emissions associated with stationary and operational imbalances. In the paper, the difference between the current system and the proposed one is expressed by the shift from rigid bookings and manual redirection to granular slot bookings and automatic replanning. This change is relevant from an energy point of view, as waiting times, vehicle parking and inefficient use of terminals generate unnecessary consumption and decrease the productivity of logistics assets. The project aims at a 25–35% reduction in rest time for chassis and wagons and better synchronization of access and transfer windows.

The third consequence is to increase the ecological resilience of the grid. In real multimodal systems, a theoretically less polluting route can become inefficient if major disturbances occur. That is why the work explicitly includes the river risk, in particular the probability of a decrease in navigable water on the Danube, and provides for capacity penalties, additional costs and continuity plans through the return of the railways. From a sustainability perspective, this is an important condition: an algorithm that only aims to minimize emissions under ideal conditions can produces fragile solutions, while an algorithm that internalizes risk and operational continuity can maintain environmental advantages without compromising service reliability.

The fourth consequence is the dematerialization of the flow of information. The eFTI Regulation allows for the electronic transmission of transport information in all relevant ways, e.g.: [3], and the project targets a share of at least 90% of paperless documents, in line with the logic of eFTI. This has a direct effect on administrative efficiency and traceability, but also an indirect effect on sustainability, as it eliminates redundant processes, reduces delays caused by manual validation and increases the availability of data for the optimization algorithm.

The fifth consequence is the possibility of a standardised measurement of climate performance. The paper explicitly indicates the use of ISO 14083 and the CountEmissionsEU framework for comparing routes and modes, including for examples of simultaneous cost and emission reductions in intermodal relations.

In the terms of the article, the relevant conclusion is that sustainability does not appear here as a separate section of ex-post evaluation, but as an emergent property of the decision-making algorithm. When the model optimises based on an objective function that includes cost, time, emissions, risk and capacity, it produces a form of operational governance compatible with current transport decarbonisation requirements. The literature supports this interpretation: AI in logistics can improve sustainability through better decisions, and digital twin infrastructures can support continuous monitoring and correction of deviations from target performance, e.g.: [1], [2], [5], [6].

3. Literature Review

In recent literature, adaptive multimodal transport is treated as an advanced form of transport organization, in which mode choice and rerouting can be adjusted in real time, based on operational data and cooperation between logistics actors. The systematic review by Rentschler, Elbert and Weber, e.g.: [7] shows that this paradigm is based on the concepts of real-time switching between modes and mode-free bookings, which gives it significant potential for operational flexibility and sustainability. At the operational level, Alaei, Durán-Micco and Macharis, e.g.: [8] model this adaptivity through a multi-agent system, in which the combination of pre- and post-transport road transport and rail or river segments is dynamically replanned. In the same vein, Zhang, Tan, Gan, Liu and Atasoy, e.g.: [10] show that the recent methodology evolves from static formulations to flexible, dynamic and collaborative operational planning, which supports the use of an ATLAS–ALMA architecture for continuous decision, not rigid planning.

A second major direction concerns the transition from deterministic optimization in adaptive planning under uncertainty, in which methods such as Q-learning, reinforcement learning, robust optimization and simulation-optimization explicitly appear. Zhang, Cheng and Zou, e.g.: [9] propose an optimization framework based on multi-objective weighted-sum Q-learning for multimodal networks with time uncertainty, in which the cost of transport, the cost of carbon emissions and the transport time are simultaneously optimized. Filom and Razavi, e.g.: [11] propose a robust learning-based optimization framework for adaptive multimodal transport under conditions of uncertainty, and Dewantara, Filom, Razavi, Atasoy, Zhang and Saeednia, e.g.: [12] develop a hybrid simulation-optimization model assisted by reinforcement learning for disruption management, reporting superior performance to always wait and always reassign policies in outage scenarios. Together, these works show that the intelligent operation of multimodal networks can no longer be addressed by static optimization, but by a combination of prediction, multi-objective evaluation and adaptive rerouting.

