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Resilient and sustainable transport networks: A novel decision-making framework for optimized logistics solution

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Abstract:

*This research presents a novel multi-level decision-making framework for high-speed transportation technologies for industries and small to medium-sized enterprises. The proposed approach facilitates a stakeholder-centred selection of objectives, indicators, features, and performance criteria on the input side, and key performance indicator selection on the output side. The framework incorporates new developments in high-speed logistics transportation, such as hyperloop technology. Advanced technologies are included, thus creating an extended set of KPIs that current frameworks do not support, as they typically only consider existing modes of transport. The approach utilises the **T**echnique for **O**rder **P**reference by **S**imilarity to the **I**deal **S**olution, which considers a variety of impacts and weight parameters. Ultimately, it aims to bridge the gap between evolving political regulations and industrial adoption within the transport sector.*

Keywords: *Hyperloop, MCDM, TOPSIS, Framework, Logistics, Physical Internet*

Physical Internet (PI) Roadmap Fitness*: Select the most relevant area(s) for your paper according to the PI roadmaps adopted in Europe and Japan:* ☒ *PI Nodes (Customer Interfaces, Logistic Hubs, Deployment Centers, Factories),* ☐ *Transportation Equipment,* ☒ *PI Networks,* ☒ *System of Logistics Networks,* ☐ *Vertical Supply Consolidation,* ☐ *Horizontal Supply Chain Alignment,* ☐ *Logistics/Commercial Data Platform,* ☐ *Access and Adoption,* ☐ *Governance.*

Targeted Delivery Mode-s*:* ☒ *Paper,* ☐ *Poster,* ☐ *Flash Video,* ☒ *In-Person presentation*

1 Introduction

Resilience and sustainability have become increasingly important aspects of today's transport networks. Crises such as the conflicts in Ukraine or the Middle East, disruptions in key global shipping routes, extreme climate events, and a lack of truck drivers in Europe clearly demonstrate their impact on logistics and global supply chains. The shortfall in CO_2 reduction targets in transport calls for a fundamental rethink in how we design, manage, and improve transport and mobility systems to enhance sustainability and resilience.

Mario Draghi's Report on the Competitiveness of Europe forecasts a 79% increase in passenger demand globally and a doubling in freight volume. To ensure that Europe remains competitive,

he proposes a green and digital revolution in transportation as one of the main objectives. Alongside Artificial Intelligence (AI) and Big Data he outlines emerging innovations such as hyperloop as a very important contribution towards meeting the set goals. The report especially mentions the greater speed, efficiency and cost savings that are expected from hyperloop. (Draghi, 2024)

With new emerging modes such as hyperloop as well as innovations in sustainable fuels and electrified fleets, new approaches for decision-making are necessary to design and select the correct mode, as well as tools to be implemented in and expand transportation networks such as the TEN-T. This paper suggests a multi-level decision making framework (cf. Figure 1) supporting stakeholders in their choices. There is a particular emphasis on the business objectives and targets of logistics companies, making them central to the development of the hyperloop technology in the proposed framework. Integrating business objectives, technological characteristics and capabilities as well as policy requirements and further boundary conditions enables selecting and weighting of the relevant stakeholder metrics for high-speed transportation.

Building on previous research (Yatskiv et al, 2025; Duin, H. *et al.* 2025), the framework adopts a multi-criteria decision-making approach while integrating the latest advancements in high-speed logistics transportation, such as hyperloop. It incorporates technical parameters of emerging technologies as input, resulting in an expanded set of metrics and key performance indicators (KPIs) that go beyond those supported by existing frameworks, which typically only address current transport modes. The method applies the **T**echnique for **O**rder **P**reference by **S**imilarity to the **I**deal **S**olution (TOPSIS), leveraging features like impact and weight for improved decision-making. This paper outlines the fundamental structure of the decision-making framework, the implementation of the modified TOPSIS approach, and the specific adaptations made to incorporate constraints and industry-specific requirements. By including new technologies and innovative transport modes like hyperloop, the framework supports informed decisions for future transportation projects. This approach is specifically focused on freight logistics, thus clearly defining the scope of the research. Important dimensions like safety which is derived from policy requirements and technological characteristics is subsequently not included in this current iteration of the framework.

