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Simulation-based decision-making framework for sustainable intermodal transport including next-generation freight electric multiple-units

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ABSTRACT

The objective of this paper is to propose a decision-making framework for evaluating alternative inland freight transport chains with the goal of increasing the use of intermodal transport and reducing negative externalities. Particularly, the combined transportation alternatives considered the use of conventional trains and next generation Freight Electric Multiple Unit (FEMU) trains in Italy. Customs Fast Corridor impact is evaluated, too. The methodological approach relies on Multi-Criteria Analysis (MCA) informed by railway microsimulation and DES models for transport times. The MCA considers also additional factors such as transport reliability, energy performance, greenhouse gases emission and local pollution. The proposed methodology has been applied to the Italian context, comparing all-road and combined transport chains from the port of Genoa to inland destinations ranging from 140 to 1000 kilometers. Results show viability of combined transport starting from around 250 km, lower than the 300 km suggested by European Union.

1. Introduction

In freight transport, decision-making transport operations remain predominantly cost-driven with operators prioritizing factors that directly or indirectly affect economic performance. However, environmental sustainability, particularly in terms of climate change impacts and human toxicity, has emerged as a critical factor that needs consideration alongside economic factors. Despite its detrimental impact on the environment in terms of local pollution and CO_2 emissions (European Environment Agency, 2022), road transport remains the dominant mode for short and medium-distance freight (European Commission, 2024). In contrast, rail and intermodal transport offer a more sustainable alternative, helping to reduce negative externalities such as pollution and infrastructure congestion. Despite these advantages, in Europe and countries such as Italy, subject of our study, the current modal share of rail is still residual, partly due to the morphology of the territory (Union Internationale pour le transport combine rail-route UIRR, 2024) and stakeholder choices dictated mainly by cost and travel time not considering the environmental impact, sustainability and safety of the chosen transportation. This is why it is important to define a model for the choice of freight transport based on criteria that take into account not only economic and time aspects, but also environmental and reliability aspects. The shift towards intermodal transport aligns with European Union policies, such as the Green Deal and the White Paper on Transport, advocating for more sustainable transportation practices (Grzelakowski, 2024; European Commission, 2023). At an international level, the ISO14083 standard serves as a reference for calculating and accounting for CO_2 emissions, an aspect of growing importance for stakeholders, especially in light of the *polluter pays* (Jephcote et al., 2016) approach. To encourage this transition, in Italy specific incentives such as "ferrobonus" have been created, which directly reimburses a share of the cost incurred for transport (RAM S.p.A., 2024). To address this challenge, this paper proposes a novel methodology to support stakeholders in selecting optimal transport chains, aiming to support more balanced and informed modal choices and transport policies. The methodology's innovation lies in its nested structure: a Multi-Criteria Analysis (MCA) incorporating a microsimulation of train operations within a Discrete Event Simulation (DES) framework spanning the entire inland transport chain. Unlike standalone MCA or DES approaches, this integration simultaneously captures macro-level trade-offs and micro-level operational dynamics, addressing critical gaps in freight chain assessment. A secondary contribution examines the innovative next-generation Freight Electric Multiple Unit (FEMU) train, currently in the design phase, as a decarbonization enabler, comparing its performance against conventional intermodal and all-road alternatives.

Table 1 provides a systematic overview of the most relevant contributions in the freight transport literature, classifying them according

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Table 1
Comparison of existing studies and contribution of this work.

Author	Methodology				Criteria			
	DES	Microsimulation	MCA	Optimization	GHG emissions	Pollutants	Costs	Travel times
Goodarzi et al. (2024)				✓	✓			✓
Abbasi et al. (2024)				✓	✓		✓	
Zaid et al. (2024)			✓		✓		✓	
Kabashkin (2023)			✓	✓	✓	✓	✓	✓
Ke (2022)				✓			✓	
Hrušovskỳ et al. (2021)	✓			✓	✓		✓	✓
Janjevic et al. (2019)			✓		✓		✓	
Kopytov and Abramov (2012)			✓		✓	✓	✓	✓
Present study	✓	✓	✓		✓	✓	✓	✓

to their focus, methodological approach and limitations with respect to the present study. This comparison highlights that existing studies typically address either strategic trade-offs or operational dynamics in isolation, whereas the proposed framework explicitly bridges these dimensions within a unified modeling architecture. For instance, Zaid et al. (2024) and Kopytov and Abramov (2012) rely exclusively on MCA to evaluate alternatives, but lack the dynamic component of simulation. Hrušovskỳ et al. (2021), instead, uses DES and agent-based simulation for real-time management, however, their decision making process is primarily based on predefined policies and cost minimization, without a structured MCA framework to balance qualitative criteria or complex stakeholder perspectives. While the present work exploits the microsimulation to model the system behavior, other studies rely on mathematical optimization, such as Goodarzi et al. (2024), Abbasi et al. (2024) and Ke (2022). Finally, some studies move towards more integrative decision-making paradigms. Janjevic et al. (2019) focuses on an iterative decision-making framework based on Complex Adaptive Systems (CAS) to harmonize stakeholder objectives, while Kabashkin (2023) introduces a hierarchy of transportation needs modeled using Petri Nets to systematically evaluate competition between alternative routes.

As a result, the proposed methodology positions itself as an integrated decision-support framework capable of jointly capturing operational realism and strategic evaluation, a gap that remains largely unaddressed in the existing literature.

The paper is structured as follows: Section 2 details the nested methodological framework for analyzing transport alternatives. Section 3 validates the methodology through a case study, with results presented in Section 4. Section 5 examines the relevance of this work for policymakers. Finally, Section 6 outlines conclusions and future research.

2. Methodological framework

2.1. Overview

The methodological framework proposed in this paper is depicted in Fig. 1. It was developed considering the Italian context but can easily be extended to other settings. As shown, three methodologies are combined together and nested: (i) a MCA, (ii) a DES model, and (iii) a microsimulation for rail transport. The criteria also include the EcoTransit tool to account for environmental sustainability and other data and unstructured interviews with a wide range of stakeholders involved in the considered logistics chains.

The comprehensive methodological framework was developed to compare five transport chains taking into consideration the Italian context:

(a) All road transport (hereinafter All-Road)
(b) Intermodal transport with conventional train (hereinafter Intermodal CONV)
(c) Intermodal transport with conventional train and Fast Corridor (hereinafter Intermodal CONV+FC)
(d) Intermodal transport with F-EMU train (hereinafter Intermodal FEMU)
(e) Intermodal transport with F-EMU train and Fast Corridor (hereinafter Intermodal FEMU + FC)

Inland waterway transport, although recognized for its high energy efficiency and low environmental impact in several European countries, was not considered among the selected alternatives. This exclusion is primarily due to the limited role that inland waterway currently plays in the Italian freight transport system, related to insufficient navigability of major rivers, inadequate maintenance of canals, and a lack of integration with core logistics and intermodal nodes. As a result, inland waterway transport remains underutilized in Italy and was not deemed a competitive or feasible alternative within the scope of this analysis. The intermodal transport chains considered, differ in the type of train used (more details in Section 2.2) and the presence of a Fast Corridor. The Fast Corridor is an innovative intangible infrastructure that allows customs procedures to be performed at inland terminals instead of ports (Caballini and Benzi, 2023). This procedure allows port congestion to be reduced and, thus, it shortens the overall transportation time. Moreover, since the analysis focuses on the transport chain, emissions and energy expenditures associated with port operations are not considered in the subsequent evaluation. This exclusion is justified by two primary reasons: (i) emissions and energy consumption in port activities are generally regarded as relatively stable across different transport chains, implying no substantial variability in port-related operations; (ii) the environmental impact and energy demands of port operations can vary significantly depending on the equipment employed and the powertrain technology utilized. While there is growing pressure on ports to transition towards electric equipment, offering some advantages in terms of performance, e.g., electric gantry cranes are much more productive than diesel ones, these technologies do not always present clear cost benefits (Olivari et al., 2024b), potentially increasing cargo handling expenses. Regarding point (i), it is essential to highlight that this assumption does not universally hold. For instance, in the context of Fast Corridor logistics, port-related emissions can be reduced due to a decrease in the number of operational activities carried out within the port. This feature, however, is not accounted for in the current methodological framework. In the present framework only diesel trucks are considered but road alternatives can exploit various powertrain technologies, changing data accordingly. The point of view is that of the stakeholder responsible for choosing the best transportation alternative, which in most cases is the shipper or freight forwarder, considering only the use of third-party transport services. The MCA with ELECTRE II method (Elimination and Choice Expressing Reality) (Figueira et al., 2005; Taherdoost and Madanchian, 2023) was implemented to rank the choice among the transport chains depicted in the Fig. 1 according to different qualitative and quantitative criteria. The graphical solution of the ranking can be exploited to perform an informed decision-making process.

For calculating the weight of each criterion, the Full Consistency Method (FUCOM) was used (Feizi et al., 2021; Ayan et al., 2023).

Several criteria could be included in the MCA when considering the point of view of the stakeholder who needs to ship the goods.

