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Model of Multi Criteria Decision-Making for Selection of Transportation Alternatives on the Base of Transport Needs Hierarchy Framework and Application of Petri Net

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Abstract: The article presents an approach for choosing alternative transport routes in a multimodal transport system. This approach includes (1) the transportation needs hierarchy method and (2) the Evaluation of Petri Nets (E-nets) as a modeling tool. The purpose of the study is to develop a methodology for choosing alternative routes for the transportation of goods, taking into account the criteria used by decision-makers. The structure of the hierarchy of transport needs is proposed, which consists of five levels: geographical, economic, institutional/political, infrastructural, and technological. For each of the levels, sets of indicators characterizing it are proposed. The Petri net model captures system dynamics and allows the evaluation of alternative routes. A set of standard rules for transforming the structure of the hierarchy of transport needs into a Petri net is proposed, considering preference parameters for each level of the hierarchy. The proposed approach and the models built on its basis can be applied in the field of cargo transportation to improve operational efficiency and improve decision-making results.

Keywords: multi criteria decision-making; large-scale transportation transit system; transportation alternatives; hierarchy of transportation needs; Petri nets

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1. Introduction

The international freight transportation industry is a complex and dynamic environment that demands robust and adaptable decision-making strategies.

Sustainability has become a paramount concern in today's world, and the freight transportation industry is no exception [1]. As the demand for global trade intensifies, so does the urgency to address the environmental impact and carbon emissions associated with freight transportation. In this context, the paper assumes critical importance by introducing a novel approach that emphasizes sustainability in decision-making processes.

The proposed approach's importance for sustainability lies in its comprehensive and systematic integration of sustainable factors into the decision-making framework. Traditionally, decision-making models in the freight transportation industry have largely focused on economic factors, often overlooking the environmental and social dimensions of sustainability [2]. However, the current global scenario necessitates a paradigm shift towards more sustainable practices.

The new reality demands comprehensive analysis and strategic foresight, particularly from cargo owners who need to determine the most efficient and cost-effective transportation routes under a plethora of factors, including sustainability. The existing methodologies, while valuable, often fall short of providing a holistic perspective, hence leaving room for a more integrated approach.

This study introduces a novel approach that bridges these gaps. It combines a multi-plane framework that meticulously examines five key factors influencing the transit sector—geographical, economical, institutional/political, infrastructure, and technological aspects. This framework provides a comprehensive and nuanced perspective on each transportation alternative, thus extending beyond the traditional one-dimensional analyses that often focus on economic factors alone.

The multi-plane framework introduced in the paper offers a remarkable advantage from a sustainability perspective. By integrating sustainability into the decision-making process, the proposed approach contributes to broader environmental goals and aligns itself with global efforts to create sustainable and resilient transportation systems.

In terms of significance, the proposed approach facilitates efficient yet adaptable analysis of route options, benefiting diverse stakeholders in the cargo transportation sector. For freight companies, it supports route optimization aligned with their specific priorities across cost, time, sustainability, and other factors. For policymakers, the framework assists infrastructure development and regulations tailored to stakeholder needs. For urban planners, it provides data to design efficient multimodal networks.

In complement to the multi-plane framework, the study introduces the use of E-net, a version of Petri net, as a powerful tool to model and visualize the decision-making process [3]. E-net's capabilities in presenting concurrency and dependencies among various factors and planes offer a precise and systematic representation. Moreover, its potential for representing time-dependent decision-making processes leads to more accurate and timely strategic decisions.

The framework delivers impact via fundamentally enhancing the multi-criteria analysis process for cargo transportation route selection. Traditional models often rely solely on economic factors and mathematical optimization of cost or time efficiency. However, real-world route decisions involve a complex interplay of geographical, sustainability, infrastructure, technological, and stakeholder considerations. By incorporating a structured hierarchy across these key dimensions, the proposed approach allows decision-makers to evaluate routes based on a richer, more representative range of criteria.

This leads to route priorities and policies better aligned with customer needs, environmental sustainability, safety, reliability, and other elements that matter for long-term transportation network success. The hierarchical analysis acts as a flexible yet systematic decision aid for logistics firms to optimize routes based on their unique requirements. It assists governments in infrastructure policies that serve stakeholder interests. Ultimately, improving decision-making drives enhanced efficiency, sustainability, and stakeholder value across cargo supply chains.

The novelty of the framework lies in the integration of two key components:

- The needs hierarchy provides a new perspective on transportation route analysis. The hierarchical levels—geographical, economic, institutional, infrastructure, and technology—offer an intuitive yet comprehensive structure.
- Petri nets bring innovation through their ability to model complex concurrent and stochastic processes like real-world transit networks. The proposed configurable Petri net approach uniquely maps the needs hierarchy into the network modeling.

This synergistic combination, customized to cargo route analysis, is innovative in decision science research. The visualized Petri net configurations enable systematic evaluation of route alternatives across different criteria. They bring scalability suitable for large, multimodal transit systems. By bridging the needs hierarchy with Petri net simulations, the framework provides a flexible decision-making method not found in current transportation literature.

The significance of the proposed framework spans multiple dimensions:

- It enhances strategic decision-making, allowing logistics firms and infrastructure planners to optimize long-term route and capacity planning based on sustainability, customer needs, and other priorities.
- It improves network efficiency via route configurations tuned to diverse stakeholder requirements.
- The structured analysis increases transparency and trust in the decision process.
- The framework's scalability suits the rising complexities in massive global transit systems.

- The customizable modeling approach provides decision support across different contexts like seaports, airports, rail networks, and urban transportation.
- By improving planning, the framework can shape transportation policies and infrastructure investments that balance economic viability with social and environmental stewardship.

The intersection of the multi-plane framework and E-net modeling brings forth a model that is not only comprehensive and systematic but also intuitive and adaptable. It allows decision-makers to evaluate and select the most effective cargo transportation alternatives considering a broad spectrum of influencing factors. This study provides a comprehensive description of this approach, discussing its theoretical underpinnings, practical applications, and potential advantages over traditional methods.

The paper presents an important approach to improve decision-making for freight transportation, with sustainability as a key consideration. Selecting optimal transportation routes is a complex challenge involving multiple criteria. Traditional models often overlook sustainability, but it has become paramount amid rising global trade and environmental concerns. The proposed multi-criteria framework integrates sustainability into transportation decision-making, aligning with efforts to create environmentally responsible networks. By incorporating carbon emissions, energy use, environmental impact, and green technologies into the hierarchical analysis, the model empowers sustainable choices. The framework's comprehensive inclusion of sustainability factors enables greener transportation policies and infrastructure investments. The approach's emphasis on sustainability and efficiency makes it vital for supporting the freight industry's transition to sustainable practices. By driving improved planning and infrastructure, the model can help shape a more sustainable transportation future. The study has wide implications, helping cargo firms minimize environmental footprints and governments promote eco-friendly transport systems. Overall, the paper delivers an impactful model integrating sustainability into strategic decision-making for freight transportation.

2. Related Works

Certainly, there have been a number of models and approaches developed for the purpose of choosing optimal methods and routes for freight transportation.

Each of these models and methods has its strengths and limitations. The choice of model often depends on the specifics of the problem, including the complexity of the transportation system, the availability of data, and the computational resources available.

Below is a brief overview of the methods and models used to select alternative options for cargo transportation, indicating their advantages and disadvantages, as well as examples of literary sources using these approaches to solve the described transport problems.

The paper [4] discusses an algorithm using mixed integer linear programming and speed-up heuristics to optimize the rescheduling of trains on a single-track railway when disturbances cause conflicts. The optimality gap metric is used to show the effectiveness and efficiencies of the speed-up heuristics developed. The article [5] demonstrates using linear programming to minimize the transportation costs for distributing five products from a company to six district offices, resulting in a minimum cost with some cartons of products to be transported to their destinations in order to attain a minimum cost, which is the goal of the company.

Multiple mixed integer linear programming models to solve a real-world vehicle routing problem with pickup and delivery for a poultry company in Tunisia are presented in [6]. The models aim to find the optimal path to simultaneously deliver products and collect empty boxes, with computational experiments showing promising results.

The paper [7] presents a mathematical model using piecewise linear functions to approximate and optimize routing risk for a heterogeneous vehicle routing problem transporting hazardous materials. A genetic algorithm estimates the piecewise linear function limits, which are integrated into a mixed integer linear programming model to minimize total routing risk. Experiments on 20-node instances show cost and risk minimization are conflicting objectives.