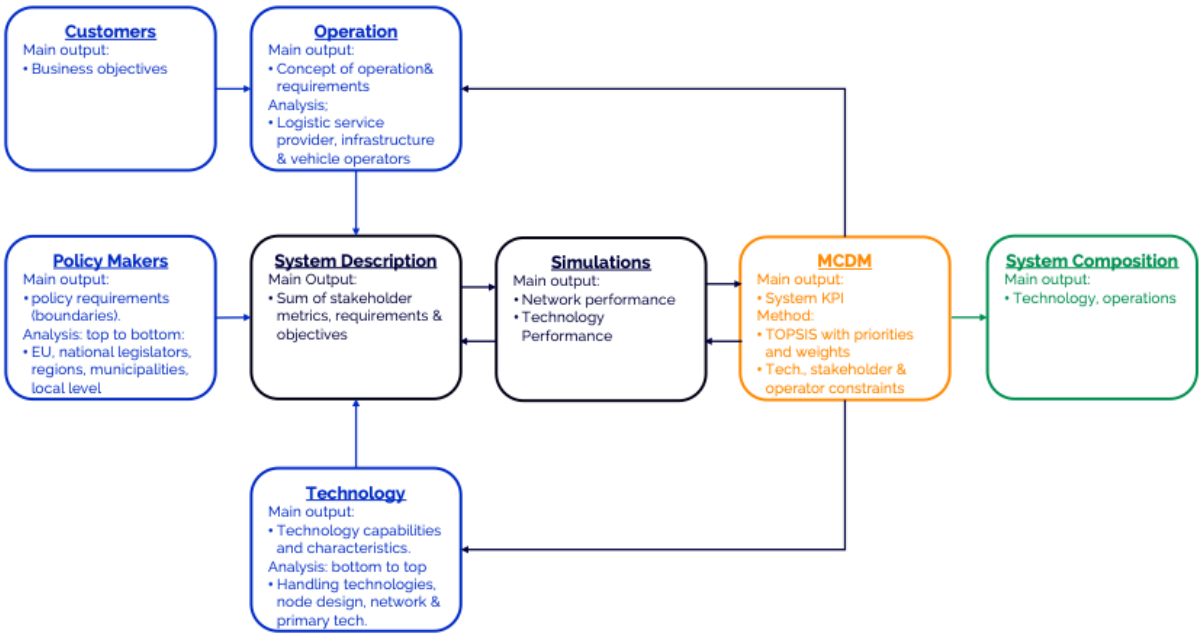

Figure 1: High-level overview of the proposed framework including stakeholders and categories.

A main goal of this research is to provide high-level guidance across many decision-making levels for a selected stakeholder group. The target beneficiaries or this new approach are industry stakeholders, from large-scale companies to small and medium sized companies (SMEs) with a special demand for robust, resilient and sustainable logistics. Emphasis is primarily placed on valuable freight with rapid added value that rely on fast logistics solutions. An application of this framework is planned after the system description and simulations are carried out.

2 Methodology

The research presented in this paper employs a multi-dimensional approach to decision-making within the context of resilient and sustainable transport networks. The methodology builds upon established multi-criteria decision-making (MCDM) techniques while extending them to address the specific challenges of incorporating emerging transport technologies such as hyperloop into existing logistics frameworks. To systematically evaluate and compare conventional and innovative transport solutions, a structured methodological framework has been developed that integrates the requirements, regulatory constraints and technological capabilities of multiple stakeholders, spanning from technology developers to policymakers and operators.