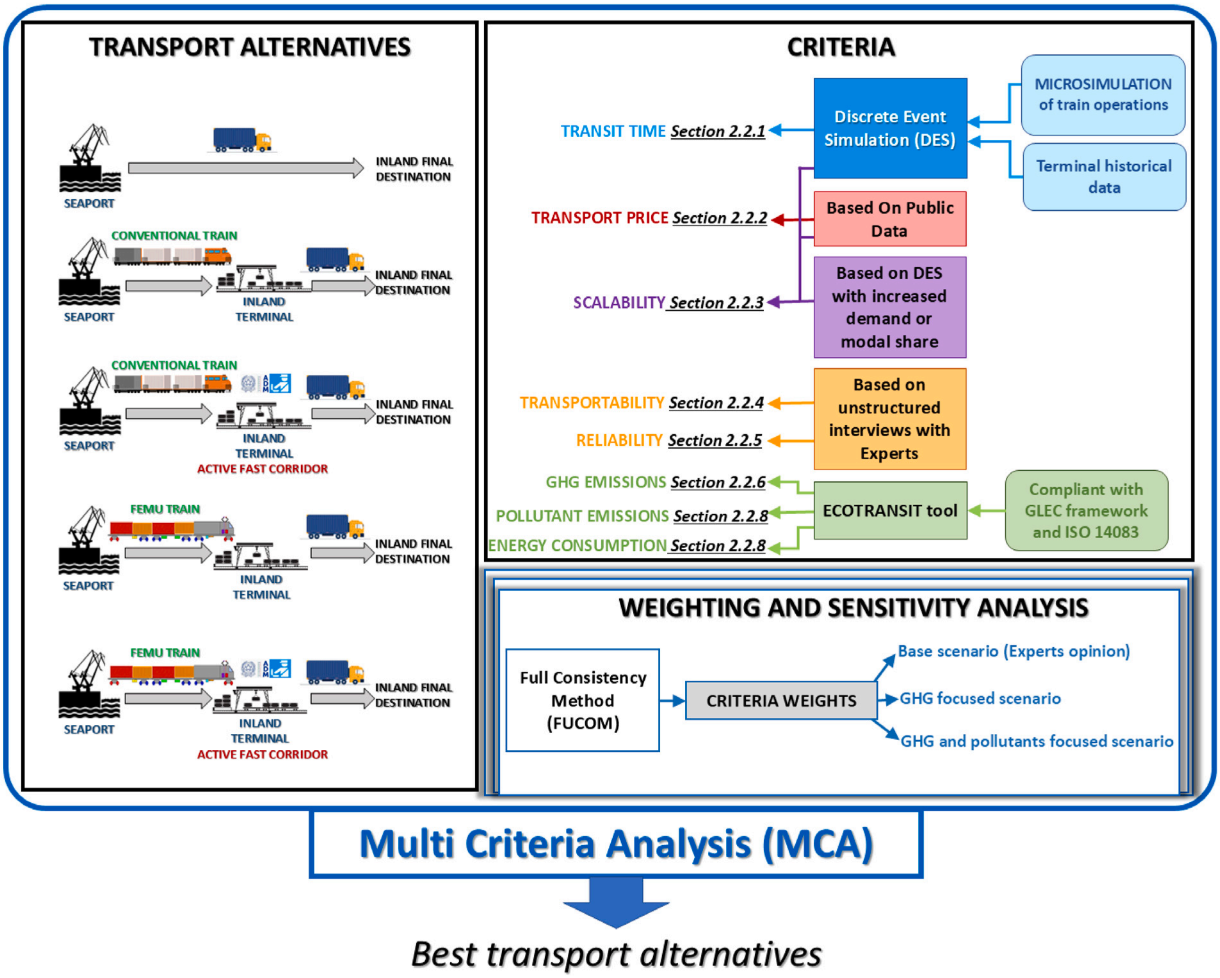

Fig. 1. Methodology overview.

The decision will depend on the cost of the service (Arencibia et al., 2015; Konstantinus et al., 2020; Feo-Valero et al., 2016) and its quality, which can be interpreted in many ways. Savings in the transit time of goods is important (Arencibia et al., 2015; Feo-Valero et al., 2016), but so are reliability (Konstantinus et al., 2020; Fowkes et al., 2004) and flexibility, especially when time is one of the constraints and there are delivery times to be respected. This is true in general from a just-in-time production perspective but especially when goods are perishable. Indeed, the type of cargo to be transported also affects the choice of transport type.

Environmental sustainability is becoming increasingly important, accentuated by emission regulatory frameworks and political pressures to promote intermodal freight transport (Bask and Rajahonka, 2017). In most cases, greater sustainability entails higher costs that shippers are not always willing to pay, hence the need for government incentives. However, the more connected a shipper is with the end consumer, the more sensitive it is to environmental issues (Fries et al., 2010). But what if incentives were progressively to decline and the concept of "the polluter pays" recently introduced by the EU Commission was implemented in earnest?

The emissions that attract the most interest from stakeholders because they are the subject of legislation are those related to CO_2e. However, they are not the only ones to be considered, since pollutant emissions are progressively attracting more attention. In the automotive sector, the EURO 7 (Consilium Europa, 2024a) will emphasize not only greenhouse gas (GHG) emissions but also pollutant emissions during vehicle homologation cycles. However, these emissions will continue to be assessed from a tank-to-wheel (TTW) perspective, excluding upstream processes.

To calculate the values associated with the different criteria considered in the MCA, KPIs such as the scalability index and methodologies such as DES were used to calculate transit times. Ultimately, some inputs to the DES model were determined using microsimulation.

In fact, DES can be used to analyze complex systems by modeling sequential discrete events over time, enabling system performance evaluation under different scenarios (Olson, 2003; Caballini et al., 2012). Microsimulation capture detailed interactions between entities (e.g., trains and infrastructure) to accurately represent operational dynamics within railway processes (Medeossi and de Fabris, 2018; Gurri' et al., 2023).

It is worth noting that the methodology developed in this research has been specifically tailored to the five transport chains under consideration. Nevertheless, by adapting and/or extending the DES model, the proposed approach can be effectively applied to evaluate other transport chain configurations or to better capture the port energy expenditure or emissions.

2.2. A next-generation freight train: FEMU

In recent decades, rail freight transport has experienced a decline in market share, following its peak during the economic boom of the 1960s. This shift was largely driven by increased demand for faster, temperature-controlled services, which facilitated the rise of refrigerated road vehicles. Technological advancements in the rail freight industry have been minimal over the past seventy years, with only incremental improvements to wagon designs. Locomotives, however, struggle to meet contemporary market demands. Efforts to increase train lengths to 740 m and corresponding weights have introduced operational challenges, particularly on steep grades. Such conditions often require the use of dual locomotives for ascents, significantly increasing costs due to additional rolling stock and labor requirements. The primary issue lies in the dynamic forces within the train. When the two locomotives are configured in a head-tail arrangement, couplers experience traction and compression forces, leading to potential failures and uneven motion. In configurations with two head locomotives, the first coupler endures excessive stress from the weight of the entire train, increasing the risk of failure and service disruptions. Additionally, the traditional pneumatic braking system hampers operational reliability. Its slow response times prolong braking distances, while its reliance on friction shoes causes wheel overheating, necessitating special procedures during steep descents. Furthermore, conventional freight trainsets are incompatible with high-speed rail infrastructure due to inadequate monitoring capabilities. In countries like Italy, where high-speed networks are designed for mixed traffic (freight and passenger), this incompatibility prevents the infrastructure from being fully exploited also for freight operations.

In this framework, it becomes of significance to briefly outline the characteristics of this next-generation train called FEMU (Gualco et al., 2021; Gurri' et al., 2023). A FEMU is an electric freight train with distributed power, which currently has been developed in its functional and logical architectures (see Table 2). It is composed of 11 modules of 3 flatbed wagons with a locked composition, which can be coupled and separated easily by Scharfenberg-type automatic couplers, which enables the transmission of the high-voltage traction current. The modules have a low-speed autonomy range that allows the train to avoid requiring a shunting locomotive to enter terminals without overhead lines. The powertrain of a FEMU can be thought of as a hybrid powertrain in which batteries and internal combustion engines powered by alternative fuels provide the necessary power both in shunting and in sections where line power is not sufficient to maintain speed performance.

The FEMU has a monitoring system, both for cargo and for the train structure itself, which enhances the reliability of this train compared to a conventional train, as well as its security and safety (Gurri' et al., 2024). The presence of the monitoring system and a low axle load, thanks to lightened wagon structures and the absence of heavy locomotives, makes it possible to run on high-speed lines (Gurri' et al., 2023) with average speeds of around 150 km/h. Since the FEMU is not yet operational, the performance parameters adopted in this study (e.g., cruising speed, terminal handling time reductions, and operational flexibility) are not derived from observed data but from scenario-based analyses presented in prior studies. In particular, sensitivity analyses on FEMU cruising speed and operational profiles were conducted on the Turin–Verona corridor to identify feasible performance envelopes compatible with existing infrastructure constraints (Gurri' et al., 2023).

The parameter values used in the present work correspond to configurations shown to be technically plausible within those analyses. Accordingly, the FEMU performance is treated here as an assumed input rather than as an empirically validated outcome. Accordingly, they should be interpreted as representative scenarios within a feasible performance range rather than as point estimates of future operational performance. The objective is not to reassess FEMU technical feasibility, but to explore its potential role within an intermodal freight chain under a consistent and previously tested set of assumptions. While absolute performance values remain subject to uncertainty until pilot operations become available, the comparative results remain informative for assessing relative impacts across transport configurations within the proposed decision-support framework.