The article [8] presents a mixed integer programming model and simulated annealing algorithm to schedule group train operations for heavy-haul railways, optimizing the weighted sum of transportation cost and total cargo travel time while matching freight supply and demand. Constraints include delivery time commitments, maintenance time, and locomotives. Experiments on real data show the proposed methodology generates high-quality solutions.

The paper [9] discusses research to optimize the scheduling of production orders in packaging using mixed integer linear programming and constraint programming models. It extends the flexible flow shop problem with precedence, parallel machines, sequence-dependent setups, and availability constraints to minimize total tardiness. A dedicated heuristic is proposed for quick solutions that outperform other algorithms on real-world data involving thousands of monthly orders. The models can be applied to other scheduling problems with similar characteristics.

The paper [10] compares linear programming (LP) and mixed integer programming (MIP) models for managing seedling transportation. The LP model uses a linear objective function, while MIP bases costs on vehicle loads. As the number of seedlings decreases over time, MIP is more accurate. Despite small allocation differences, LP is adequate for Finnish nurseries. Planting throughout the growth period increases costs in the seedling business. The results are relevant for analogous transportation problems.

Applying evolutionary algorithms to solve a multi-objective transportation problem formulated as a linear optimization problem is discussed in [11]. A bipartite graph encoding method is used to represent feasible solutions. Evolutionary operators are applied to find an optimal compromise solution, with a numerical example used for illustration.

The paper [12] discusses a multi-objective, two-stage stochastic programming model for disaster management to minimize casualties not transported, additional ambulances needed, and total transportation time. It assumes a data-driven tool tracks casualties and hospital capacity to direct ambulances. The model is applied to an earthquake scenario in Istanbul with multiple objectives, periods, and locations. The augmented epsilon-constraint method generates Pareto optimal solutions compared to minimizing just transportation time to see the effect of directing ambulances based on hospital availability. Strategies are presented to help decision-makers. Results show equity in transporting casualties requires the data-driven tool.

A multi-objective mathematical model to design a four-echelon intermodal multi-product perishable supply chain network that balances cost, delivery time, emissions, and supply–demand mismatch is developed in [13]. It addresses fresh fruit supply chains and combines objectives into a weighted function to support strategic decisions on locations, capacities, flows, and staffing and tactical decisions on harvest time, delivery, routing, and transport mode. The model is demonstrated for Vietnam's Mekong Delta, and sensitivity analysis is performed on objective weights to assess configuration changes.

The article [14] proposes a simulation model for small freight deliveries using trams in Poznan, Poland, to facilitate shifting road deliveries to rail using existing infrastructure. Operational planning occurs under uncertainty in demand and the risk of incomplete customer service. The model evaluates tram depot locations and routes to minimize carrier costs within time limits using genetic algorithms. Simulation experiments determine distribution laws and expected values for the city's transport and distribution system parameters under uncertainty and risk.

The paper [15] presents a simulation and optimization-based system to combine public transit with ride-pooling services as feeders, with ride-pooling as the first/last leg and public transit in between. An optimization model with heuristics quickly analyzes permutations for each request. The model is tested in Barcelona.

An approach to modeling a cargo road transportation system in Poland using data from a national survey, avoiding assumptions about demand, is discussed in [16]. Demand is estimated from a sample representing all freight traffic entities. Python scripts implement procedures to develop a nationwide model. The approach demonstrates survey-data-based modeling to reduce assumptions in complex transport simulations.

A review of transportation simulation models, identifying model variables, types, and operational characteristics related to energy consumption and emissions, is provided in [17]. Several existing models are examined to propose a new simulation model incorporating energy and emissions for public transport. This addresses sustainability goals of minimizing externalities from urban passenger transport energy use and emissions.

The paper [18] introduces TRANSSIM, a simulation tool for comparing different transportation models. TRANSSIM uses a combination of programming languages and an analytical optimization approach. Inputs include available resources, requirements, and costs. Outputs are product allocations and total costs. TRANSSIM simulates and compares transportation model results to guide optimization strategy.

A systematic review of 58 papers from 2003–2019 that use the Analytic Hierarchy Process (AHP) to address transportation problems is provided in [19]. Most apply conventional AHP to public transport and logistics issues. TOPSIS is most integrated with AHP versus other MCDM methods. The review illustrates AHP criteria, alternatives, and extensions for transportation decision support. It highlights contributions and policy implications.

The paper [20] proposes an integrated multi-criteria decision-making methodology to evaluate park and ride facility locations from expert perspectives. A survey of 10 transport experts adopts a fuzzy analytic hierarchy process, handling vagueness and reasoning limitations. The methodology is applied to a real-world case in Cuenca, Ecuador. Results highlight accessibility as the most significant factor and provide more flexibility than pure AHP. The study illustrates using fuzzy AHP integrated with surveys to address ambiguity in multi-criteria transport facility location decisions.

In [21], a multimodal freight transportation system with finite known route and mode alternatives is discussed. The research aims to suggest an approach to evaluate and choose cargo transportation alternatives. The main tasks are selecting efficiency indices, forming optimization criteria, modeling the system, and calculating performance criteria. AHP is presented as the most suitable approach for the comparative evaluation of different cargo transportation routes and modes.

The paper [22] proposes an uncertain multi-criteria decision-making method to evaluate predictions of transportation system reliability, which can provide useful information for reducing congestion. The method introduces uncertainty theory into the analytic hierarchy process to handle evaluation with alternatives and criteria in an uncertain environment. It is applied to evaluate regional travel time reliability belief in a case study and compared to other MCDM methods, showing uncertainty theory combines well with AHP for this problem.

The article [23] reviews the literature on applying AHP, a leading multi-criteria decision-making method, to urban mobility decision problems. As cities grow, but states/municipalities respond slowly, AHP can evaluate mobility plans. The review identifies three keyword clusters: AHP methodology research, innovation and public management discussing coordination, and urban mobility with hybrid/non-AHP applications.

The paper [24] surveys research on using Petri nets (PNs) to model intelligent transportation systems for smart, safe, environmentally friendly logistics and transportation management. PNs are effective for discrete event dynamics in these systems for simulation, analysis, optimization, and control. High-level PN models address complex, large-scale, real-world freight logistics and transportation problems. Contributions are classified using strategic/tactical vs. operational level and PN formalism used.

A new method to model highway traffic using Probabilistic Petri nets (PPNs) is proposed in [25]. The highway is partitioned into discrete segments with probabilistic measures derived from traffic data on vehicle movements. The model is validated on a dataset of real driving scenarios. The method generates PPN graphical structures and attributes representing real traffic data.

The paper [26] discusses using Batches Petri Nets (BPN), an extension of hybrid Petri nets, to model variable speed limit (VSL) control for road networks like highways. BPN represents variable delays on continuous flows using batch nodes, useful for modeling vehicle flows for real-time VSL strategies. A BPN model with controllable batch speed is applied in the Netherlands to evaluate VSL control laws based on vehicle accumulation fronts.

The article [27] proposes an object-oriented stratified timed Petri net model for analyzing conflicts in multi-objective, multi-path, multi-vehicle relay operations of mine locomotives under complex conditions. Materials are modeled as objects combined with locomotive rules and time constraints. Results demonstrate the modeling and conflict analysis approach is effective and feasible for safe mine production system operations.

A new methodology using Fermatean fuzzy techniques to solve multi-objective transportation problems with conflicting parameters is proposed in [28]. Numerical computations demonstrate and validate the proposed methodology as an alternate fuzzy programming approach for multi-objective transportation problems.

The mathematical models for intermodal freight transportation to determine goods flows, vehicles, and transferred volumes between origins and destinations are developed in [29]. A mixed integer linear programming (MILP) model minimizes total cost, including fixed, transportation, intermodal, and CO_2 costs. The models are tested on real data from Vietnam.

The paper [30] discusses an innovative real-world nonlinear solid transportation problem where total cost depends on procurement type, items, and distance. An impurity constraint is also considered, with the fuzzy, imprecise model optimized using two fuzzy programming techniques, fractional programming and the generalized gradient method in LINGO. The two solution methods for the transportation problem with fuzzy, nonlinear costs and an impurity constraint are analyzed.