A third direction, of direct interest for the present study, is the integration of sustainability into the objective function of decision models. Abusalih and Liu, e.g.: [13] address the issue at a strategic level and formulate a mixed optimisation model for intermodal infrastructure development and long-term transport decisions, explicitly including the emissions component and hybrid hubs integrating `rail and inland waterway transport. At the operational level, Guo, Yin, and Zheng, e.g.: [14] develop a 0–1 multi-objective model that minimizes the total cost of transportation, the cost of carbon emissions, and total time, and the simulation evaluation shows that the rail–water scheme is the most operable in their case study. Consequently, the recent literature no longer treats carbon as an ex-post reporting indicator, but introduces it directly into the optimization function, which provides clear methodological support for the inclusion of emissions in the AI algorithm proposed in this study.

Finally, for network-scale deployment, two directions are essential: agent-based modeling and digital interoperability. Khussanov et al., e.g.: [15] use agent-based modelling to represent multimodal flows on a national scale in the transport system in Kazakhstan and point out that complex simulations integrating real infrastructure, multimodal routing, border bottlenecks and the dominance of rail transit are still rare. In addition, Silalahi, Pujawan and Singgih, e.g.: [16] show that, in a fragmented air cargo system, the effects of digitalization do not increase linearly: the simulation identifies an interoperability threshold of about 60%, beyond which performance improves rapidly, clearance times decrease by more than 40%, and capacity utilization exceeds 85%. BAlthough the study focuses on air transport, its conclusion is directly relevant for the design of an integrated digital platform, where the benefits of coordination only emerge after a sufficient level of connectivity between actors and systems is achieved.

Overall, these papers converge towards four conclusions relevant to the present theme. The first is that adaptive multimodal transport provides the appropriate conceptual framework for dynamic switching between modes, e.g.: [7], [8],[10]. The second is that robust learning and optimization algorithms are suitable for routing and rerouting under uncertainty, e.g.: [9], [11], [12]. The third is that sustainability must be introduced into the objective function through the cost of emissions and the assessment of alternative modes, e.g.: [13], [14]. The fourth is that agent-based modelling and digital interoperability are conditions for scaling and systemic efficiency, e.g.: [15], [16]. On this basis, the proposed methodology can be formulated as an integrated decision model for a smart multimodal network, capable of combining operational optimisation with explicit sustainability objectives.

4. Methodologies

The research approach is configured as a design and validation study of a decision-making system for the intelligent operation of a multimodal freight transport network. The proposed approach combines logistics network modeling, agent-based representation of the logistics unit, multi-objective optimization and simulation of disruption scenarios, in a methodological framework that reflects recent directions in the literature. The analyzed works show that the adaptive operation of multimodal transport must be treated as a dynamic operational system, and the optimization under uncertainty must be approached through methods of learning, replanning and robust decision, e.g.: [7], [8], [9], [10], [11], [12]. In this context, the proposed methodology aims to integrate the coordination at network level with the decision at the level of each logistics unit, in accordance with the ATLAS–ALMA architecture in the project, where ATLAS optimizes the network, and ALMA manages the transport demand individually.

The model is organized around two complementary components. ATLAS represents the central layer of network orchestration and integrates the digital infrastructure model, network health estimation, predictive services and slot reservation mechanism. ALMA functions as the digital agent of the independent logistics unit and has the role of generating candidate routes, requesting capacity and monitoring the execution of the transport. From a methodological point of view, this separation allows for the distinct treatment of global and local decision-making, in line with recent studies on adaptive replanning and agent-based simulation in multimodal networks, e.g.: [8], [15]. In addition, the literature on digital interoperability shows that the performance of the system is directly dependent on the degree of of connection between actors, terminals and platforms, which justifies treating the AI algorithm not as an isolated module, but as an integrated part of a larger decision-making architecture, e.g.: [16].