The functional characteristics of a FEMU that are of primary importance for the considered methodology are:

Table 2
State-of-the-art of the FEMU.

Phase	Completion level
Economic analysis	••◦◦◦
Functional architecture	•••••
Logical architecture	••••◦
Physical design	••◦◦◦
Prototyping	•◦◦◦◦
Industrialization	◦◦◦◦◦

– higher cruising speed that reduces transit time (Gurri' et al., 2023)
– automatic couplers that ensure the possibility of longer trains and faster shunting
– active monitorability, which increases reliability (Gurri' et al., 2024)
– availability of on-board power that avoids shunting locomotive and the resulting pollution

This comes at the expense of a higher transportation cost, since it depends on the speed of the train (RFI, Ferrovie dello Stato, 2023), and a higher initial investment, but the latter is not taken into account by the methodology used.

2.3. MCA criteria

When developing an MCA, the criteria should follow specific features (Dean, 2022):

– *Exhaustiveness*: criteria should cover all the important aspects that have an impact and the decision process
– *Manageability*: criteria should not be over-detailed and not too high in number
– *Understandability*: each criterion should be clearly explained and eventual assumptions must be shared
– *Measurability*: both qualitative and quantitative criteria must be clearly measurable
– *Non-redundancy*: there should be no criteria that measure similar performance.

Many factors affect the modal choice of freight transportation. Based on the literature, the opinion of industry experts interviewed, and the data available, eight main criteria were selected to be implemented in the MCA: (i) transit time (Section 2.3.1), (ii) transport price (Section 2.3.2), (iii) scalability (Section 2.3.3), (iv) transportability (Section 2.3.4), (v) reliability (Section 2.3.5), (vi) GHG emissions (Section 2.3.6), (vii) pollutant emissions (Section 2.3.7) and (viii) energy consumption (Section 2.3.8). For this analysis, it was considered the point of view of the shipper who has to ship a container (1 TEU) from point A to point B and has to evaluate which is the best choice of land-side transport using third parties services.

2.3.1. Transit time: a nested simulation approach

In this analysis, transit time is defined as the time between the arrival of the container at the port and its arrival at the final destination. The transit time of the container across the different transport chains and scenarios considered was estimated using a simulative approach. In particular, a DES model has been developed by the authors themselves and implemented with Arena software (Rockwell Automation, 2024). Inside this model, microsimulation of railways has been used to compute time distributions for rail-related processes.

DES model. The objective of the DES model is to compute the total transit time. For this research, an academic software license was used. It does not necessitate laptops equipped with specialized features to function. The authors used an Acer Aspire A515-45, with 8 GB RAM. Furthermore, each simulation execution requires only a few seconds.

The model includes all the main processes to which the container is subjected during transport and is divided into macro areas:

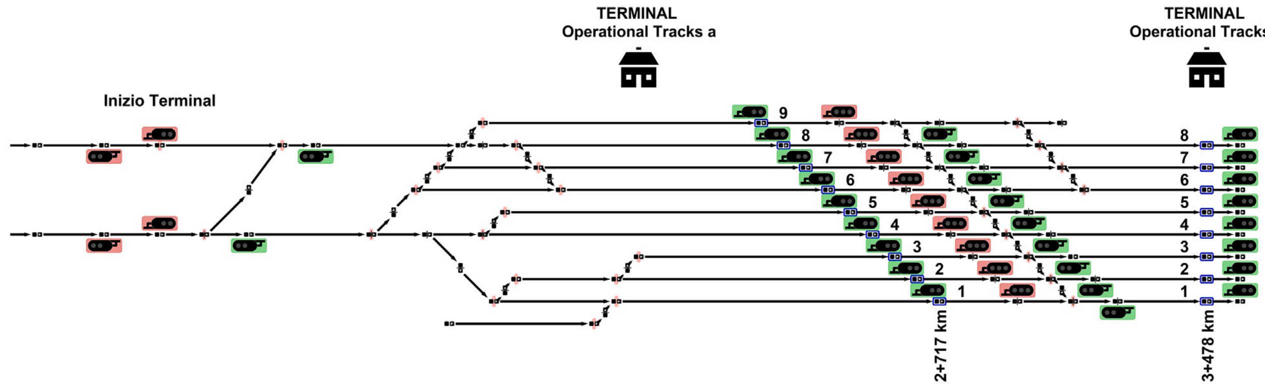

Fig. 2. Microsimulation of the railway terminal inside the port of Genoa.

- *Maritime port*, where the container is unloaded and undergoes many processes such as internal transport, yard storage, and eventual customs inspection;
- *Road transport*, which includes the process of loading containers on trucks and related checks, gate exit, and road transportation in the case of all road transport;
- *Rail terminal* within the port area, that includes all processes related to train preparation, shunting and verification, and container loading on wagons in the case of intermodal transport;
- *Intermodal terminal* - which can be a freight village or a dry port - where the container arrives by train and departs by truck for its final destination. It includes all rail processes, the container unloading from the train, storage, and eventual customs checks if a Fast Corridor is active.
- *Last mile*, which includes the process of loading the container on the truck to leave the terminal towards its final destination.

Note that, in some cases, the processes are aggregated because of the format of the input data available to the authors. Time distributions for the bulk of the processes can be derived from the historical data of the terminals. Instead, the time distributions of trucks' travel time, both for all-road haulage and last-mile, can be determined using the Google Maps API, taking into account various departure times throughout the day and considering multiple days of the year. By employing this sampling method, a comprehensive distribution of travel times for each destination can be constructed.

Microsimulation of railway processes. The DES model was fed with data from microsimulations for the processes related to train operations. This modeling technique replicates and analyzes the intricate dynamic behavior of individual trains and their interactions within a railway network. Using specialized software such as Trenissimo (De Fabris et al., 2018), microsimulation enables the precise simulation of complex scenarios, such as train maneuvers within freight terminals, the management of track assignments, and the optimization of operational workflows. Through this approach, key performance metrics, including time distribution, capacity utilization, bottleneck identification, and overall operational efficiency, can be evaluated under varying conditions. This level of granularity facilitates informed decision-making and, for this reason, the time distributions determined with Trenissimo are utilized within the DES simulation for railway operations. As an example, in Fig. 2 the model for the railway terminal of the port of Genoa can be appreciated.

2.3.2. Total price for the transport service

The price list made available by the individual terminal, together with unstructured interviews with shippers and freight forwarders, can be used to compute the costs to be paid for the transport. It should be mentioned that prices are subject to negotiation, but given the comparative purposes of this paper, average prices are taken into account for the application to the case study. In calculating the total service price, the main cost items were considered as suggested by the terminals consulted. Some items such as container detention costs were not considered in the methodology, because they are invariants with the transport chain. Some others, like yard storage costs, were neglected because on average, in the simulated scenarios, the free-of-charge storage period was never exceeded.

This criterion refers to the transport price of a container (1 TEU, 25 tons) from the time it is unloaded from the ship to its final destination. For all transport chains, there is a Terminal Handling Charge (THC), which is a fixed fee collected from terminal operators for handling the container at a particular terminal, either port terminal or inland terminal with different pricing. These fees generally cover the cost of services related to the loading, unloading, and storage of goods (within a certain allowance) at the terminal facility in addition to all necessary administrative activities. For intermodal transport, besides additional costs of THC at the intermodal terminal for loading and unloading the container to and from the train, shunting costs must be taken into account. However, these are not calculated in the case of the FEMU, which can perform maneuvering itself without the need for locomotive shunting, as seen in Section 2.2. The cost related to rail transport [euro/km] is the sum of costs that depend on the speed class, the axial load of the train, the number of pantographs, and a fixed cost involving signaling (RFI, Ferrovie dello Stato, 2023). In the case of FEMU for example, the speed class will be higher than that of the standard freight train. Road transport price is calculated based on a [euro/km] tariff. In contrast, in the case of intermodal transport, last-mile road transport is considered a fixed tariff, since for a limited number of kilometers that fall within a last-mile logic, the price is flat. Table 3 summarizes the cost items considered in the transportation chains included in the choice alternatives.

When calculating costs, if future scenarios are considered, at least inflation needs to be taken into account if no provisional estimate is available. As with the timing calculations, the methodology neglects what happens before the container arrives at the port and instead starts the analysis from the moment the container is unloaded from the ship. This does not create issues in the multi-criteria since the preceding steps are common to all alternatives considered, as this paper only deals with the forwarding of the goods in the inland territory.

2.3.3. Scalability

Scalability is a key performance indicator (KPI) that measures how the performance of the considered transport chain varies as the scenarios considered in the analyses change. In the present research, scalability was considered under scenarios that take into account changes in modal share and transport demand to assess the response of a given transport chain in terms of time and cost. The KPI developed for this methodology is applicable even if the scenarios are made to vary according to factors other than those considered here. However,

Table 3
Costs considered for the multicriteria analysis.

Cost items	All-road	Intermodal CONV	Intermodal CONV+FC	Intermodal FEMU	Intermodal FEMU+FC
THC	✓	✓	✓	✓	✓
THC rail terminal		✓	✓	✓	✓
Customs checks	✓	✓		✓	
Fast Corridor			✓		✓
Shunting operations (port)		✓	✓		
Shunting operations (inland)		✓	✓		
Rail transport		✓	✓	✓	✓
Road transport	✓	✓	✓	✓	✓

modal share and demand variations are major factors to account for when choosing between all-road and intermodal transport chains.