The article [31] presents a fuzzy compromise programming approach for multi-objective transportation problems. It synthetically considers individual and global objective evaluations with marginal and weighted preferences. A compromise model is formulated using the global evaluation, covering Zimmermann's fuzzy programming as a special case. An optimization technique solves for a non-dominated compromise solution, maximizing the synthetic global membership degree. A numerical example demonstrates the efficiency of the proposed approach.

The paper [32] reviews research on methodologies for sustainable transportation systems considering environmental and social impacts. It discusses using simulation, optimization, machine learning, and fuzzy sets to design and operate sustainable long-distance and metropolitan systems. The review classifies challenges, best practices, future trends, and open research questions for researchers and practitioners working on transportation sustainability, which has increased in importance alongside economic factors in recent decades.

The article [33] reviews research on using machine learning for surface transportation systems. It finds that 74% of over 100 papers focus on forecasting, with simple ML algorithms predominating versus more sophisticated ones. Root cause analysis indicates a lack of collaboration between ML and transportation experts, with transportation problems used to test ML algorithms rather than address mobility or safety issues. Additionally, the transportation community does not clearly define problems or provide public datasets. Accelerating progress requires an open platform to present concerns and spatiotemporal data to ML experts. Transportation has not fully utilized ML despite parallel advances.

A self-constructed deep fuzzy neural network (SCDFNN) for interpretable traffic flow prediction, important for intelligent transportation systems, is proposed in [34]. It learns transparent traffic cognitive rules via neuro-symbolic computation versus just feature/result interpretability. Innovations include a fuzzy architecture capturing spatiotemporal dependencies and a modified Wang-Mendel method fusing regional traffic differences into adaptive fuzzy rules without losing interpretability. Experiments show that SCDFNN matches deep models and enables model-level transparency for persuasive traffic prediction.

The paper [35] proposes a physics information-based neural network (PINN) framework for traffic state estimation (TSE) on networks, which is important for intelligent transportation systems. PINNs combine model-driven and data-driven methods to leverage their advantages and overcome individual limitations. A PINN is demonstrated to solve the traffic flow model on simple simulated highway networks using little observational data. Experiments show the approach accurately estimates network traffic by incorporating physics-based modeling in neural networks for TSE.

A state-of-the-art review of multi-criteria decision-making models in the transport sector and a comprehensive review of the literature are also provided in review studies [36–40].

Indeed, while existing methods for selecting transportation alternatives have been instrumental in shaping strategic decisions, they have faced several limitations:

- Most traditional methods tend to analyze decision-making factors on a single plane, usually economic. Such an approach can overlook the interdependencies and complexities among various elements, such as geographical constraints, political stability, infrastructure quality, and technological readiness, leading to potentially sub-optimal decisions.
- Traditional methods like linear or integer programming often fall short of accurately representing concurrency and dependencies among decision factors. This could lead to misjudgment of risks and benefits associated with different alternatives.
- Many existing methods are mathematically abstract and lack a visual representation. This lack of visualization can make it challenging for decision-makers to understand the decision-making process and communicate it effectively to other stakeholders.
- Traditional models are often static and may not reflect the rapidly changing realities of the global economy, such as sudden political changes, infrastructure developments, or technological innovations.
- Some models might struggle to scale as the number of routes or the complexity of each hierarchical level increases. This scalability issue could limit their usefulness in large-scale or complex decision-making scenarios.
- Traditional models may lack flexibility in adapting to different contexts or scenarios. They usually stick to a predetermined set of criteria, making it challenging to incorporate new decision parameters or adjust existing ones in response to changing circumstances.

Addressing these limitations requires a comprehensive, adaptable, and scalable approach that can reflect the complex dynamics of the international transportation environment, which is precisely what our proposed model aims to deliver.

In addition to the classical methods of studying multi-criteria problems, which are indicated in Table 1, there is another approach to solving such problems based on the hierarchy of needs. It draws inspiration from Maslow's theory [41], which suggests that human needs can be organized into a hierarchical structure, with lower-level needs needing to be fulfilled before higher-level needs can be addressed.

Table 1. Parameters that influence decision-making at each level of the transport needs hierarchy framework are of utmost importance.

Plans of Transport Needs Hierarchy Framework	Possible Parameters	Description of Parameters
Geographical Plane	Distance	The parameter characterizes the physical distance between the points of departure and the destination of cargo transportation. More efficient are alternatives with shorter routes.

Table 1. *Cont.*

Plans of Transport Needs Hierarchy Framework	Possible Parameters	Description of Parameters
	Accessibility	The parameter fixes the degree of accessibility to the transportation route. Routes with high accessibility to the main transport corridors, the presence of reserve sections of the transport network, etc., are more efficient.
	Geographical Constraints	The parameter takes into account the presence of geographical features of the route that may affect the transportation process, for example, the presence of mountains, the risk of landslides, river floods, or other natural obstacles.
	Climate and Weather Conditions	The parameter takes into account the risks of the impact of climatic and weather conditions on the efficiency of transportation along the selected routes, such as average temperatures, precipitation, strong winds, and the presence of other extreme weather events.
	Sustainability and Environmental Impact	To take into account sustainability factors and to minimize the impact of transport on the environment, parameters can be used that take into account the environmental consequences associated with each route of transportation, for example, the level of carbon emissions, the degree of transport's impact on environmental degradation, and others.
Economic Plane	Cost	The indicator determines the effectiveness of each of the selected alternative transportation routes from an economic point of view, evaluating the profitability of the routes and all types of direct and indirect costs in the transportation process.
	Time Efficiency	The indicator characterizes the time costs in the process of transporting goods along alternative routes (total travel time, transit delays, customs clearance time, and other time factors).
	Reliability	The indicator characterizes the stability, predictability, and reliability of the route, determined on the basis of historical data on the passage of goods along this route, performance feedback, and the overall efficiency of logistics operations along the route.
	Capacity	The parameter characterizes the capacity and scalability of transport routes in order to ensure that the selected routes can meet the expected demand and provide adequate logistical support based on an analysis of factors such as the availability of sufficient infrastructure, fleet size, and cargo volume invariance.
	Risk and Insurance	The parameter takes into account the potential risks of a complex of unfavorable factors and the possibility of their compensation in case of occurrence due to insurance coverage.

Table 1. *Cont.*

Plans of Transport Needs Hierarchy Framework	Possible Parameters	Description of Parameters
	Market Accessibility	The parameter determines the ease of access to target markets or distribution networks for each alternative supply route. An assessment is made to ensure the route's market advantage, taking into account such factors as proximity to customers, the competitive environment in the region of the route, the density of distribution centers, and others.
Institutional/Political Plane	Political Stability	As a parameter, parameters assessed using international organizations can be used, for example, the World Bank's index of political stability and absence of violence/terrorism.
	Regulatory Environment	The parameter can be assessed using both internationally recognized indicators of the effectiveness of the legal environment for business in the countries along which the route passes, for example, using the World Bank Ease of Doing Business Index, and based on specific transport regulations that affect freight traffic along the route of transport.
	Trade Agreements	The parameter can characterize the existence and features of bilateral or multilateral trade agreements that affect the efficiency of the transportation of goods between their countries of origin and destination.
	Customs Efficiency	The parameter characterizes the time and complexity of customs procedures for the transportation of goods, as well as the conditions of visa control for persons accompanying the goods.
	Security	The parameter determines the level of crime, the risk of theft, the risk of military actions, and other security issues on the route.
	Corruption Index	Indicators related to corruption and other barriers and risks in dealing with official structures related to cargo transportation in different regions, one of which can be, for example, Transparency International's Corruption Perceptions Index.
	Environmental Regulations	Parameters characterizing the degree of stringency of environmental regulations relating to the transport and logistics sector can significantly influence the choice of transport alternatives.
Infrastructure Plane	Transportation Infrastructure Quality	Indicators that characterize the overall quality and level of development of transport infrastructure (roads and railways, terminals, airports and ports, etc.) can significantly affect. For example, the Logistics Performance Index from the World Bank can be used as one of these parameters.