The logistics network is modeled as an oriented graph, where the set contains the logistics nodes, and the set represents the connections between them. The nodes include intermodal terminals, ports, logistics hubs and road access points, while the edges correspond to the rail, road, river or sea segments. Each edge is described by a set of operational attributes, namely estimated transit time, logistics cost, associated emissions, available capacity and operational risk level. Formally, for each edge, the attribute vector is defined as:

$$G = (V, E) V E e_{ij}$$

$$e_{ij} = \{t_{ij}, c_{ij}, em_{ij}, cap_{ij}, r_{ij}\} \quad (1)$$

where t_{ij} represents the estimated transit time, c_{ij} logistics cost, em_{ij} associated emissions, cap_{ij} available capacity and r_{ij} operational risk score. Such representation allows for the simultaneous integration of infrastructure and operational data and is compatible with recent approaches to network planning and intermodal optimisation, e.g.: [13], [14]. At the same time, the framework corresponds to the logic of the project, where the Network Digital Twin is defined by nodes, edges, TEN-T constraints and available capacity.

The advantage of this formulation lies in the possibility of simulating disturbances by dynamically changing values and, depending on railway restrictions, terminal congestion or river conditions.

The independent logistics unit is modeled as a software agent with its own identity and operational profile. The agent shall contain information on origin, destination, type of goods, quantity, delivery time, priority, maximum accepted cost and emission threshold. This representation is consistent with the role assigned to ALMA in the project, where it is described as a digital entity capable of selecting the optimal route, reserving slots, and rerouting based on events. Formally, the agent can be expressed as follows:a_k

$$a_k = \{o_k, d_k, q_k, ddl_k, p_k, c_k^{max}, em_k^{max}\} \tag{2}$$

where o_k is the origin, d_k destination, q_k quantity or type of logistics facility, ddl_k delivery deadline, p_k priority level, c_k^{max} maximum accepted cost and em_k^{max} accepted emission threshold. This structure makes it possible to differentiate between logistics requests and allows flexible allocation of transport modes according to the constraints and objectives of each delivery, which is also supported by the recent literature on adaptive multimodal transport operation, e.g.: [7], [10].

The decision-making process is formulated as a sequential algorithm with continuous updating. It starts with taking over the transport request and identifying the profile of the logistics unit, after which the ALMA agent queries the ATLAS platform to obtain the status of the network, the available capacity, the predictions on the delivery times and current operational risks. Based on this information, candidate routes are generated, which are then evaluated and ordered according to a multi-criteria objective function. After selecting the best option, the agent submits the request for capacity reservation and initiates the execution of the transport. If a relevant disturbance occurs during execution, the algorithm returns to the route recalculation stage, based on the updated network status. Such a logic is consistent with the results in the literature on adaptive replanning, robust optimization, and simulation–optimization models, e.g.: [8], [11], [12].

The selection of the optimal route is treated as a multi-objective optimization problem. Instead of minimizing a single criterion, the model simultaneously integrates total cost, total transit time, total emissions, and aggregate operational risk. This choice is supported by recent literature, in which the optimisation of multimodal routes is explicitly formulated in multi-objective terms and in which sustainability is introduced directly into the decision function, e.g.: [9], [13], [14], [17]. The proposed objective function has the form:

$$F(x) = \alpha \cdot C(x) + \beta \cdot \\ \cdot T(x) + \gamma \cdot EM(x) + \delta \cdot R(x) \tag{3}$$

where C(x) represents the total cost of the route, T(x) total transit time, EM(x) total emissions, EM(x) operational risk and R(x) are weighting coefficients. The values of these coefficients are adapted according to the transport profile. For goods with $\alpha, \beta, \gamma, \delta$ at the critical time, the share of time becomes higher, while for ESG-oriented transports or carbon-capped trade relations, the share associated with emissions increases. In this way, the methodology preserves both operational flexibility and traceability of the algorithmic decision.