Hereinafter the computations for the scalability KPI are presented. The following variables can be defined:

- t_i: Transit time for scenario i
- p_i: Total price for scenario i
- $t_{n,i}$: Normalized transit time for scenario i
- $p_{n,i}$: Normalized total price for scenario i
- $\overline{t}_n$: Average normalized transit time across scenarios
- $\overline{p}_n$: Average normalized total price across scenarios
- KPI: Scalability Key Performance Indicator
- N: Total number of scenarios

By applying the steps described in Section 2.3.1 and in Section 2.3.2, it is possible to compute the transit time t_i and the total price p_i for each scenario i (where $i = 1, 2, \dots, N$). After that, for each of the two indicators, a normalization on the maximum is implemented to find the percentage deviation of the currently analyzed scenario.

$$t_{n,i} = \frac{t_i}{\max(t_1, t_2, \dots, t_N)}, \qquad \forall i \tag{1}$$

$$p_{n,i} = \frac{p_i}{\max(p_1, p_2, \dots, p_N)}, \qquad \forall i \tag{2}$$

At this point, the resilience of the various transportation networks is assessed by calculating the average of each indicator for each alternative across all possible scenarios.

$$\overline{t}_n = \frac{1}{N}\sum_{i=1}^{N} t_{n,i} \tag{3}$$

$$\overline{p}_n = \frac{1}{N}\sum_{i=1}^{N} p_{n,i} \tag{4}$$

Given the objective of selecting a single KPI for scalability that encompasses both time and cost, aligning with the most relevant criteria identified during interviews, the average percentage of time improvement was combined with the one of cost improvement. Hence, the computation for the KPI Scalability results in the simple average:

$$KPI = \frac{\overline{t}_n + \overline{p}_n}{2} \tag{5}$$

2.3.4. Transportability

Transportability refers to the ease of transporting a specific type of goods. This index is a value between 0 and 1 where 0 means that a particular good category cannot or is not transported by the modes of transportation included in the considered chain, and 1 the opposite. To evaluate this parameter, the following categories of goods were considered: high-value (such as luxury items and high tech), perishable, heavy, dangerous, and average goods. With the advice of experts in the field, Table 4 was filled in taking into account that they refer specifically to the Italian context analyzed in the case study.

In general, it is more difficult to transport heavy goods by road over long distances. For this reason, an intermediate score has been assigned. In contrast, this type of cargo is easily transported by train. The same intermediate score applies to perishable goods, often transported by truck mainly due to the tight delivery times for certain specific types of these products. Intermodal transport is less suitable, and, therefore, often less used also for high-value goods (Samsung SDS, 2024; Dionori et al., 2015; Hanssen and Mathisen, 2011). The experts consulted state that in Italy, the transport of these goods by train is negligible, which is why it was decided to assign a value of 0. The FEMU, among its advantages, can easily transport all types of goods.

2.3.5. Reliability

The Reliability criterion is an aggregate index that takes into account several factors: on-time delivery, monitorability, safety, and security. This index also includes reliability in the transportation service offering since, for example, in road transport, there is great difficulty in finding drivers throughout Europe. This criterion was rated by the consulted experts during unstructured interviews through a Likert scale [1,5] where 1 means that the transport chain is not at all reliable while 5 means that the considered chain is very reliable, subjectively considering all the factors that contribute to the reliability of the service. Table 5 shows the reliability index, calculated as arithmetic average of all responses provided and used as a summary variable for the MCA analysis.

Road transportation is widely regarded as the most reliable and flexible mode of transportation. However, experts generally acknowledge the challenge of securing drivers for extended routes, which has become a significant issue across Europe, particularly in Italy. Intermodal transportation is generally considered less reliable due to several factors. Firstly, there is a high incidence of delays. Secondly, the container is transferred under the responsibility of multiple stakeholders. In general, the greater the number of stakeholders involved in the container's movement, the higher the likelihood of an error occurring. Additionally, there may be instances when the container is less monitored, increasing its susceptibility to theft. Fast corridors are generally favored because they facilitate the reduction of delays and, consequently, the overall transit time. Moreover, the fast corridors routes are thoroughly monitored via Customs Agency platforms and are therefore significantly more secure. Finally, the FEMU is not yet operational, but experts consider the absence of certain stakeholders (such as the shunting company) as an improvement in terms of reliability and delay reduction. Furthermore, given its monitorability, it significantly reduces theft risks and enables tracking of the cargo. The high speed of the train could further enhance its ability to arrive on time (for more details refer to Section 2.2). The same considerations previously done on FC apply also here.

2.3.6. Greenhouse gas emissions

Emission reduction targets (European Commission, 2019; Consilium Europa, 2024b) under European regulations are based on Tank To Wheel (TTW) emissions or local emissions, also known as tailpipe emissions. However, in this research, it was decided to consider Well-to-wheel (WTW) emissions, taking a more comprehensive Life Cycle Assessment (LCA) perspective of transportation. This approach is increasingly used, especially in the evaluation of alternatives to make informed decisions in the transportation sector. Specifically, the chosen

Table 4
Transportability.

Goods category	All-road	Intermodal CONV	Intermodal CONV+FC	Intermodal FEMU	Intermodal FEMU+FC
High value goods	1	0	0	1	1
Perishable goods	1	0.5	0.5	1	1
Heavy goods	0.5	1	1	1	1
Dangerous goods	1	1	1	1	1
Average goods	1	1	1	1	1
Transportability (Mean value)	**0.9**	**0.7**	**0.7**	**1**	**1**

Table 5
Reliability.

	All-road	Intermodal CONV	Intermodal CONV+FC	Intermodal FEMU	Intermodal FEMU+FC
Reliability (Likert scale)	4	2	3	3	4

criterion considers CO_2e emissions, usually used as a climate change indicator. ISO 14083 (International Organization for Standardization, 2023) defines an international standard for calculating CO_2e emissions in logistics chains. There are several tools compliant with the standard that help in calculating and reporting emissions (Olivari et al., 2024a). Emission calculations were performed using EcoTransit, a commercial tool compliant with ISO 14083 and the GLEC Framework. EcoTransit applies country- and mode-specific emission factors internally, including rail-specific electricity mixes that differ from national average electricity generation mixes. These parameters are automatically selected based on the geographical routing of the transport chain and the reference year of the dataset. The tool also includes emissions related to nodes that are part of the transportation chain in the calculation.

For the Italian context, the electricity mix applied corresponds to the EcoTransit database available at the time of analysis (2024), which is based on the latest consolidated national statistics (reference year 2021; as an example the Italian electricity mix EcoTransit used for the calculation was as follows: Coal: 4.7%; Oil: 2.1%; Gas: 51.5%; Renewables: 34.6%; Other: 7.1%). As EcoTransit periodically updates emission factors and electricity mixes internally, individual emission factors for different fuels are not reported explicitly in order to avoid inconsistencies between documented values and the tool's calculations.

The use of only standard diesel-powered shunting operations within EcoTransit represents a conservative modeling choice, intentionally avoiding optimistic assumptions that could overestimate the environmental performance of rail-based solutions. Alternative low-emission rail propulsion technologies, such as hydrogen-powered freight trains, in fact, were not included in the analysis. While promising, these technologies are currently limited to pilot or demonstrator projects and are not part of standard freight rail operations in the Italian context. Their exclusion reflects a deliberate focus on technologies that are currently deployable at scale, in line with the applied decision-support perspective.

2.3.7. Pollutant emissions

As with GHG emissions, also in the case of pollutants, WTW emissions were considered. In this regard, the following were considered and calculated with the assistance of EcoTransit:

- Particulate matter (kg PM)
- Nitrogen oxides (kg NO_x)
- Non methane hydrocarbons(kg NMHC)
- Sulfur dioxide (kg SO_2)

Pollutant emissions were considered aggregated in this analysis by adding the different items together. Since these emissions are still under-considered as a factor in transportation mode choice, given that no "polluter pays" policy exists in this regard, it was not worth considering them unbundled. As with GHG emissions, pollutant emission factors and upstream processes were applied using EcoTransit's country- and mode-specific datasets within a WTW framework.

Table 6
Base set of criteria weights.

Criteria	Nomenclature	Value
Transit time	w_1	0.145
Total price	w_2	0.3
Transportability	w_3	0.03
Reliability	w_4	0.295
Scalability	w_5	0.05
Energy consumption	w_6	0.03
GHG emissions	w_7	0.1
Pollutant emissions	w_8	0.05

2.3.8. Energy consumption

In addition to emissions, the energy consumption required to carry out the transport was also taken into account, again following a WTW logic. This approach ensures a comprehensive assessment by considering not only the direct operational energy use but also the upstream processes associated with fuel production, distribution, and conversion. By adopting the WTW perspective, the analysis captures the full environmental impact of transport activities, providing a more accurate comparison between different transport modes and fuel types. The energy consumption values were calculated using the EcoTransit tool, by allowing for the estimation of both direct and indirect energy inputs, thereby enhancing the reliability and depth of the results. Energy consumption values are therefore consistent with the same emission factor datasets used for GHG and pollutant calculations, ensuring internal coherence across all environmental indicators. Overall, incorporating energy consumption alongside emissions offers a more holistic understanding of the sustainability performance of the transport options evaluated in this study.