Table 1. *Cont.*

Plans of Transport Needs Hierarchy Framework	Possible Parameters	Description of Parameters
	Availability of Multimodal Transportation	Indicators characterizing, if necessary, the possibility of using the possibilities of various modes of transport and their combination, as well as combined transport.
	Reliability of Infrastructure	The indicators evaluate factors such as infrastructure disruption due to maintenance and repair operations, infrastructure accidents, construction and modernization work, and other similar ones.
	Capacity of Infrastructure	The parameter determines the invariance of the infrastructure to the volume of cargo that can be transported along certain routes or modes of transport, which depends on factors such as the width and condition of roads, the throughput of ports, airports, or railways, the availability of toll roads, and others.
	Accessibility	The indicator characterizes the degree of accessibility to key infrastructure transport facilities, such as ports, logistics centers, terminals, warehouses, etc. In some cases, when delivering goods to remote areas or hard-to-reach places, it is necessary to take into account the possibility of using infrastructure that corresponds to the type of transport means used to deliver goods.
	Infrastructure Development Projects	Information about ongoing and expected transport infrastructure development projects that may affect future transportation options.
	Digital Infrastructure	The quality and availability of intelligent transport systems, information systems, communication networks, GPS tracking, and other digital tools used in modern logistics and transport.
Technology Plane	Availability of Advanced Transportation Technologies	Indicators that take into account the possibility of using automated loading and unloading systems, innovative transport technologies, or advanced delivery technologies (for example, larger and more efficient container ships, robotic loaders, drones, and others).
	Supply Chain Visibility Technologies	Metrics that take into account the availability and ability to use cargo tracking systems such as GPS tracking, RFID, or IoT devices that provide real-time updates on the location and status of the cargo.
	Communication and Information Systems	Indicators of the availability and reliability of the use of automatic data exchange information systems, such as electronic data interchange (EDI) systems, in some cases, can be significant.
	Automation Capabilities	Indicators that take into account the possibilities of paperless technologies (degree of automation of warehousing, customs clearance, or logistics management processes) and related robotic and information systems.

Table 1. *Cont.*

Plans of Transport Needs Hierarchy Framework	Possible Parameters	Description of Parameters
	Technological Readiness	The indicator can characterize the readiness of transport service providers and other stakeholders to implement and use advanced technologies, including their adaptation to technologies already used by the carrier.
	Digital Security	Indicators that take into account the resilience and degree of protection of digital technologies from cyber attacks and data leakage, including measures for the use of encryption standards, as well as historical data on the number of violations in this area.
	Sustainability Technologies	Indicators that take into account the use of technologies that increase environmental sustainability, such as the use of energy-efficient transport means, renewable energy sources in transport, or technologies that reduce waste and emissions.

The concept of applying a hierarchy of transportation needs, akin to Maslow's hierarchy of needs, has been explored in the analysis of passenger transportation [42,43]. The hierarchy of transportation needs typically encompasses a range of factors important for passengers, such as safety, accessibility, reliability, comfort, affordability, and environmental sustainability. However, the potential application of the same concept in freight transportation remains largely untapped.

This paper aims to bridge this gap by proposing a five-level framework for the hierarchy of transport needs specifically tailored to cargo transportation. By integrating this framework with a model based on Petri nets, the study presents a comprehensive approach to address the multi-criteria decision-making challenges in selecting optimal transport alternatives for freight transportation.

3. Materials and Methods

In the field of freight transport, decision-makers (DMs) face the difficult task of choosing the most suitable alternatives for the transport of goods. We use an approach based on the hierarchy of transport preferences (HTP) to solve this problem. HTP establishes the structure of the hierarchy of transport needs using analogy with how decision-makers use it in practice. This structure consists of five levels, where each level represents a certain dimension of transport preferences. The decision-making process begins at the lower level, at which alternative options acceptable to the decision-maker are selected, then it is similarly repeated at higher levels.

Figure 1 illustrates the proposed framework of transportation needs hierarchy. It consists of five key planes—geographical, economic, institutional/political, infrastructure, and technology. The selection of optimal transportation alternatives occurs in a structured top-down approach across these planes.

At the geographical plane, the initial set of route options between the origin and destination are identified. Factors like distance, terrain, climate, accessibility, and environmental impact are evaluated to choose routes that meet the basic logistical and sustainability requirements. Unfeasible or non-preferred routes are filtered out.

The filtered geographical alternatives then enter the economic plane. Detailed cost–benefit analysis occurs, assessing metrics like transportation costs, time efficiency, capacity scalability, risk mitigation, and market accessibility. Routes not meeting the economic thresholds and strategic priorities are excluded.

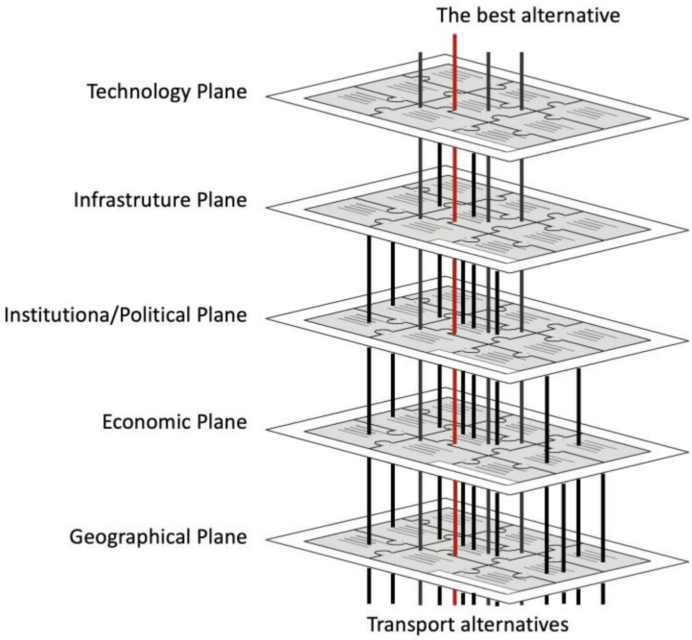


Figure 1. The framework of transport needs hierarchy.

The alternatives meeting both geographical and economic criteria proceed to the institutional/political plane. Routes undergo due diligence on factors like regulations, trade agreements, political stability, customs efficiency, and corruption indexes. Routes facing significant institutional barriers or risks are removed from consideration.

The filtered options enter the infrastructure plane, where the adequacy and quality of roads, terminals, ports, and digital systems are evaluated. Routes with infrastructure limitations or bottlenecks that cannot be addressed are excluded.

Finally, at the technology plane, parameters like automation, sustainability, visibility, security, and innovation adoption are analyzed to select routes aligned with technological strategic imperatives. The route option that optimizes across all five planes is the recommended transport alternative.

The top-down flow enables lower-level criteria to be met before evaluating higher-level needs. Alternatives are filtered stage-by-stage, allowing systematic selection aligned with organizational objectives, constraints, and capabilities. The hierarchical approach provides a calibrated, transparent decision-making framework suited for complex multi-criteria transportation route selection.

In the proposed approach, sustainability considerations can be included in various planes of the multi-plane framework, enhancing decision-making across different dimensions:

- In the geographical plane, sustainability considerations can focus on optimizing transportation routes to minimize carbon emissions and environmental impact. Decision-makers can assess the environmental footprint of each alternative route, taking into account factors such as distance traveled, fuel consumption, and the use of eco-friendly transport modes. By selecting routes that are more fuel-efficient and eco-friendly, the geographical plane contributes to reducing the overall environmental impact of freight transportation.
- In the economic plane, sustainability considerations can be intertwined with cost-efficiency. Decision-makers can evaluate the long-term benefits of adopting sustainable practices, such as investing in energy-efficient transportation technologies, utilizing renewable energy sources, and adopting green logistics practices. By factoring in the cost of carbon emissions and potential savings from sustainable initiatives, the economic plane ensures that sustainable choices align with both environmental and financial goals.

- In the institutional/political plane, sustainability considerations revolve around regulatory compliance and adherence to environmental standards. Decision-makers can assess the environmental policies and regulations of different regions and countries to ensure that transportation alternatives align with sustainability guidelines. This plane also encourages collaboration with industry stakeholders to promote sustainable practices and contribute to collective efforts in achieving environmental objectives.
- The infrastructure plane plays a pivotal role in promoting sustainability by prioritizing investments in eco-friendly infrastructure. Decision-makers can evaluate and prioritize sustainable infrastructure projects, such as green ports, energy-efficient terminals, and smart logistics hubs. Furthermore, the infrastructure plane can incorporate sustainability criteria in evaluating the impact of transportation infrastructure on local ecosystems and communities.
- In the technological plane, sustainability considerations can focus on adopting advanced transportation technologies that minimize environmental impact. Decision-makers can explore eco-friendly technologies, such as electric and hybrid vehicles, alternative fuels, and autonomous transportation systems. Additionally, this plane encourages research and development of innovative technologies that contribute to sustainable transportation solutions.