At the core of the approach lies TOPSIS, which has been adapted and enhanced to accommodate the complex, multi-level nature of transportation decision-making. TOPSIS represents an ideal foundation for the framework as it enables the effective handling of conflicting objectives, which are inherent in transportation network planning and optimization. The method allows for the simultaneous consideration of diverse criteria, making it particularly suitable for comparing heterogeneous transportation modes across multiple dimensions of performance. (Awasthi et al, 2011; Chatterjee and Lim, 2022)

2.1 Integration and Application

The multi-dimensional, multi-level structure enables the framework to capture the diverse requirements of all relevant stakeholders, support the evaluation of both established and emerging transport solutions and facilitate the selection and weighting of metrics and KPIs tailored to specific use cases and stakeholder needs.

By systematically mapping objectives, features, and performance criteria across these dimensions and levels, the framework ensures that decision-making processes are robust, transparent, and adaptable to future technological and regulatory developments.

2.2 Structure: Dimensions and Levels

This chapter details the multi-dimensional structure of the proposed decision-making framework for resilient and sustainable transport networks. The framework is designed to address the varying priorities, objectives, requirements and constraints of three key stakeholder groups (in the following called dimensions): Technology developers, operators, and policy makers. For each group, relevant levels and metrics are defined to ensure a comprehensive and stakeholder-centred approach to evaluating and selecting high-speed logistics solutions, including emerging technologies such as hyperloop:

- Technology developers: Focused on the technical capabilities and performance characteristics.
- Operators: Encompassing the objectives and performance of network operators, logistics service providers, and customers.

- Policy makers: Addressing regulatory and boundary conditions at the European, national, and local levels.

Each dimension is further subdivided into levels to capture the complexity and granularity of decision-making. The various levels of the three dimensions are listed below. Figure 2 shows the integration of the stakeholder metrics within the framework and the dimensions and multi-level structure.

Technology developers:

- Network & primary technologies: Assessment of core system architectures and enabling technologies as well as system compatibility and scalability (Hyper4Rail Project, 2024).
- Node design: Evaluation of node-level performance through simulations, focusing on throughput, resilience, and operational efficiency.
- Physical handling layer technologies: Analysis of process descriptions and the effectiveness of material handling systems.

Operators:

- Network operator: Metrics related to overall network performance, reliability, and utilization.
- Logistics service provider: Focus on vehicle fill rates, turnaround times, and delivery productivity.
- Customer: Emphasis on service quality, including on-time performance, cost efficiency, and environmental impact.

Policy makers:

- European union: Macro-level regulatory compliance, investment leverage, integration with existing modes and infrastructure (T-ENT), analysis of EU regulatory framework and sustainability targets.
- State/national level: National regulations and alignment with broader policy objectives.
- Local level: Regional economic output, local interests, and community impact such as noise exposure.