2.4. Criteria weighting and sensitivity analysis

In terms of assigning weights to each criterion included in the MCA, the full consistency method (FUCOM) was used (Feizi et al., 2021; Ayan et al., 2023). FUCOM is a MCA method designed to calculate criterion weights using a structured procedure that ensures high consistency among expert or decision-maker preferences. It is mainly used when criteria are to be ranked according to their relative importance and is particularly valued for its mathematical rigor and ability to eliminate inconsistencies in ratings.

The weights calculated for the criteria considered from the opinion of industry experts consulted through unstructured interviews and applying FUCOM are shown in Table 6.

When conducting an MCA, it is good practice to perform a sensitivity analysis to assess the robustness and reliability of the decisions made. This is a critical step to understanding how variations in parameters or criteria weights may affect the results and conclusions of the analysis. Since several scenarios had already been considered

Table 7
Criteria weights for sensitivity analysis.

Criteria	Nomenclature	GHG focused weights	GHG and pollutants focused weights
Transit time	w_1	0.1	0.09
Total price	w_2	0.24	0.15
Transportability	w_3	0.03	0.02
Reliability	w_4	0.2	0.2
Scalability	w_5	0.05	0.04
Energy consumption	w_6	0.03	0.02
GHG emissions	w_7	0.3	0.24
Pollutant emissions	w_8	0.05	0.24

in the scalability KPI, it was decided to vary only the weights by making considerations of possible future scenarios that might lead to a reassessment of the relative importance of the criteria. Environmental sustainability considerations are very common at this time in history considering the rapid regulatory changes in this context. Therefore, it is reasonable to consider these aspects to assess the robustness of the results. Specifically, the following questions were addressed:

- What if, in the future, the concept of "the polluter pays" forces stringent accounting of GHG emissions?
- What if the concept of "the polluter pays" compelled stringent accounting of pollutant emissions as well?

Table 7 shows the weights used for the sensitivity analysis.

This methodology applies in general. As such, the weights can be varied based on the needs and considerations of the specific case being considered. Having the weights vary based on changes in the importance given to environmental factors is just one possible example.

3. Case study

3.1. Origin and destinations

In order to validate the presented methodology, the application to a relevant case study for the Italian context is reported here, namely the case of the port of Genoa and possible industrial destinations in the Italian territory.

The Port of Genoa PSA, with a throughput of more than 1.5 million TEUs (Pozzo, 2024), is one of the major Italian ports, but it suffers from the lack of space and the quality of the inland connections in terms of transportation infrastructure around it (Buonfanti, 2014). This is noticeable from the center of gravity of the so-called European Blue Banana, which is much more shifted towards northern ports, more able to better exploit, thanks to the orography of the territory and more efficient infrastructures, the connections with inland areas (Buonfanti, 2014).

For this analysis, the Italian peninsular territory was divided into 6 macro-regions: the North–West, Lombardy, the North–East, the Central area, the South–East, and the South–West. For each of these six macro-regions, a reference rail terminal was chosen, and around it, within a 50-km radius, 4 final destinations. The map with the destinations analyzed is shown in Fig. 3 and it is possible to find more details in Table 8. In particular, for the last mile, it is relevant to underline that the highest average distance is registered in the North–West (50 km on average), then the Central Area with 49 km on average, followed by South–West with 48 km, Lombardy with 47 and finally North–East with 37 and South–East with 36.

3.2. Future scenarios definition

As already mentioned in Section 1, freight transport in Italy is dominated by road haulage. Therefore, the base scenario of the analyses takes into account the average Italian modal share, which is 85% road - 15% intermodal rail-road (Dumont, 2024). Starting from this baseline, several scenarios were developed to assess the system scalability under different configurations. The 25% increase in demand was selected to represent the expected growth in freight volume at the port of Genoa in the coming years due to infrastructural development. With regard to modal share the cases were defined in line with the medium and long term objectives set by the European Union to increase the contribution of rail transport to freight transport, while an additional 'equal split' case (50%–50%) was introduced as a highly optimistic reference scenario. Once the key parameters to be varied in the different scenarios and their respective levels had been defined, these were treated as exogenous inputs within the model. A full factorial experimental design was adopted to systematically explore all possible combinations as summarized in Table 9. These scenarios were used for the computation of the "Scalability KPI".

In addition, given what has been said about the issue of storage space, the Fast Corridor alternative acquires significance, not only in terms of time or costs (faster operations, lower price) but also as a solution for better space management from the port point of view, especially in correspondence with the peak volumes of containers unloaded by cargo ships.

3.3. Assumption for the case study

For the case study, average data were used for data not retrieved from historical port and/or terminal records. This was the case for both port and fast corridor customs controls. The assumption is that, on average, 10% of containers undergo customs control, regardless of modal choice. The fast corridor is exclusively utilized for intermodal transport (both conventional and with FEMU), and also in this case, 10% of containers transported via this mode are subject to customs inspection. Another figure that is not available in the records as a statistical distribution but which we had to consider as an average is the average level of train loading. A 78% fill ratio was considered for both conventional trains and FEMUs since this is the only data provided by the terminal operator. It is important to underline that the FEMU (with 11 three-car modules capable of carrying up to 99 TEUs) has a greater capacity compared to a conventional train (assumed to average 66 TEUs at full load).

With regards to road transportation, four different energy carrier technologies have been considered: diesel, compressed natural gas (CNG), and liquefied natural gas (LNG) for internal combustion engines; and battery electric vehicles.

The scores assigned to transportability and reliability, and the criteria weighting were obtained through an unstructured expert interview process. The objective of this process was to provide realistic and context-consistent inputs for the validation of the proposed decision-support methodology. The reliability criterion aggregates multiple qualitative dimensions, including on-time delivery, safety, security, and monitorability. These dimensions were jointly considered by experts during the interview process, based on their operational experience, rather than being combined through a formal statistical weighting or data-driven aggregation procedure.

A total of 19 experts were involved in the interview process. The panel included professionals with extensive experience in railway operations, intermodal terminals, ports, shunting services, freight forwarding, trucking companies, and railway infrastructure management. All participants had direct operational responsibilities and long-term professional exposure to Italian and European freight transport chains. Their assessments were therefore informed by internal operational data and practical experience; however, such internal datasets were not accessible to the authors and could not be independently validated or disclosed.

Given the heterogeneity of stakeholder roles and objectives, full consensus was not observed across all dimensions. The resulting scores therefore reflect aggregated expert judgment rather than statistically derived indicators. As such, they should be interpreted as indicative and scenario-specific inputs, suitable for methodological validation in a real-world case study context, but not as universally applicable or statistically validated performance metrics.

Fig. 3. Case study destinations Map.

Table 8
Destination divided in macro-regions.

Macro-region	Railway terminal	Final destinations	Average distance
North–West	SITO Torino	Torino, Alba, Asti, Ivrea	141 km
Lombardy	Melzo	Milano, Bergamo, Pavia, Como	176 km
North–East	Padova	Padova, Vicenza, Treviso, Venezia	385 km
Central area	Orte scalo	Viterbo, Sassacci P.i.P., Rieti, Roma	492 km
South–West	Nola	Napoli, Caserta, Salerno, Battipaglia	738 km
South–East	Bari	Bari, Bisceglie, Andria, Monopoli	942 km

Table 9
Scenarios definition. They will be used in the computation of the scalability KPI.

Scenario	Import demand	Road modal share	Railway modal share
Base scenario	Current demand	85%	15%
Base + higher demand	+25%	85%	15%
30-by-30	Current demand	70%	30%
30-by-30 + higher demand	+25%	70%	30%
Equal share	Current demand	50%	50%
Equal share + higher demand	+25%	50%	50%

4. Results and discussion

Next, the results of applying the methodology to the case study presented in the previous section are illustrated and discussed. The first notable result is shown in Fig. 4. Intermodal transport, be it with conventional trains or FEMUs, shows a stable cost in terms of [€/container] with respect to road transport. Cost convenience is, hence, reached at around 250 km, below the 300 km target envisaged by the European Union, justifying the policy of mode diversion for medium to long distances. However, this exact value of 250 km is bounded to the specific context and data availability.

Shown in Fig. 5 are the dominance graphs resulting from applying the MCA to the six macro-regions.

The five alternatives are represented on the graphs' nodes. Specifically, "All-Road" refers to all-road transport, "CONV" is traditional intermodal, "FC" represents fast corridor, and "FEMU" represents intermodal transport but with the next-generation train. The connecting arcs between the nodes are oriented in the direction of surclassing, i.e., when option A_i is preferable to A_j it is represented by $A_i \rightarrow A_j$. Moreover, if A_i and A_j are incomparable there is no arc between the two alternatives, whereas if they are indifferent the graph is not oriented. This condition is represented in the figure by an arrow with two arrowheads. In general, the dominant solution is represented by the node with the highest number of exiting arcs, and conversely, the dominated one by the node with the highest number of entering arcs.

With these assumptions, it is clear from Fig. 6, that each region has its own unique dynamics of interaction among transport modes, reflecting localized preferences or infrastructural limitations, which mainly affect transportation costs and times.