By integrating sustainability considerations into each plane of the multi-plane framework, the proposed approach ensures that decision-making accounts for environmental, social, and economic dimensions. This holistic approach empowers stakeholders to make informed choices that promote sustainability and responsible resource management throughout the freight transportation industry.

In the proposed multi criteria decision-making (MCDM) method, the selection of criteria is a crucial step in the decision-making process. The criteria serve as the foundation for evaluating and comparing different transportation alternatives, and their careful selection ensures that the decision-making process aligns with the objectives and priorities of the stakeholders. Therefore, it is essential to provide a clear and comprehensive explanation for the chosen criteria to justify their relevance and significance.

In this study, the criteria may be chosen to form a comprehensive and balanced evaluation of transportation alternatives. Each criterion reflects a specific dimension that contributes to the effectiveness and sustainability of transportation alternatives.

The main chosen MCDM criteria may be as follows:

Transportation efficiency. This criterion assesses the physical distance between the origin and destination points and the time required for transporting goods from the origin to the destination. Shorter travel time and distance are generally preferred as they lead to quicker deliveries and reduced lead times.

Environmental Impact. This criterion assesses the environmental footprint of each transportation alternative, considering factors such as carbon emissions, fuel consumption, and air and water pollution. It aligns with the broader goals of reducing the ecological impact of freight transportation and promoting eco-friendly practices.

Intermodal Connectivity. This criterion examines the connectivity between different transportation modes, such as road, rail, sea, and air. A well-integrated intermodal system allows for smoother and more efficient cargo transportation, reducing transit times and improving overall logistics performance.

Accessibility. This criterion considers the accessibility of transport infrastructure and facilities, including ports, terminals, and distribution centers. Well-connected and easily accessible locations contribute to smoother cargo handling and efficient transportation operations.

Cost Efficiency. This criterion evaluates the economic feasibility and cost-effectiveness of each transportation alternative. It takes into account factors such as transportation costs, operational expenses, and potential savings from sustainable initiatives, providing a balanced perspective on economic viability.

Regulatory Compliance. This criterion ensures that transportation alternatives adhere to international and regional environmental regulations and standards. It considers the alignment of choices with sustainable practices and legal obligations to support responsible and compliant decision-making.

Infrastructure Compatibility. This criterion examines the compatibility of each transportation alternative with existing infrastructure and logistics networks. It assesses the potential for seamless integration into the current system, optimizing resource utilization and enhancing overall efficiency.

Technological Readiness. This criterion gauges the readiness and appropriateness of advanced transportation technologies in each alternative. It considers factors such as technology reliability, scalability, and the potential for reducing environmental impact.

Each of the selected criteria addresses a specific aspect of sustainability and decision-making in the context of transportation. They have been chosen based on their relevance to the industry's challenges and the need for sustainable solutions. Moreover, the chosen criteria have been carefully balanced to ensure that the decision-making process is comprehensive, taking into account economic, environmental, and social considerations.

By incorporating these criteria into the proposed MCDM method, stakeholders can make informed and responsible decisions that contribute to the long-term sustainability and efficiency of the international freight transportation industry. The inclusion of these criteria enhances the method's applicability and relevance, aligning it with the goals of promoting sustainability and intelligent infrastructural and transport management.

To take into account each of the criteria and set their priority, various parameters can be selected that characterize the above criteria when choosing solutions. These parameters play a decisive role in shaping decisions both at each level of the hierarchy of preferences and in determining the most efficient option for cargo transportation in general. Based on these parameters, decision-makers can objectively compare options at each level of the hierarchy and make an informed choice in accordance with their specific goals and priorities.

An essential aspect of the framework is its flexibility to customize and tailor the parameters based on the specific context and requirements of the decision-makers. Different industries, cargo types, or regional considerations may warrant the inclusion of additional parameters or modifications to existing ones. This customization allows decision-makers to adapt the framework to their unique circumstances, ensuring that the exploration and analysis of alternatives are directly aligned with their specific needs and preferences.

By incorporating parameters within the framework, decision-makers can introduce objectivity into the decision-making process. Each parameter can be quantified or assigned a weight, allowing for systematic comparison and evaluation of alternative transport options. This objective approach reduces the influence of subjective biases and ensures that decisions are based on well-defined criteria and measurable factors.

The exploration of the described framework for transport alternatives heavily relies on the identification and consideration of parameters at each level of the hierarchy. In Table 1, the parameters that could be considered within each plane or factor of influence in the framework are proposed. It should be noted that this is a high-level general representation, and the actual parameters could vary based on specific contextual factors related to the cargo, route, or regional considerations. The approach, in general, is customizable—infrastructure planners can tailor criteria weighting to their unique goals, capacities, and constraints. The transparent multi-stakeholder analysis builds trust and acceptance of sustainability initiatives. For urban networks, the framework can optimize last-mile sustainability using metrics like reduced waste, noise, and congestion.

Continuing the ascent, the institutional/political plane becomes a crucial level of the transport needs hierarchy framework. DMs take into account factors such as regulations, policies, and political stability that may influence the transportation process. This level of analysis further refines the set of preferences, considering the feasibility of each alternative option within the institutional and political landscape. As preferences become more specific and stringent, the area of feasible solutions narrows even further.

The subsequent level in the transport needs hierarchy framework is the infrastructure plane, which examines the availability and adequacy of transportation infrastructure along the chosen routes. DMs evaluate factors such as road conditions, port facilities, warehouse capabilities, and transportation networks. This evaluation process aids in narrowing down the range of feasible solutions, as certain routes may be excluded due to infrastructure limitations or inefficiencies.

Finally, the technology plane takes center stage. DMs consider technological advancements, innovations, and capabilities that can enhance the efficiency, safety, and sustainability of the transportation process. This analysis results in a refined set of preferences, which incorporate preferences for advanced transportation technologies, supply chain visibility, communication systems, automation capabilities, digital security, and sustainability technologies.

We can consider each of the five influence factors as hierarchical levels of decision-making. This means that the evaluation of higher-level factors will only take place for those alternatives that have been positively evaluated at all lower levels.

Let us denote the total number of geographic alternatives by n, and the corresponding geographic alternatives as G_j $(j = 1, 2, \ldots n)$. Then, the set of geographic alternatives can be represented as $G = \{G_1, G_2, \ldots G_n\}$.

For each geographic alternative G_j, we can calculate the cost of transportation for an economic plan, denoted as E_i. Therefore, we have an economic vector $E = \{E_1, E_2, \ldots E_n\}$.

The alternatives that pass the economic evaluation (i.e., those with costs less than or equal to a predefined budget B) form the set of alternatives for the next Institutional/political level.

The institutional/political evaluation can be performed for the alternatives in P, resulting in a set of alternatives that pass the institutional/political evaluation. This process can be repeated for the infrastructure and technology planes. Finally, we will obtain a set of alternatives that pass all levels of evaluation:

1. Geographic plane: $G = \{G_j : j = 1, 2, \ldots n\}$.
2. Economic plane: $E = \{G_j \in G \,|\, \forall j : E_j \leq B\}$.
3. Institutional/political plane: $P = \{G_j \in E \,|\, \forall j : P_j \geq V_P\}$.
4. Infrastructure plane: $I = \{G_j \in P \,|\, \forall j : P_j \geq V_I\}$.
5. Technology plane: $T = \{G_j \in I \,|\, \forall j : T_j \geq V_T\}$.

Where P_j, I_j, T_j are the institutional/political, infrastructure, and technology parameters of the alternative G_j, $j = \overline{1, n}$, and V_P, V_I, V_T are the predefined thresholds for these parameters.

The optimal alternative is then the one with the lowest cost among the alternatives that pass all levels of evaluation:

$$j_{opt} = argmin \{E_j : G_j \in T\}$$

In this notation, j_{opt} represents the index or identifier of the alternative G_j that minimizes the cost of transportation.

Using this mathematical representation, we can observe the progressive refinement and narrowing of feasible solutions as decision-makers move up the hierarchy of transport preferences. By incorporating mathematical functions that capture the evaluation and criteria at each level, we can precisely analyze and select the optimal alternative options for cargo transportation based on the decision-makers' preferences and constraints.