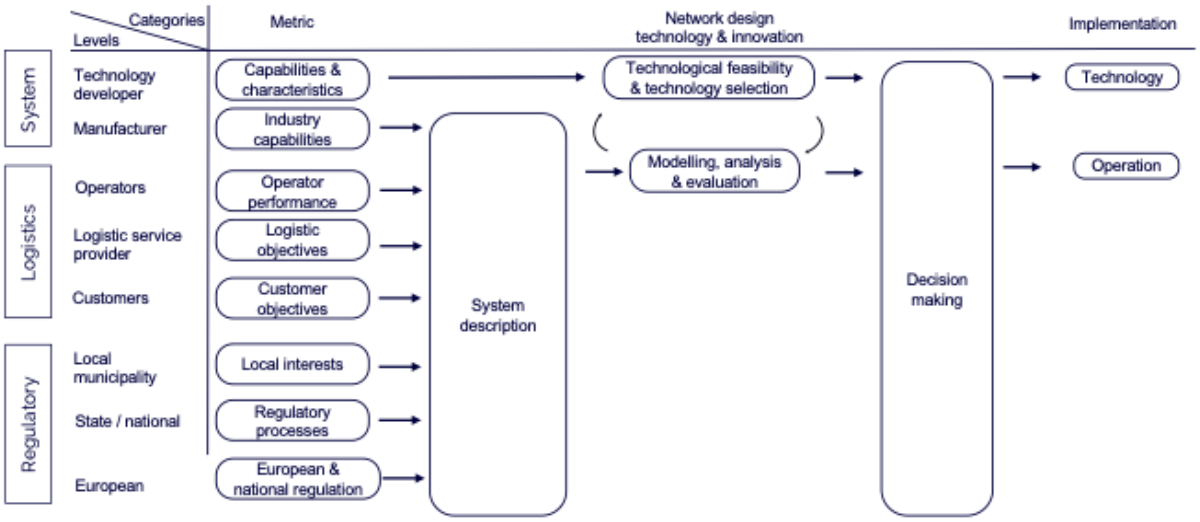

Figure 2: Stakeholder metrics integration into the framework.

2.3 Multi-level Decision Making with Constraints

The traditional TOPSIS method, while effective for many decision-making scenarios, requires significant adaptation to address the specific challenges of multi-stakeholder, multi-criteria transportation decisions involving emerging technologies. This framework implements a constraint-based TOPSIS approach that extends the conventional methodology to incorporate multiple levels of constraints and requirements beyond standard KPIs.

2.3.1 Theoretical Foundation and Adaptation

Drawing inspiration from the TOPSIS-inspired ranking method for constrained decision-making analysis (Chatterjee and LIM 2022), the approach is geared towards producing better compromised solutions in the event of conflicting objectives. In the traditional TOPSIS method, finding the appropriate weighting schemes and normalization criteria represents two complex tasks. Moreover, determining a positive ideal and negative ideal solution is crucial, as ranking can change due to the chosen ideal solution and normalization procedure. This approach therefore employs dynamic reference solutions according to the technological characteristics of possible top level hyperloop solutions. Furthermore, constraints are used during normalization and a feasibility check is carried out to only allow technologically feasible options with possible concepts of operations, validated through simulations. The general adaptations are shown in the following list:

1. **Option Set Generation:** Analytic calculations evolve candidate solutions from inputs (e.g., hyperloop technology compatibility) while respecting constraints like operations and node layout.
2. **Feasibility check:** Methods combine metaheuristics with TOPSIS to first generate feasible solutions and then rank them. This decouples constraint satisfaction from preference ranking, enhancing scalability.
3. **Dynamic Reference Solutions:** Traditional static ideals are replaced with context-dependent references derived from Pareto-optimal fronts or generated option sets. This aligns with real-world scenarios where “perfect” solutions are unattainable due to conflicting stakeholder priorities.
4. **Compromise Solution Identification**: TOPSIS ranks near-optimal solutions based on their distance from ideal coverage (all equations satisfied) and nadir coverage (minimal satisfaction) (Hu and Fang, 2015).
5. **Constraint Embedding in Normalization:** Normalization procedures account for constraint violations. For example, solutions exceeding a metrics limits receive penalized scores during normalization, ensuring infeasible options are systematically deprioritized.
6. **Adaptive Ideal Solutions:** Instead of static ideal values (e.g., for benefit-cost criteria), the method selects reference solutions from the Pareto front, ensuring realism in trade-offs (Chatterjee and LIM 2022).

The presented adaptation addresses these limitations by integrating elements from multi-objective constraint optimization. Therefore, the framework seeks to find a reference solution that better represents the near-optimal solution that optimizes conflicting objectives specific to transportation networks.