Apart from the case of the North–West where the low total distance and relatively long last-mile distance tend to make road the clearly dominant option, in the other conditions intermodal transport always turns out to be rather convenient. However, this is also clear from the rankings, depicted in the figure, where as the distance increases, the most convenient options are intermodal transport, preferably with Fast Corridor, which increases the speed of service and lowers the costs associated with customs clearance. As mentioned earlier, the methodology does not take into account other positive externalities, such as reduced road congestion in areas near the port resulting in lower local emissions, or better space management, as dealing with the issue of putting oneself from the point of view of those who have to ship a container, but these benefits, too, could support the case for using this service. The higher cost of FEMU, in the current

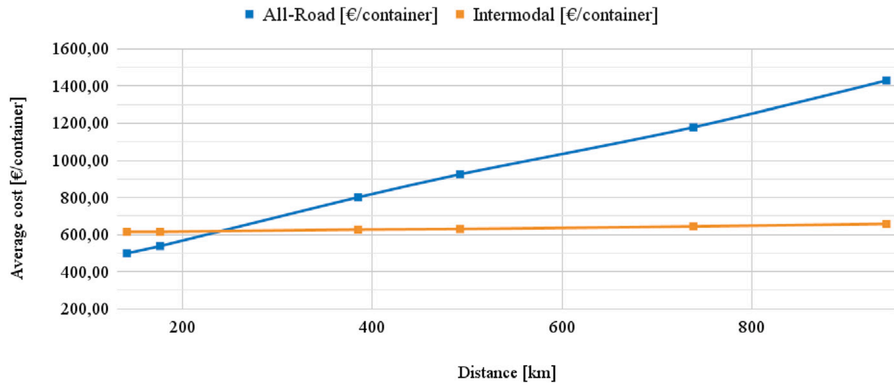

Fig. 4. Costs as function of distance for combined and all-road transport.

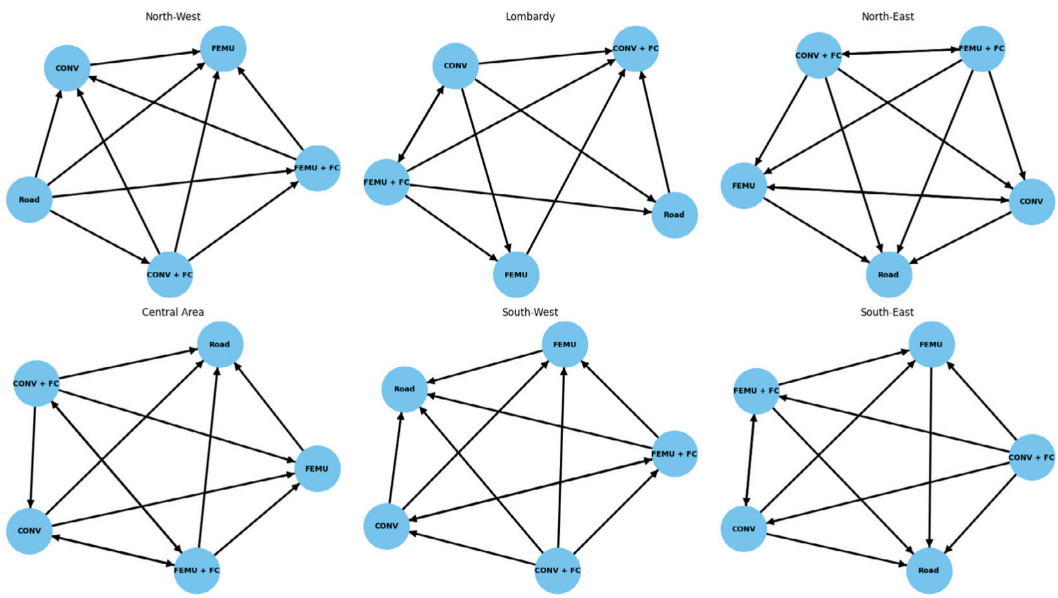

Fig. 5. Dominance graphs for the six regions with the base set of weights as in Table 6.

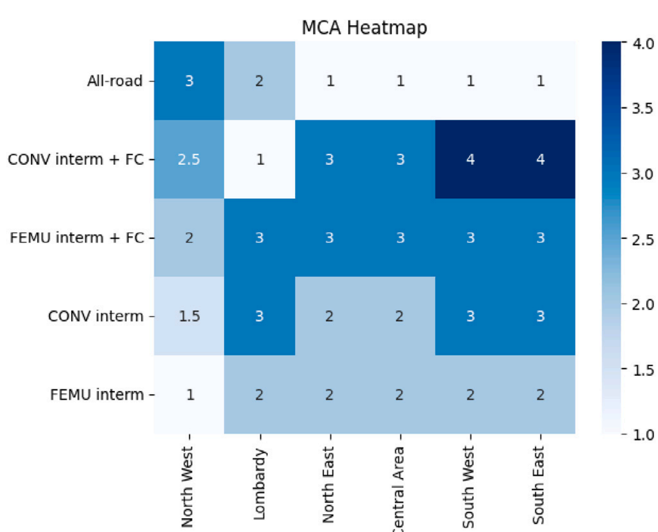

Fig. 6. Heatmap of the ranking of choices as a function of the distance. Base weights for the criteria.

evaluation of the criteria weights as indicated by the experts, tends to lower its ranking. This problem could be curbed by data exchange strategies with the infrastructure operator, an aspect not taken into account by the proposed methodology, which instead is based on list prices. The FEMU, in fact, has, as mentioned above, an advanced monitoring system, for both the cargo and the train's running dynamics. In particular, it has a pantograph-to-overhead contact line monitoring system, gyroscopes, and accelerometers, making the FEMU exploitable as a diagnostic train for the infrastructure. An agreement to reduce high-speed rail fares in exchange for data for better network maintenance might actually make the FEMU more cost-effective as well. The fast corridor ("+ FC") appears critical for both FEMU and CONV options in most regions, greatly improving rankings and underscoring the importance of advanced infrastructure in freight transport.

To justify the dominance graphs and the ranking of alternatives, the results of each criterion for the North–West and South–East macro-regions are provided for the sake of clarity. All other cases have the total and last-mile distances between the two illustrated here. Note that for the sensitivity analysis, as already illustrated in Table 7, only the values of the criteria weights change, while the values assumed by the criteria themselves remain constant.

As can be seen in Table 10, for the North–West macro-region, even if transit times are almost comparable, the price to be paid is much higher for train alternatives. The absence of shunting locomotives compensates for the higher price per km for the FEMU with respect to

Table 10
Values of criteria for each alternative in the North–West macro-region.

North–West	Transit time [h]	Total price [€/container]	Transportability [–]	Reliability [–]	Scalability [–]	Energy consumption [liters of diesel equivalent]	GHG [ton]	Pollutant emissions [kg]
All-road	132.75	491.40	0.9	4.0	0.31	99.09	0.22	0.60
CONV	148.21	632.24	0.7	2.0	0.12	100.10	0.23	0.65
CONV + FC	144.55	602.24	0.7	3.0	0.15	100.10	0.23	0.65
FEMU	143.43	627.36	1.0	3.0	0.26	97.77	0.23	0.64
FEMU + FC	137.79	597.36	1.0	4.0	0.29	97.77	0.23	0.64

Table 11
Values of criteria for each alternative in the South–East macro-region.

South–East	Transit time [h]	Total price [€/container]	Transportability [–]	Reliability [–]	Scalability [–]	Energy consumption [liters of diesel equivalent]	GHG [ton]	Pollutant emissions [kg]
All-road	140.53	1395.40	0.9	4.0	0.21	669.78	1.51	4.05
CONV	159.01	671.80	0.7	2.0	0.38	231.32	0.42	1.35
CONV + FC	153.33	641.80	0.7	3.0	0.40	231.32	0.42	1.35
FEMU	149.47	674.47	1.0	3.0	0.53	151.34	0.29	0.94
FEMU + FC	143.10	644.47	1.0	4.0	0.54	151.34	0.29	0.94

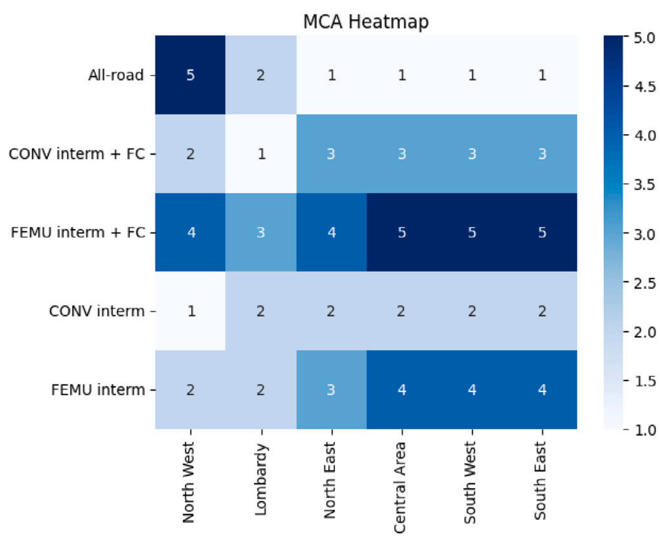

Fig. 7. Heatmap of the ranking of choices as a function of the distance. GHG-focused weight.