The approach based on the hierarchy of transport preferences provides decision-makers in cargo transportation with a systematic transport needs hierarchy framework for selecting alternative options. As the DM moves from one level of the hierarchy to another, passing sequentially through geographic, economic, institutional/political, infrastructural, and technological plans, the area of acceptable alternatives narrows. This is ensured using the analysis of acceptable solutions at each of the hierarchical levels, which ultimately leads to the selection of the most appropriate and optimal alternative transportation options.

By analyzing and classifying transport needs in a hierarchy, decision-makers can consistently solve the problem of multi-criteria decision-making within their usual priorities based on intuitive principles.

The decision-making approach to the base of transportation needs hierarchy is oriented on better consideration of the diverse and complex needs of transportation users. It helps guide decision-making processes and resource allocation by recognizing that different levels of needs must be addressed to create an effective and user-centric transportation system.

The concept of using the hierarchy of transport needs, the principle of which is similar to Maslow's well-known hierarchy of needs, is of particular interest for modeling a multimodal transport system:

- The hierarchy of transport needs is a kind of decision-making model for decision-makers in the transportation of goods. In this regard, the results obtained using this approach are more reliable and more credible for these persons.
- A hierarchy of transport needs can help transport planners and providers adapt services, infrastructure, and transport policies to better meet the specific requirements and expectations of different user segments.
- The hierarchy of transport needs can be used to form policy and investment decisions tailored to user expectations. The resources and priorities of transport initiatives should focus on meeting expectations in the area of higher hierarchy of needs, gradually moving to lower priority levels. Such transport decision-making, in line with the carriers' decision-making model, can help to ensure that investments meet the most pressing needs of users and lead to more efficient transport outcomes.

The application of the transport needs hierarchy approach requires empirical research and verification to determine, first of all, the parameters that characterize their significance and magnitude in specific conditions for each of the levels of the hierarchy. This may require the collection of additional data about user preferences. In addition, this approach will likely need to take into account the cultural, geographic, and socio-economic differences of decision-makers in different regions.

4. Results

The proposed approach to decision-making based on the use of a hierarchy of transport needs is only a framework, not a method or model. It allows for a more systematic analysis of alternative transport routes from the user's (decision-maker's) point of view, taking into account multiple aspects such as geography, economics, institutional/political factors, infrastructure, and technology.

The transport needs hierarchy framework can be used as a heuristic decision model based on personal experience and preferences. Its combination with known methods and models can further improve the analytical accuracy and objectivity of the decision-making process for the evaluation and selection of alternative transport routes, which leads to more informed and effective decision-making results.

This paper proposes the use of Petri nets as a modeling tool using the framework described above. Petri nets, while maintaining the visibility of the model representation, allow a good display of the dynamics of the transport system while maintaining a multi-level hierarchical approach, taking into account all relevant factors. Petri nets can be beneficial in modeling the proposed structure of transport needs compared to other methods:

- Petri nets have a graphical representation that, on the one hand, makes it possible to visualize the interactions of different elements of the transport system, and on the other hand, it makes it easier for decision-makers to understand and analyze the dynamics of the system.
- Petri nets are useful for modeling parallel processes, which is typical for the problem under consideration when the analysis of the movement of goods along parallel but different transport routes takes place.

- The structure of Petri nets has a good association with the hierarchy of transport needs and provides a clear visual representation of the decision-making process during modeling.
- Petri nets are flexible, extensible, and scalable, making it easy to include additional elements or parameters during the development of the model. This gives additional opportunity for model extension to accumulate changes in the structure of transport needs or to incorporate additional factors or decision criteria over time.
- Petri nets have many modeling and analysis tools available, making them easy to use in practice.

Petri net is a mathematical modeling language that is especially useful for building models of parallel, asynchronous, distributed, non-deterministic, and/or stochastic systems [44]. For the considered class of problems of modeling alternative transport routes and related parameters, the Evaluation of Petri nets, or E-nets, which are an extension of Petri nets presented in [45], seem to be especially convenient. The E-net can be described using a set of components:

$$N = (P, T, A, M)$$

where P is a set of places, T is a set of transitions, A is a set of arcs, M is an initial marking.

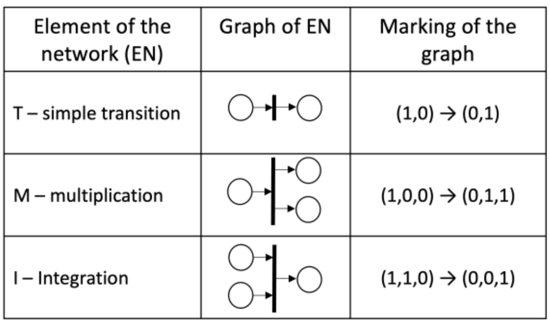
Places P represent conditions or states in our decision-making system. Transitions T are events or activities that can cause changes in the system state. In this context, these could be changes in the parameters associated with each of the planes (Geographical, Economical, Institutional/Political, Infrastructure, Technology). E-nets introduce different types of transitions, including deterministic (always execute as soon as they are enabled) and stochastic (have a certain probability of executing once enabled). Depending on the specific dynamics of our system, we might choose to use different types of transitions.

Arcs are directed connections between places and transitions. Arcs from places to transitions denote the conditions necessary for a transition to fire, while arcs from transitions to places denote the changes in state that occur when a transition fires:

$$A \subseteq (P \times T) \bigcup (T \times P)$$

The functioning of the system in dynamics is described using the movement of tokens between places P. The distribution of tokens over the places (a marking) represents a particular configuration of the transportation system, i.e., a specific set of alternative transportation routes and their associated parameter values. Set M is an initial marking.

For modeling, we will use a combination of the three basic elementary networks proposed in [45]: simple transition, multiplication, and integration. The configuration of these elementary networks of their transitions is shown in Figure 2.



Element of the network (EN)	Graph of EN	Marking of the graph
T – simple transition		(1,0) → (0,1)
M – multiplication		(1,0,0) → (0,1,1)
I – Integration		(1,1,0) → (0,0,1)

Figure 2. The basic elementary networks of E-net.

The basic model of the E-net, corresponding to the transport needs hierarchy framework, is shown in Figure 3. It consists of a chain of series-connected simple transitions in which P_S and P_F positions are the start and finish of the modeling process, P_i, $(i - 1, \ldots 5)$—the position of the start of modeling of the corresponding i level of the transport needs hierarchy framework, t_i—time transition corresponding to the performance indicator of the corresponding transport needs hierarchy framework plan (G—Geographical, E—Economic, P—Institutional/Political, I—Infrastructure, T—Technology plans).

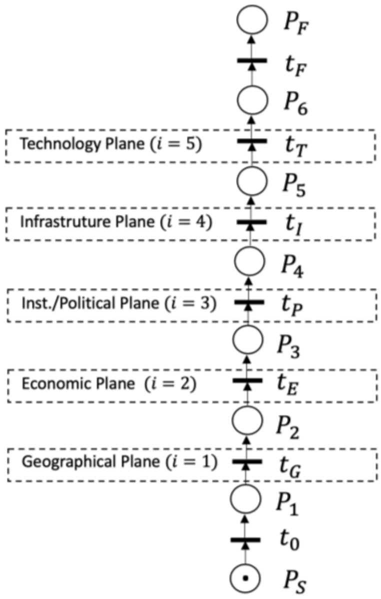


Figure 3. The basic model of the E-net corresponds to the transport needs hierarchy framework.

Each plan of the transport needs hierarchy framework can be evaluated using a different number of parameters, examples of which are shown in Table 2. If more than one parameter is used at each level of the hierarchy, the corresponding transition of this level is transformed into a network consisting of k elementary networks of the simple transition type, where k—the number of parameters that determine the effectiveness of operations at a given level of the hierarchy (Figure 4).

Table 2. Disadvantages of the existing MCDM methods for the transport industry compared with the proposed method.