Sustainability is integrated into the algorithm not as a secondary indicator, but as part of the route choice mechanism. This means that emissions, and where possible also energy consumption or carbon penalties, are fed directly into the assessment and optimisation process. Methodologically, sustainability integration is achieved by estimating emissions for each edge and for each complete route, by applying eligibility constraints that exclude variants exceeding a certain carbon threshold and by explicitly including emissions in the objective function, along with cost and time. In this way, the algorithm can favor rail–water or road–rail combinations when they offer environmental advantage without compromising logistical performance, e.g.: [13], [14]. This option is compatible with the project, where sustainability is treated as an integrated element in the decision score and not just as a reporting result.

To deal with operational uncertainty, the methodology includes an explicit rerouting mechanism. It is activated when ATLAS detects a relevant change in the state of the network, such as reduced navigability of the Danube, the appearance of railway restrictions or severe congestion in a terminal. In such situations, the affected edges change their capacity and risk attributes, and the ALMA agent recalculates the route based on the new state of the network. From the point of view of methodologically, rerouting is treated as a local re-optimization problem, carried out without fully reconstructing the systemic plan for all transports. This approach is consistent with recent models of resilient multimodal transport and decision-making methods under disruption, e.g.: [11], [12] and has the advantage of allowing for the continuity of logistics flows under conditions of uncertainty.

The model (Fig.1) requires four main categories of data: structural data on infrastructure and terminals, real-time operational data on times, capacities and constraints, data related to the logistics unit and customer requirements, as well as assessment factors for cost, emissions and risk. In practice, this data can come from railway operators, infrastructure managers, terminals, port systems, road traffic services and digital document platforms.

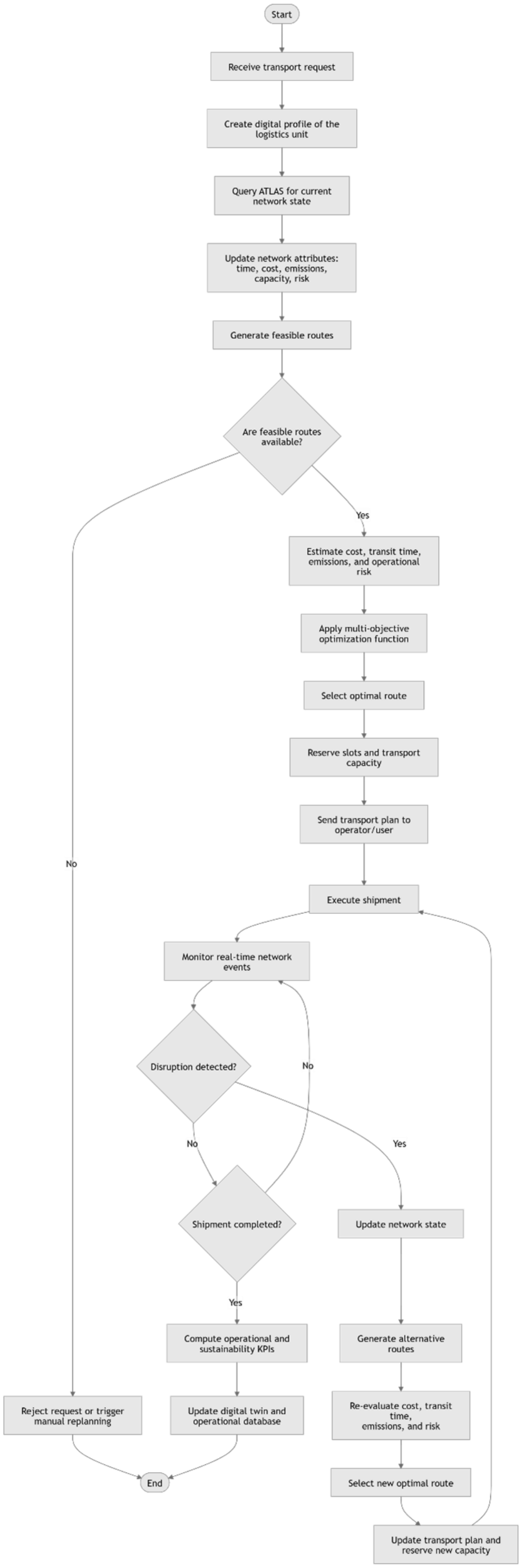

Figure 1. The logic flow of the AI algorithm within the ATLAS–ALMA architecture

The project already mentions minimum interfaces for network status, reservations, telemetry and event notifications. When access to complete real-time data is limited, the experimental implementation can use historical sets and synthetic scenarios, a solution frequently found in simulation-optimization and agent-based planning studies, e.g.: [8], [15], [18].