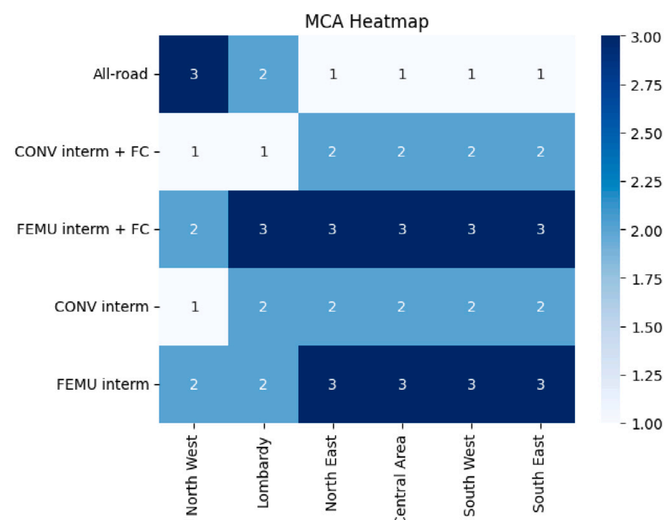

Fig. 8. Heatmap of the ranking of choices as a function of the distance. Pollutants and GHG-focused weight.

the conventional train. The prices are, in any case, much higher than the road and, especially for this reason, it is preferable to all the other modes of transport.

The case of the South–East, Table 11, is on the opposite side with respect to the previous one. In fact, the prices for intermodal transport (both conventional and with the FEMU) remain much lower when compared to the road alternative, which ranks last for this macro-region. It is possible to notice that the FEMU alternative, particularly with FC, results in good transit time (less than 3 h more than the road) and drastically reduced environmental impact. The ranking relationships as decision makers' priorities change are then examined. In particular, the cases when the "polluter pays" policy comes into effect are analyzed. In the first case, Fig. 7, a focus is given to GHG emissions, while in the second case, Fig. 8, an equal importance of pollutants is also considered.

In both cases, the relative weight of cost and transportation time on the choice decreases, leaving room for the most sustainable options. It is evident how under this approach the FEMU gains positions for all distances. In particular, due to shunting without locomotives and due to more TEUs transported, the options with FEMU outperform those of conventional intermodal. All-Road remains convenient only for short distances, where the intermodal terminal is inconveniently located relative to the final destinations of choice.

In the case of Fig. 7 the choice is more straightforward than for Fig. 8, but again it is limiting not to contemplate the benefits of Fast Corridor the presence of positive externalities such as reduced congestion and thus fewer pollutants in the areas adjacent to the port. Despite this, it is correct for shippers that the choice between the alternatives with and without fast corridor is less obvious, as in this scenario the cost and time of transportation have combined weight equal to GHG only or pollutants emissions only and therefore are much less relevant. In all regions, the All-Road option drops significantly in the ranking, as road transport generates significantly higher GHG and pollutant emissions than rail alternatives. This is not affected by the presence of electric trucks in the tally since, although they have less carbon footprint, the added weight contributes to the elevation of the energy required for travel, and consequently, given the consideration of a WTW perspective, also of GHG and pollutants. However, the importance of fast corridors remains significant, particularly for FEMU configurations, where the infrastructure amplifies the environmental benefits of next-generation freight trains. However, such results underscore the transformative effect of greater weighting of environmental considerations. The FEMU design, especially in combination with fast corridors, emerges as the most sustainable option, especially over medium and long distances. The results demonstrate how aligning transportation strategies with GHG reduction goals can shift regional preferences and underscore the need to invest in low-emission intermodal transportation solutions.

5. Policy implications and framework transferability

5.1. Context

Although this study focuses on the simulation and evaluation of freight transport alternatives using a technical decision-making framework, modal shift in freight transport is widely recognized as a socio-technical process that cannot be explained by techno-economic performance alone. Freight transport choices are embedded in a complex institutional and political environment, shaped by a wide range of stakeholders whose interests may diverge or conflict. Within this context, policy design and implementation play a decisive role in determining both the feasibility and effectiveness of intermodal solutions.

The framework presented in this study is designed to be independent of specific policy instruments. Its primary aim is to support decision-makers by objectively evaluating the conditions under intermodal transport becomes the most advantageous option economically, operationally, and environmentally. The results demonstrate that intermodal solutions outperform all-road alternatives beyond certain distance thresholds, particularly when externalities such as emissions are taken into account.

However, despite this evidence, modal choices in freight transport are often influenced by established practices and habits, as well as by incumbent stakeholder interests and established operational routines, such as a preference for road transport simply because “it has always worked well”. This kind of inertia can persist even when intermodal options offer clear advantages. In this context, public policies and incentives may not be strictly required from a purely rational cost-benefit perspective, but they can play an important role in overcoming structural resistance and accelerating the transition to more sustainable logistics models. These considerations do not undermine the technical and environmental advantages of intermodal transport identified in this study. Rather, they highlight the importance of aligning technical solutions with institutional and policy frameworks to ensure their successful implementation.

Incentive mechanisms like Italy’s Ferrobonus program, which provides partial reimbursement for rail transport costs, are just an example of how economic levers can be used to encourage modal shift. However, the long-term impact of such schemes depends not only on their economic rationale, but also on factors such as political alignment and budgetary constraints.

Subsidies and incentives can serve not only environmental goals but also support broader development objectives, including the development of specific sectors and regions. Promoting intermodal transport, for example, may encourage investment in terminal infrastructure and logistics technologies, thereby indirectly fostering innovation and regional development.

The European Commission promotes modal shift through the Green Deal and regulatory instruments aligned with the Polluter Pays Principle. However, the implementation of carbon pricing or pollutant surcharges, such as the proposed expansion of the European Emissions Trading System to road freight (ETS-2), has encountered organized opposition from road transport stakeholders concerned about cost competitiveness and distributional impacts. Consequently, these tensions have, in several cases, led to delays or exemptions in key regulatory mechanisms.

While the multi-criteria evaluation framework proposed in this paper is generalizable in terms of the criteria selected and the methodology used to compute them, the set of alternatives evaluated and the scenario assumptions are context-specific and refer to the Italian case study. For instance, elements such as the Fast Corridor customs procedure or the assumptions regarding freight demand growth reflect institutional and operational characteristics that are specific to the case study considered.

As a result, the policy insights derived from the analysis should not be interpreted as universally applicable, but rather as context-dependent findings. However, this does not reduce the validity or relevance of the proposed framework. On the contrary, its structure is designed to be flexible and adaptable: by adjusting the set of alternatives, input data, and contextual assumptions, the same methodological approach can be applied in different regions or countries to support informed and evidence-based decision-making.

Policy transfer, therefore, is possible, but it requires careful consideration of institutional differences, regulatory frameworks, and logistical conditions. As in many transport policy domains, transferability may be limited by path dependencies, regulatory fragmentation, and the uneven capacity of local administrations.

5.2. Relevance of the proposed framework

In addition to supporting the assessment of modal alternatives from the perspective of individual shippers or logistics operators, the proposed framework can be interpreted as a decision-support tool for public authorities involved in transport planning and policy design. When adopted from a policy-making perspective, the same methodological structure can be used to evaluate the systemic effects of regulatory interventions, incentive schemes, and infrastructure strategies under multiple scenarios.

In particular, the integration of multicriteria analysis with discrete event simulation enables the assessment of how policy instruments alter the relative performance of competing transport chains, not only in absolute terms, but also in terms of robustness across varying demand levels, congestion conditions, and regulatory assumptions. By explicitly modeling transit time, costs, scalability, and environmental externalities, the framework helps policymakers to anticipate second-order and indirect effects that may otherwise be neglected, such as congestion spillovers, capacity saturation, and reliability degradation under increased demand.

From a governance perspective, the framework can be used to support the design of targeted and performance-based incentive mechanisms. Instead of uniform subsidies applied irrespective of outcomes, incentives to companies may be conditionally linked to measurable improvements in selected criteria, such as reductions in greenhouse gas emissions, enhanced reliability, or improved scalability under high-demand scenarios. In this sense, the framework supports the transition from generalized support schemes towards outcome-oriented subsidy design, aligning public expenditure more closely with policy objectives related to sustainability, efficiency, and system resilience and strengthening the accountability of public intervention.

The framework also provides a structured basis for addressing regional equity considerations in freight transport policy. By applying the same modeling approach to different corridors, ports, or hinterland regions, policymakers can assess the spatial distribution of benefits and costs associated with alternative policy choices. This enables the identification of asymmetric impacts across territories, such as the concentration of logistics advantages in specific regions or the marginalization of peripheral areas. Rather than assuming territorial neutrality, the framework makes distributional effects explicit, thereby supporting more informed decisions regarding regional compensation measures, differentiated incentives, or prioritized infrastructure investments.

Furthermore, when fed with statistically significant data, transparency and formalization of criteria, weights, and scenario assumptions help mitigate the influence of interest pressures in transport decision-making. Policy proposals can be evaluated within a consistent analytical structure, where claimed benefits must be reflected in observable improvements in one or more performance indicators. While the framework does not eliminate political negotiation or stakeholder influence, it provides a common quantitative reference that can reduce informational asymmetries and improve accountability. In this respect, it can be interpreted as a governance-support tool that enhances transparency and limits discretionary decision-making, by distinguishing between interventions that generate systemic value and those that primarily deliver localized or sector-specific advantages.