2.3.2 Implementation of the constraint-based TOPSIS model

The implementation follows a modified algorithm with the following key steps:

1. Problem Formulation: Define the decision matrix representing alternative technological solutions across multiple criteria.
2. Constraint Integration: Unlike conventional TOPSIS, our approach explicitly incorporates three categories of constraints:
   - Technological constraints (TRL levels, interoperability requirements)
   - Regulatory constraints (compliance with European, national, and local regulations)
   - Operational constraints (capacity limitations, resource availability)
3. Normalization with Constraint Consideration: The normalized decision matrix is used while accounting for constraint boundaries, ensuring that solutions violating fundamental constraints are properly penalized.
4. Weighted Normalization with Stakeholder Priorities: The weights assigned to different criteria reflect not only their relative importance but also their relevance to specific stakeholder groups as identified in the framework dimensions.

In general, the framework and decision-making concept highly values stakeholder-centric weighting. The novelty of this approach lies in the integration of a modified TOPSIS that can handle the specific requirements of multi-level decision-making for transportation networks.

3 Metrics

For each stakeholder and level, the framework establishes specific metrics to enable objective evaluation and comparison. These metrics are selected to reflect both traditional and innovative performance criteria, supporting the integration of new technologies and operational models. In the following tables a few of the selected metrics for the different dimensions and levels are shown.

Table 1: Policymaker metrics

European Union	State governments (national level)	Municipalities (local level)
Annual Public Investment: Capital expenditure on transport infrastructure **Transport Volume:** Total volume carried per hour **European Regulation:** Compliance with transport regulations **Carbon Equivalent per ton:** Environmental impact measurement of operations **Infrastructure Resilience Index:** Evaluates climate adaptation capacity with weighted scores for flood protection, heat-resistant materials, and redundancy **Public-Private Investment Leverage Ratio:** Compares private sector contributions to government transport spending	**National Regulation:** Compliance with transport regulations **Freight Cost of GDP:** Amount of freight transport Cost required per unit of economic output	**Regional Economic Output:** Economic benefits from transport activities **Local Interests:** Alignment with community priorities for transportation **Local Noise Exposure:** Noise levels from transport operations affecting local areas

Table 2: Technology developer metrics

Network level	Hub / Node level	Cargo interface
Network Resiliency: Ability to maintain operations during disruptions	**Station Throughput:** Number of passengers or freight units processed per hour	**Technology Readiness Level:** Measurement of technology maturity from 1-9
Annual cost of Maintenance	**Station Footprint:** Area the station occupies	**Technological Feasibility:** Assessment of technical viability of proposed solutions
Modelling, Analysis & Evaluation: Quality of operational simulation and planning	**Station Capacity:** Maximum number of vehicles that can be accommodated	**Technological Boundaries:** Limits of current technology capabilities
Traffic Management and Control Measures: Effectiveness of traffic flow management systems	**Transit Time within Stations:** Time required for passenger/freight processing within	**Energy Consumption Rates:** Efficiency of power usage for transportation system
Incident/ Disruption Detection: Speed and accuracy of detecting transportation disruptions	**Station Resiliency**: Ability to maintain operations during disruptions	**Handling Equipment Performance:** Efficiency and reliability of material handling systems
	Maintainability Index: Ease of performing maintenance on station equipment	**Maintainability Index:** Ease of performing maintenance on material handling systems
	Station Complexity: Measure for the complexity of the Station infrastructure & operations	**Cargo Transfer Speed:** Time required to transfer cargo between the vehicle and the node
		System Adaptability: Capability to handle different cargo types and sizes
		Interoperability Maturity Level: Assesses compatibility between new technologies and legacy systems on 0-5 scale
		Interface Complexity: Measure for the complexity of the technological & operational complexity
		Manufacturability
		Reliability