The validation of the methodology is carried out through a case study and comparative simulation. For each origin-destination relationship, two categories of scenarios are analyzed: conventional road transport and multimodal transport coordinated by the proposed algorithm. In addition, disruption scenarios are introduced to assess the robustness and resilience of the system. Performance is measured by operational and sustainability indicators, the most relevant of which are total logistics cost, total transit time, ETA (Estimated Time of Arrival) accuracy, terminal utilization, percentage of successful rerouting, emissions per logistics unit or per tonne-kilometre, time spent in terminals and the percentage of paperless processes. These indicators are compatible with both the project and the recent literature on the assessment of adaptive multimodal systems and logistics interoperability, e.g.: [10], [16].

Overall, the proposed methodology treats the multimodal network as a dynamic system and the logistics unit as a decision-maker. ATLAS provides the network image and predictive services, and ALMA performs route selection, capacity reservation and rerouting at the level of each request. The decision problem is formulated as multi-objective optimization under capacity and risk constraints, and performance is evaluated through operational and sustainability indicators. In this way, the methodology directly responds to the gap identified in the literature review. The proposed model separately validates the adaptive operation of multimodal transport, optimisation under uncertainty, emission integration and agent-based simulation; however, the proposed model brings them together in a unitary operational framework for an intelligent multimodal network, e.g.: [7] – [16].

5. Decision Algorithm and Adaptive Rerouting

The proposed algorithm constitutes the operational mechanism by which the system transforms a transport demand into a feasible and adaptable multimodal routing decision. Its role is not only to select an initial route, but also to maintain the validity of the decision for the duration of execution, given that the state of the network can vary dynamically. In this logic, the algorithm works as an iterative process of evaluation, selection and updating, in which each possible route is analyzed in relation to the overall performance of the transport.

The process begins when the transport request is taken over by the system and transformed into a decision-making object. Based on the current state of the network, the algorithm generates a set of candidate routes compatible with the transport requirements. Each of these variants is assessed by aggregating the relevant criteria, and the result is expressed as an overall score. The route selected is the one that offers the best compromise between the criteria introduced in the objective function and that remains operationally feasible at the time of the decision. At this stage, the algorithm does not follow the shortest or cheapest route in isolation, but the alternative with the most total performance good in the given context.

The logical flow of the proposed algorithm is illustrated in figure 1. The schema highlights that the decision is not one-time and static, but iterative and dependent on the current state of the network. After generating and evaluating feasible routes, the system selects the route with the minimum global score and initiates the capacity reservation.

In the execution phase, continuous monitoring of the network allows the detection of disturbances and recalculation of the route, which gives the model resilience and adaptivity properties. This wording is consistent with recent approaches in the literature on adaptive multimodal transport replanning and optimisation under uncertainty, e.g.: [8], [11], [12], [19].

As long as the network maintains its estimated conditions, the transport continues on the selected route. When a disturbance is identified that affects the feasibility or efficiency of the current route, the algorithm reactivates the search and evaluation sequence and produces an alternative variant. In this way, rerouting does not appear as an external exception, but as a constituent part of the decision-making mechanism.

The distinguishing feature of the algorithm is the controlled rerouting capability. When a significant change occurs in the network, the system does not automatically cancel the existing plan, but reevaluates the current route against the new conditions and compares this option with the available alternative routes. A new route is only adopted if it offers a clear improvement in feasibility or overall performance. This condition is important because it avoids decision instability and prevents excessive rerouting, which can introduce additional costs or timing losses between modes. Consequently, the algorithm does not aim for flexibility per se, but for operationally justified flexibility.