Finally, the framework is particularly suited to supporting policy decisions under evolving regulatory contexts, such as the progressive internalization of external costs through carbon pricing or pollutant-based charges. Sensitivity analyses on criteria weights, as presented in this study, allow policymakers to explore prospective regulatory regimes before their formal implementation, assessing how different transport chains would respond to stricter environmental accounting. The ability to be proactive is particularly important in contexts characterized by regulatory uncertainty and stakeholder resistance, as it allows for the development of transitional measures that preserve competitiveness while remaining consistent with long-term climate and sustainability goals.

Overall, while the framework was applied in this study to a specific Italian case, its value extends beyond comparative technical evaluation. When reframed from a public-sector perspective, it can function as a policy experimentation and assessment sandbox, supporting evidence-based transport governance, transparent subsidy allocation, and territorially balanced logistics development.

6. Conclusions

In this paper, a novel methodological approach is proposed to support the decision-making process in intermodal freight transportation, with the ultimate goal of favoring the use of intermodal transport and enhancing sustainability. The methodology is a multicriteria analysis based on the simulation of alternative transport chains. The criteria considered in the selection include transit time, total price, scalability, transportability, reliability, energy consumption, GHG, and pollutant emissions. The weights were defined according to experts' opinions and reshaped by the FUCOM method. The five transport chains analyzed (all-road, conventional intermodal, conventional intermodal with fast corridor, intermodal with FEMU, and intermodal with FEMU and fast corridor) were simulated with a discrete event model developed by the authors. Nested within these simulations is the rail microsimulation, which allowed statistical distributions of times to be determined. The environmental sustainability of the alternatives was assessed with a well-to-wheel perspective, unlike what current policies stipulate. This is to take into account all emissions actually produced by alternatives with different powertrains and energy carriers.

The proposed methodology, which here considers only the five alternatives described, can be extended to other transportation chains and criteria due to its flexibility and generalizability. Indeed, in decision-making processes, the most complex thing is to find reliable data. The methodology proposed here reduces this issue by simulating most of the processes involved. However, more precise and primary data allows the outputs of the simulations to be more accurate. Among the criteria used, for our case study, reliability is an estimation based on unstructured interviews. As said, this criterion includes several factors (such as safety, and on-time delivery) that could have been separated for greater accuracy of the MCA. To do this, it is necessary to arrange more structured interviews with shippers and to obtain a distribution of freight train delays from the rail infrastructure manager. This issue will be targeted in upcoming research. A further factor that this methodology underestimates is the positive externalities of using the Fast Corridor, especially derived from the reduced congestion near ports. Regarding the transportation chains analyzed in the case study, it is clear how intermodal transportation can be the winning one if environmental sustainability policies begin to play a greater role. In particular, a new generation train such as the FEMU, can further improve the performance of intermodal transport, making it more competitive. The results also show that especially for short routes the rail terminal must be in a strategic location, to make intermodal competitive and this is not always the case in our case study. In any case, the study shows that for distances higher than approximately 250 km intermodal transport results more competitive than road transport, in line with the policies promulgated by EU. Fast Corridor stands as an improving factor in intermodal chains, with cost and transit time gains.

This research provides the tools to assess the true cost-effectiveness of intermodal transport and the impact of emerging technologies on logistics. By enabling informed decision-making, it paves the way for revitalizing rail as the backbone of freight transport, contributing to climate change mitigation through strategic and sustainable choices.

CRediT authorship contribution statement

Erika Olivari: Writing – original draft, Writing – Review & Editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Simona Gurrì:** Writing – original draft, Writing – Review & Editing, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Francesca De Marinis:** Writing – original draft, Writing – Review & Editing, Visualization, Investigation, Data curation. **Claudia Caballini:** Writing – original draft, Supervision, Data curation.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Criteria weighting method: FUCOM

A brief introduction of the method is given below and then the results are shown in Tables A.12 and A.13.

The FUCOM consists of 4 steps:

1. *Criteria Ranking*: The criteria $C = \{C_1, \ldots, C_n\}$ are ranked in descending order of importance, based on the preferences of the decision-makers.

$$C_{j(1)} > C_{j(2>)} > \cdots > C_{j(k)} \tag{A.1}$$

2. *Comparing the ranked criteria*: The comparative priority $\phi_{\frac{k}{k+1}}$ of the criteria (with $k = 1, 2, \ldots, n$ representing the rank of the criteria) is determined according to the equation:

$$\phi = \{\phi_{\frac{1}{2}}, \phi_{\frac{2}{3}}, \ldots, \phi_{\frac{k}{k+1}}\} \tag{A.2}$$

3. *Weight coefficient are calculated*: Weight coefficients of the targeting criteria $(w_1, w_2, \ldots, w_n)^T$ are calculated. These values should meet the following conditions:

Table A.12
Comparative priority matrix FUCOM.

Comparative priority								
	Price	Reliability	Time	GHG	Scalability	Pollutants	Transportability	Energy
Price	1	1	0,5	0,33	0,2	0,25	0,2	0,2
Reliability	1	1	0,5	1	1	1	1	1
Time	2	2	2	2	1,25	1	1	1
GHG	3,03	1,52	2,98	3	4,17	1	1	1
Scalability	5	1,65	8	3,61	5	3,33	1	1
Pollutants	4	0,8	8	12	6,02	4	2	1
Transportability	5	1,25	10	15	25	10	5	6,25
Energy	5	1	10	15	25	20	4	4

Table A.13
Consistency matrix FUCOM.

Consistency								
	Price	Reliability	Time	GHG	Scalability	Pollutants	Transportability	Energy
Price	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0
Reliability	1,02	0,00	0,00	0,00	0,00	0,00	0,00	0
Time	2,07	2,03	0,00	0,00	0,00	0,00	0,00	0
GHG	3,00	2,95	1,45	0,00	0,00	0,00	0,00	0
Scalability	6,00	5,90	2,90	2,00	0,00	0,00	0,00	0
Pollutants	6,00	5,90	2,90	2,00	1,00	0,00	0,00	0
Transportability	10,00	9,83	4,83	3,33	1,67	1,67	0,00	0
Energy	10,00	9,83	4,83	3,33	1,67	1,67	1,00	0

Table B.14
Concordance matrix North East region, base set of weights.

	All-road	CONV interm	CONV interm + FC	FEMU	FEMU interm + FC
All-road	0.000	0.805	0.805	0.775	0.775
CONV interm	0.195	0.000	0.655	0.625	0.625
CONV interm + FC	0.195	0.555	0.000	0.620	0.625
FEMU	0.225	0.375	0.675	0.000	0.655
FEMU interm + FC	0.520	0.375	0.375	0.555	0.000

Table B.15
Disordance matrix North East region, base set of weights.

	All-road	CONV interm	CONV interm + FC	FEMU	FEMU interm + FC
All-road	0.0	0.0517	0.038	0.0334	0.014
CONV interm	0.889	0.0	0.003	0.0034	0.007
CONV interm + FC	0.992	0.103	0.0	0.0955	0.003
FEMU	0.897	0.02	0.02	0.0	0.003
FEMU interm + FC	1.0	0.1106	0.0237	0.103	0.0

Table B.16
Credibility matrix North East region, base set of weights.

	All-road	CONV interm	CONV interm + FC	FEMU	FEMU interm + FC
All-road	0.0	Ss	Ss	Ss	Ss
CONV interm	0.0	0.0	Ws	0.0	0.0
CONV interm + FC	0.0	0.0	0.0	0.0	0.0
FEMU	0.0	0.0	Ws	0.0	Ws
FEMU interm + FC	0.0	0.0	0.0	0.0	0.0

Table B.17
Credibility matrix North East region, base set of weights.

	All-road	CONV interm	CONV interm + FC	FEMU	FEMU interm + FC
All-road	0	P+	P+	P+	P+
CONV interm	P−	0	P+	I	P+
CONV interm + FC	P−	P−	0	P−	I
FEMU	P−	I	P+	0	P+
FEMU interm + FC	P−	P−	I	P−	0

(a)

$$\frac{w_k}{w_{k+1}} = \phi_{\frac{k}{k+1}} \tag{A.3}$$

(b)

$$\phi_{\frac{k}{k+1}} * \phi_{\frac{k+1}{k+2}} = \phi_{\frac{k}{k+2}} \tag{A.4}$$

4. *Optimization problem*: The following optimization problem has to be solved.
Min X
s.t.

$$\left| \frac{w_{j(k)}}{w_{j(k+1)}} - \phi_{\frac{k}{k+1}} \right| = X, \forall j \tag{A.5}$$

$$\left| \frac{w_{j(k)}}{w_{j(k+2)}} - \phi_{\frac{k}{k+1}} * \phi_{\frac{k+1}{k+2}} \right| = X, \forall j \tag{A.6}$$

$$\sum_{j=1}^{n} w_i = 1 \tag{A.7}$$

$$w_j \geq 0, \forall j \tag{A.8}$$

Appendix B. MCA results

Electre II method has been used. As an example, the results for case "North–East" with the base set of weights is reported in Tables B.14–B.17.

Data availability

Data and full computations will be made available upon request.

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