Table 3: Operator metrics

Customer	Logistics service provider & station / vehicle operator	Network operator
On-Time Pickups: Percentage of pickups made within the scheduled timeframe	**Vehicle Fill Percentage:** Measurement of how well vehicle load space is being utilized based on weight or pallet spaces	**Network Resiliency:** Ability to maintain operations during disruptions
On-Time Delivery: Percentage of deliveries completed within the promised time frame	**Vehicle Turnaround Time:** Average time elapsed between a vehicle arriving at a distribution center and its departure	**Through-freight Share:** Percentage of total freight demand passing through
Cost per Unit: Total costs of transportation divided by the number of units shipped	**Cost per Vehicle:** Transport cost calculated per vehicle	**Routing Efficiency:** Optimization of vehicle routes to minimize distance/time
Cost per Ton: Transport cost reduced to one ton	**Carbon Equivalent per Ton:** Environmental impact measurement of operations	
Carbon Emissions/Equivalent per Ton: Environmental impact measurement of air freight operations	**Full Utilization Rate:** Percentage of time the system is running in full capacity	
	Delivery Productivity: Number of deliveries per vehicle per hour	

Reliability Index: Ratio of total on-time arrivals	**Terminal Occupancy:** Percentage of terminal capacity in use
Average Transit Time: Total time for shipment movement from origin to destination	**Station Efficiency:** Average time for cargo loading/unloading at ports
	Container Dwell Time: Average time a container spends at the station before onward shipment

4 Results & Discussions

Current research highlights the importance of integrating resilience and sustainability in transport systems (Mitoulis et. al., 2023; López-Castro and Solano-Charris, 2021; Goodarzi et. Al., 2024; Mian et. al., 2023; Teixeira et. al., 2022) While there are efforts to involve industry stakeholders in KPI development, gaps remain-particularly regarding the comprehensive and standardized integration of KPIs for new and emerging transport solutions. Much of the existing research and practice still focuses on established modes and traditional performance criteria, underscoring the need for more adaptive and stakeholder-inclusive KPI frameworks. The suggested framework stimulates a new decision-making approach and performance criteria that are not covered by traditional methods, allowing for an extension of new innovative transportation solutions and tools for the integration into logistics applications. This research aims to fill the gap including metrics and KPI for these innovative and developing modes and solutions.

With a transport network analysis, focusing on the highlighted stakeholders, long term impacts of selecting novel transport modes and innovative solutions are examined. Technologies and systems such as freight handover, automation potential and requirements for intermodality are under investigation, modelled and simulated specifically for different modes, as with the introduction of new systems, additional interfaces are introduced.

As a result of this work, a new framework of technology selection and operations development for a high-speed logistics network is proposed through the combination of decision making and simulations. In future research the technological stack is further described and simulations are used to evaluate the system performance. A stack of KPI is used for evaluating the system and operational procedures provided by the framework and those could include cost, lifecycle performance, and particular emissions as well as throughput, service frequency, cargo volume, regulation (such as a carbon tax or prices on emissions) (compare for lifecycle performance and sustainability metrics; Wurst et. al. 2025). For the technological performance, KPI such as the following that arise from analytical models and simulations can be used: energy demand, maintenance and resource efficiency. For the output of the framework additional KPI such as emissions per unit, uptime, resilience, sustainability, stakeholder satisfaction, public perception and order fulfilment time are suggested as well.

5 Conclusion

The proposed decision-making framework outlines a structured way of solving problems and implementation of strategic decision-making. By putting industry stakeholders from large-scale companies to SMEs first in this novel approach, multiple levels of their strategic, tactical and operational organization can be mapped to specific KPIs. This allows them to make a more informed selection of transport modes, specifically tailored to their logistical needs. By

including high-speed transportation requirements and criteria, the framework is particularly relevant for emerging transportation technologies and their development such as hyperloop and digital tools such as AI which are becoming essential to meet the future demand for both passenger and freight transport.

Additionally, the framework bridges the gap between current political developments with new regulation, novel technologies and their adoption from the logistics industry in first use cases. The approach outlined in this framework could be envisioned to be implemented in logistics tools and software at later stages as well. In real world use cases and high-speed transport corridors in Europe, the framework can provide an improvement, especially considering novel solutions.

Not included in this framework are requirements and KPI such as safety, passenger comfort, and risk which are needed for passenger transport, but cannot be included to limit the scope of this research. They should be included in future enhancements to improve the comprehensiveness of the decision making approach for transport modes.

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