Another important aspect is the integration of sustainability directly into the selection mechanism. missions are not only assessed after the transport is completed, but influence the choice of route from the initial stage of comparing alternatives. In this way, the algorithm can favor intermodal routes with better climate performance when they remain compatible with the delivery time and capacity constraints. This approach transforms sustainability from a descriptive indicator into an active decision criterion.

In its final form, the algorithm must be understood as a continuous decision-making mechanism, not as a one-off planning procedure. It selects, validates, monitors and, when necessary, reconfigures the route, maintaining the balance between logistical efficiency, operational robustness and environmental performance. It is precisely this combination that makes it relevant for the intelligent operation of multimodal freight transport networks.

6. Results and Discussions

For the evaluation of the proposed model, two representative routes for relevant industrial flows in the Romanian context were analyzed, both related to a standardized logistics unit of approximately 2 TEU, equivalent to a 40 ft container or an intermodal semi-trailer, with an average load of approximately 20 t. The first route, Munich–Craiova, corresponds to an intra-European corridor specific to automotive supply chains and mainly includes structural metal components, stamped automotive parts and palletized or containerized industrial subassemblies. The second route, Turkey–Craiova, reflects a regional corridor associated with nearshoring strategies and includes gearboxes, transmission components, metal parts and semi-finished materials. The choice of these two routes allows the comparison of the algorithm's behavior both on a long route, where the advantages of multimodal transfer are more pronounced, and on a medium route, where the trade-offs between cost, time and emissions are more balanced.

The results shall be interpreted as estimated results and target results, derived from the scenarios formulated in the project and from the comparison between the current vehicle-centric model and the proposed logistics unit-centric model. At the system level, the work indicates a significant increase in end-to-end visibility, much better ETA accuracy, reduced downtime and an almost complete digitization of transport documents. In addition, aggregate reductions in total transit time, logistics cost and CO_2 emissions are expected, as well as an increase in terminal utilization.

Table 1. Key indicators of the current system vs. the proposed system

Indicator	Current system	Proposed system
End-to-end visibility	40–60%	95–100%
ETA accuracy	±4–8 a.m.	±15–30 min
Downtime Logistics Assets	30–40% unused time	25–35% discount
Documente paperless	10–20%	90–100%
Degree of use of terminals	–	~70%
Reduction of total transit time	–	15–25%
Total logistics cost reduction	–	20–30%

At route level, the Munich–Craiova case highlights the most clearly the advantage of multimodal transfer for standardised industrial goods that are relatively insensitive to increased transit time. In the conventional road scenario, the logistics unit is transported entirely by truck over a distance of approximately 1,200 km, with an estimated cost of approximately €1,440, a time of approximately 20 h and emissions of approximately 2,579 kg CO_2 per logistics unit. In the multimodal scenario, the transport chain is composed of Munich–Vienna (rail), Vienna–Calafat (Danube), Calafat–Craiova (road), with a total cost of around €1,245, a time of 72–82 h and emissions of around 1,028 kg CO_2. The result indicates a reduction of around 14% in cost and around 60% in emissions, but accompanied by a substantial increase in transport time. This configuration is therefore particularly suitable for non-urgent industrial goods.

Table 2. Comparison on the Munich–Craiova route

Indicator	Road	Multimodal	Variation
Cost (€/logistics unit)	1.440	1.245	−14%
Time (h)	~20	72–82	+260%
CO_2 emissions (kg/logistics unit)	2.579	1.028	−60%

The multimodal solution is economically competitive and clearly superior from a climate point of view, but it involves a longer duration of transport.