Method	Disadvantages of Existing Methods
Linear Programming Models	Linear programming models often consider only one objective function, typically based on cost optimization. They may not adequately capture the complexity of multi-criteria decision-making in the transport sector, leading to suboptimal solutions when other critical factors like sustainability and reliability are not explicitly considered.
Mixed Integer Programming Models	While mixed integer programming allows for the consideration of discrete decision variables, it may become computationally challenging for larger-scale problems involving multiple criteria and constraints. The optimization process might be time-consuming and may not effectively capture dynamic changes in the transportation environment.
Multi-Objective Programming Models	Multi-objective programming methods consider multiple criteria simultaneously. However, they often lack the ability to provide clear insights into the trade-offs between conflicting objectives, making it challenging for decision-makers to make informed choices. Additionally, these models may not inherently incorporate sustainability aspects.
Monte Carlo Simulation Models	Monte Carlo simulation models can be effective for scenario analysis but may require significant data input and computation time. They might not offer a systematic approach to decision-making, and the results may not be as precise or easily interpretable as those from other methods.

Table 2. *Cont.*

Method	Disadvantages of Existing Methods
Analytic Hierarchy Process	While AHP helps structure decision-making by quantifying subjective judgments, it may be limited in addressing dynamic and time-dependent decision-making. Moreover, AHP might not inherently integrate multiple planes of influence, potentially leading to an oversimplified evaluation of transport alternatives.
Fuzzy Logic Models	Fuzzy logic models can handle imprecise and uncertain data, but they might struggle to provide a clear representation of the decision-making process. Interpretability might be challenging, making it difficult to communicate results effectively to stakeholders.
Neural Network Models	Neural network models excel at pattern recognition and learning from data but might not be as suitable for multi-criteria decision-making. The complexity of neural networks may hinder transparency in the decision-making process, leading to difficulty in understanding the reasons behind certain choices.

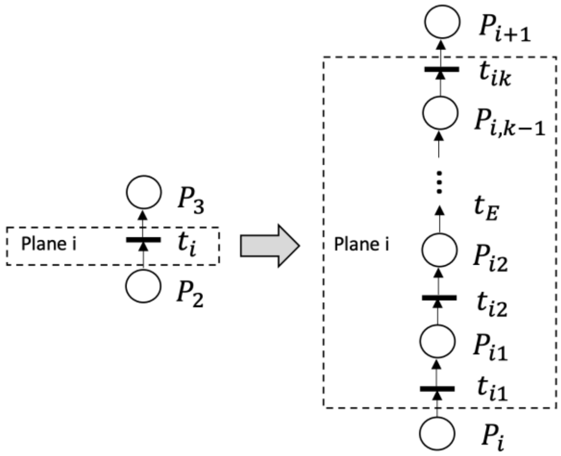


Figure 4. Transformation of basic model plane for multi-parameters representation.

If we analyze several transport alternatives to select the best one, each of the alternative routes is modeled with its own similar E-net. The beginning of all networks of alternative routes is united by an elementary network of the multiplication type t_0, and their final positions are united by an elementary network of the integration type t_F (Figure 5).

To determine the transition delay in the Petri Net based on a parameter value, we can use a mathematical function or equation specific to the parameter.

If the delay in triggering a time transition of Petri net is directly proportional to a parameter, as, for example, in the case of a geographic plan, which is characterized by the distance of a transport alternative, we can use a linear function that relates distance to time, such as $t_{Gi} = \alpha_i d_i$, where t_{Gi} is the delay, α_i is a coefficient, and d_i is the distance for i transport alternative. The same approach we can use for parameters of the economical plane with a delay in time transition $t_{Ei} = \beta_i c_i$, where β_i is a coefficient, and c_i c is the cost of i transport alternative.

If the delay in triggering a Petri net transition is inversely proportional to a parameter (for institutional/political, infrastructure, and technological planes), we can consider using the following mathematical expressions as options:

- Exponential delay $\tau = \alpha e^{-\beta}$, where τ is the delay, α is a coefficient related to the parameter, and β is another coefficient determining the rate of decay.
- Power function $\tau = \alpha / \beta^{\gamma}$, where τ is the delay, α and β are coefficients related to the parameter, and γ is a parameter determining the power of the function.
- Reciprocal function $\tau = \alpha / (\beta + \gamma)$, where τ is the delay, α, β and γ are coefficients related to the parameter, and β and γ determine the shape and scale of the reciprocal function.

- Logarithmic function $\tau = \alpha / ln(\beta + \gamma)$, where τ is the delay, α, β and γ are coefficients related to the parameter, and β and γ determine the shape and scale of the logarithmic function.

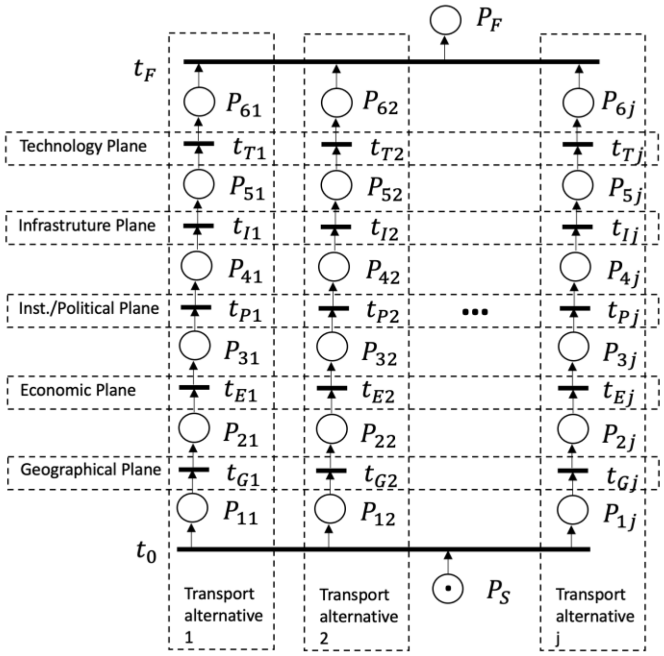


Figure 5. The E-net model for multi-alternative transportation.

These mathematical expressions can be adjusted and customized based on the specific characteristics and requirements of the parameter in each plan. The coefficients α, β, γ can be determined using analysis, expert judgment, or statistical methods to accurately represent the inverse relationship between the parameter and the delay in the Petri net transition.

Random values distributed according to different distribution laws can also be used as the transition delay time if their parameters are known as a result of special studies or expert assessments.

To calculate the time of passing the token from the initiating position to the end position of the last plan of transport needs hierarchy framework, we can sum the transition delays for each plan in the framework $T_\Sigma = \tau_1 + \tau_2 + \ldots + \tau_5$, where $\tau_1,\ \tau_2,\ \ldots\ \tau_5$ represent the transition delays for each plan.

5. Discussion

By following this refined methodology and incorporating the additional requirements, we can effectively determine the most efficient alternative transport route based on the minimal time for the token to traverse the framework.

The methodology for compiling and applying the described model for choosing alternative transport routes in a large-scale transportation transit system can be outlined as follows.

1. Determine the number and routes of transportation alternatives that will be considered in the study.
2. For each framework plan, define a set of indicators that will be used to evaluate and compare alternatives. These indicators should reflect the relevant factors and criteria influencing decision-making at each level of the hierarchy.
3. Modify the basic E-net for each level of the framework hierarchy, taking into account the number of parameters chosen for each level of the hierarchy.
4. Establish mathematical expressions that determine the transition delay in the Petri Net based on the parameter values. Each parameter should have a corresponding

expression that maps its value to the delay in the transition. Consider using functions, formulas, or equations that accurately represent the relationship between the parameter and the delay.

5. Build a Petri net model using known modeling tools or software [46]. Set up the initial marking and run a simulation to observe the flow of the markers and the behavior of the transition. This will give an understanding of the decision-making process and the criteria for selecting alternatives at each level of the framework plan hierarchy.
6. Analyze the results of the simulation by estimating the time required for the marker to travel from the start position to the end position of the model. As the optimal solution, select the option with the minimum time for the marker to travel this path.

In this study, the proposed E-net tool has a number of advantages over other types of Petri nets:

- Greater flexibility of E-net when modeling complex systems compared to other types of Petri nets, which is provided by additional synchronization mechanisms that extend its modeling capabilities for the example under consideration.
- The ability to simulate parallel processes in the E-net makes it particularly suitable for the present case of analyzing alternative transport routes.
- The ability to visually represent the behavior of the system in the E-net makes it easier for stakeholders to understand the model and increases confidence in its results. At the same time, visualization clearly demonstrates the bottlenecks in the system, which leads to better analysis and more effective decision-making.
- The scalability and modularity of E-net models allow you to simulate large-scale systems while maintaining their original hierarchical structure.
- The ability to easily adapt and modify the E-net model allows you to make changes and refinements to it as you understand the system or new requirements appear. This adaptability ensures that the model remains up-to-date and can be updated to reflect changes in the system as it evolves over time.