For the Turkey–Craiova route, the effects are similar, but more moderate. In the road scenario, direct transport has an estimated cost of around €960, a time of 14–16 h and emissions of around 1,719 kg CO_2 per logistics unit. In the multimodal scenario, the chain is composed of Turkey–Ruse (road), Ruse–Calafat (Danube), Calafat–Craiova (road), with a total cost of approximately €810, a duration of approximately 2 days and emissions of approximately 1,245 kg CO_2. The result indicates a reduction of around 15% in cost and around 28% in emissions, confirming that multimodal transfer also remains advantageous on regional corridors, but with a lower climate benefit than on long routes.

Table 3. Turkey–Craiova route comparison

Indicator	Road	Multimodal	Variation
Cost (€/logistics unit)	960	810	−15%
Time (h)	14–16	~2 days	moderate growth
CO_2 emissions (kg/logistics unit)	1.719	1.245	−28%

Overall, the results support three conclusions. The first is that the proposed architecture produces systemic value by increasing operational transparency, improving ETA and reducing downtime, not just by changing the mode of transport. The second is that multimodal transfer is most effective for standardized industrial flows and for long relationships, where the reduction of emissions becomes very significant. The third is that the performance of the system depends on the ability to integrate operational data, digitize documents, and synchronize terminals and modes in a single decision-making framework. From this perspective, the ATLAS-ALMA algorithm and architecture not only optimize the route, but creates the conditions in which modal shift becomes simultaneously feasible, competitive and sustainable.

7. Conclusions

The paper proposes the ATLAS–ALMA architecture as a conceptual and operational model for the integration of artificial intelligence in the management of multimodal freight transport networks. The main contribution lies in the shift from a vehicle-centric planning logic to a logistics unit-centric model, treated as a digital entity capable of being assessed, routed and rerouted according to cost, time, emissions and operational risk. In this formulation, ATLAS fulfills the role of network orchestrator and logistics digital twin, and ALMA functions as an adaptive management agent of each transport request.

The literature review highlights the convergence of recent research towards four key directions: adaptive multimodal planning, optimization under uncertainty, integration of sustainability into objective function, and network-scale agent-based modeling. The proposed methodology brings together these components in a unitary framework, in which the logistical decision is continuously updated based on the state of the infrastructure, the availability of capacity and network disruptions. From this perspective, the algorithm is not just a routing tool, but a mechanism for dynamic coordination between the transport demand and the actual operating conditions.

The estimated results indicate that the model can generate relevant benefits at both operational and sustainability levels. The comparison of the analyzed routes shows that multimodal solutions coordinated by the proposed architecture can reduce logistics cost and CO_2 emissions, especially on long routes and for standardized industrial flows, even if these advantages may be accompanied by an increase in transit time. At the system level, the results suggest improvements in end-to-end visibility, document digitization and logistics infrastructure utilization, confirming that the value of the model does not derive exclusively from modal shift, but also from the reduction of operational inefficiencies.

An important result of the study is that sustainability is not treated as a side effect of digitalization, but as an internal property of the decision algorithm. By introducing emissions into the target function and correlating them with the risk and available capacity, the model allows for the selection of pathways that are not only feasible and competitive, but also compatible with current transport decarbonisation targets. This approach is relevant in the current European context, where data interoperability, eFTI and standardisation of emissions calculation create the prerequisites for the smart operation of multimodal corridors.

However, the work also has clear limits. The results presented are formulated as estimates and target values derived from project scenarios and proposed modelling, not from a full validation in actual operation. Consequently, a necessary direction of future research is to test the model on extensive operational data, under real network conditions, as well as to calibrate the objective function coefficients in relation to different commodity profiles, business priorities and ESG constraints. Extending the analysis to more complex shock scenarios and long-term economic assessment would allow for more rigorous validation of the robustness of the system.

Overall, the study argues that the ATLAS–ALMA architecture provides a credible framework for modernising the operation of multimodal freight transport by integrating the digital twin, AI algorithms and sustainability criteria into a single decision-making mechanism. In this respect, the contribution of the work is not limited to a technical proposal, but configures an operating model capable of correlating the digital transformation with the logistical efficiency and environmental objectives of contemporary European transport.

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