The proposed MCDM method combines a multi-plane framework and E-net modeling, offering a more integrated and systematic approach to decision-making in the specific transportation domain. By incorporating sustainability factors and considering multiple influencing planes, the proposed method provides decision-makers with a more comprehensive view of transport alternatives. It offers a more nuanced and strategic decision-making process for discussed transportation problems.

To validate the effectiveness and superiority of our approach, a crucial aspect is to compare our model's performance with other well-known techniques in the field, often referred to as State-Of-The-Art (SOTA) models. By conducting evaluations and comparisons with prominent SOTA models, we can gain insights into the strengths and potential advantages of our proposed approach.

Table 2 compares the proposed MCDM method with different existing universal methods and highlights the disadvantages of the known methods within the frame of transportation issues.

- While each of these methods has its strengths and has been valuable in various decision-making scenarios, they may not fully address the complexity and dynamics of the transportation sector's multi-criteria decision-making. The proposed method, with its multi-plane framework and E-net modeling, offers a comprehensive, dynamic, and visually intuitive approach, explicitly considering sustainability factors and providing more effective solutions for selecting the best transport alternatives.
- Despite its valuable contributions, the proposed study also has certain limitations:
    - The effectiveness of the model heavily relies on the availability and quality of data. Gathering comprehensive and accurate data on various criteria across different planes of influence can be challenging, which involves multiple stakeholders and jurisdictions.

    - While E-net offers powerful modeling capabilities, it may require specialized expertise and computational resources for implementation and analysis. This could potentially limit its adoption by smaller organizations or those without access to advanced modeling tools.
    - The process of assigning weights to different criteria in the decision-making process involves subjective judgment. The study should provide a clear and transparent methodology for eliciting and incorporating decision-makers' preferences, but inherent biases and variations in weighting may still exist.
- The practical implications of the proposed approach extend to a wide range of users, from cargo owners and logistics managers to policymakers and researchers. It empowers decision-makers to make informed and sustainable choices, leading to optimized transportation networks, reduced environmental impact, and improved overall efficiency of transport.
- The proposed approach enables cargo owners and shippers to make well-informed decisions when selecting transport alternatives. They can consider a comprehensive set of criteria, including geographical, economic, institutional, infrastructural, technological, and sustainability factors, to optimize their supply chain and reduce transportation costs. By incorporating sustainability considerations, cargo owners can align their transportation practices with environmental and social goals, promoting responsible and eco-friendly shipping solutions.
- Logistics managers can use the proposed model to identify the most efficient and reliable transportation routes. The E-net modeling facilitates a systematic representation of dependencies and concurrency, aiding in strategic planning and resource allocation. Real-time decision support provided using the model allows logistics managers to respond promptly to disruptions and dynamically adjust operations to maintain efficient and smooth cargo flow.
- Policymakers can leverage the proposed approach to assess the impact of transportation policies and infrastructure investments. They can use the model's analysis to prioritize projects that improve connectivity, reduce emissions, and enhance the overall efficiency of transportation networks. Incorporating sustainability factors into decision-making supports policymakers in promoting environmentally friendly transportation practices and achieving national and international sustainability goals.
- Transportation services providers can utilize the proposed approach to differentiate themselves in the market by offering more sustainable and efficient transport solutions. By meeting the growing demand for environmentally responsible services, they can attract environmentally conscious customers and gain a competitive advantage. The model's insights can aid in optimizing fleet management, route planning, and capacity utilization, leading to cost savings and improved service levels.
- The proposed approach contributes to the academic and research community by introducing a novel combination of the transport needs hierarchy framework and E-net modeling. Scholars can build upon this work to advance the field of multi-criteria decision-making in transportation and explore further applications in different industries. The comprehensive and systematic nature of the proposed approach opens avenues for interdisciplinary research, encouraging collaboration between experts in logistics, environmental studies, and transportation planning.

6. Conclusions

The paper describes the research-oriented on the development of a transport needs hierarchy framework and the proposed model using Evaluation Petri Nets (E-nets) for analyzing and selecting alternative transport routes based on the preferences and priorities of decision-makers. The study aimed to address the limitations of existing methods and models in the field by incorporating a hierarchical framework and utilizing E-nets as a modeling tool.

The study proposes a transport needs hierarchy structure consisting of five levels: geographic, economic, institutional/political, infrastructural, and technological. Each plane of the specified hierarchy represents a different level of priority and influence on the decision-making process, which makes it possible to evaluate and rank various transport alternatives for decision-makers, taking into account the specific preferences and requirements of DM.

For effective modeling and analysis of the structure of the hierarchy of transport needs, the article proposes to use E-nets as an extension of Petri nets. The methodology for constructing the E-network model is described in the article.

The main feature of the proposed model lies in its ability to cope with a complex hierarchy of transport needs and provide a systematic approach to decision-making on the choice of alternative routes for multimodal transit systems, including such traditional factors as cost efficiency, as well as any other factors that matter, such as sustainability. By implementing the E-net model, decision-makers can explore various scenarios, evaluate alternative routes, and determine the most efficient options based on predefined criteria and preferences.

By introducing a multi-plane framework that emphasizes sustainability factors and leveraging E-net modeling for accurate decision-making, the proposed approach addresses the critical need for responsible and environmentally conscious choices in the dynamic world of freight transportation. As stakeholders in the industry increasingly recognize the value of sustainable practices, this research paves the way for a more ecologically responsible and resilient future for freight transportation.

The impact of the article is far-reaching, significantly transforming the landscape of decision-making in the freight transportation industry. By incorporating a multi-plane framework, the study addresses the limitations of traditional methodologies that often focus solely on economic factors. The framework's comprehensive analysis of geographical, economical, institutional/political, infrastructure, and technological aspects provides decision-makers with a nuanced perspective on each transportation alternative.

The integration of E-net modeling into the decision-making process further enhances the impact of the approach. E-net's ability to represent concurrency and dependencies among various factors and planes enables a more sophisticated analysis, capturing the complexities of real-world transportation systems. Decision-makers can now evaluate multiple influencing factors simultaneously, leading to more informed and efficient decisions.

The article's novelty lies in its unique combination of the multi-plane framework and E-net modeling, offering a holistic and innovative approach to decision-making in freight transportation. While previous studies have explored various decision-making models and frameworks, the proposed approach presents a novel synthesis that fills critical gaps in the current literature.

The introduction of the multi-plane framework, which aligns with the hierarchy of transportation needs, adds a new dimension to decision-making. By considering factors in their hierarchical order of importance, the framework reflects real-world decision processes, making it more relevant and practical for industry applications.

The utilization of E-net as a version of Petri net is also a novel aspect of the study. E-net's potential for representing time-dependent decision-making processes, combined with its ability to visualize complex interactions, distinguishes it from other modeling approaches and marks a new frontier in decision-making systems.

The proposed approach holds significant implications for decision-making systems in the freight transportation industry:

- By adopting the multi-plane framework, decision-makers can make more informed choices when selecting transportation alternatives. Consideration of a broad spectrum of influencing factors ensures a comprehensive evaluation, leading to improved efficiency and cost-effectiveness.
- The integration of E-net modeling empowers decision-makers with a powerful tool to capture the intricacies of the transportation system. E-net's ability to represent

time-dependent decision-making processes ensures that strategic decisions are not only accurate but also timely, enabling adaptability in a dynamic environment.

By combining these two components, the transport needs hierarchy structure and the E-nets model, the study provides a robust methodology for solving the problems of choosing the best route for multimodal transport. This approach improves the decision-making process, allowing stakeholders to optimize their choices and improve overall freight efficiency.

The study's extends beyond the freight transportation industry. The approach's focus on sustainability aligns with global efforts to reduce environmental impact and carbon emissions. By incorporating sustainability factors into decision-making, the proposed approach contributes to a more environmentally responsible and resilient transportation industry.

The integration of a multi-plane framework and E-net modeling provides decision-makers with a comprehensive and innovative approach to evaluate transportation alternatives, offering valuable insights for cargo owners, transport operators, and policymakers alike. The emphasis on sustainability aligns with global environmental goals, making the proposed approach not only relevant but also vital for the future of freight transportation.

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