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Original Article

MODELLING SOLUTIONS FOR COST OPTIMIZATION IN MULTIMODAL TRANSPORTS CONSIDERING THE OPERATIONAL RISK VARIABLES

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Highlights:

- the Fault Tree Analysis (FTA) method is applied to assess maritime transport risks within multimodal chains, using the case study of Port of Constanta (Romania);
- statistical data from the Romanian Naval Authority is modelled to quantify incident probabilities in maritime operations across human, environmental, technical, and cargo-related factors;
- human error is identified as the most significant risk contributor (78%) in port incidents, highlighting the need for targeted safety strategies;
- Boolean logic and probability theory are employed to structure and compute a comprehensive risk model for maritime operations;
- the results provide port administrators with a robust, data-driven tool for improving risk mitigation, maintenance planning, and emergency preparedness.

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Abstract. The general risk assessment usually has the potential of setting a viable ground for pursuing a complex mathematical model based on an objective function, defined by several variables and constraints, which can be further applied for the specific analysis of multimodal transport. In order to assess the operational risks in multimodal transports, the authors have formulated an objective function with the aim of minimizes the sum of total cost of transportation on route components depending on the risk variables, respectively for road, maritime and railway subsystems of multimodal transport, in different combinatorial perspectives. The main objective of this study is to provide a method to value the overall risk assessment based on the defined objective function, considering both the variables that may influence the cost effectiveness and the relevant probabilities for each route component of multimodal transport. In this perspective, the authors have sought to provide practical solutions for decision-making process in multimodal routing, to optimize the costs on different routes and to contribute for decision-making process in routing and transports mode selection. The main contribution is residing from the novelty of decision-making process approach, considering the risk variables in different combination, facile to be applied professional in multimodal transportation in routing process, when risks are to be considered as significant for process reliability.

Keywords: risk management, multimodal transport, modelling, transport cost, cost optimization, objective function, route selection.

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Notations

The applied abbreviations, indices, parameters and variables used in the mathematical calculations of the studied model are defined below.

Abbreviations:

FTA – fault tree analysis;

TEU – 20-foot equivalent unit.

Indices:

b – regions of movement within the transportation chain, b = 1, ..., B;

i – cargo consignments, i = 1, ..., I;

t – points of transportation demand, j = 1, ..., J;

k – multimodal transportation route components, $k = k_2$ (maritime transport) and $k = k_3$ (railway transport);

t – period of transportation services, t = 1, ..., T.

Parameters:

a_{jbit} – demand of i cargo consignments from/to b regions [unit];

$c2_{jbk2}$ – cost of maritime transportation between j and b on the price level $k2$ [cost/price];

$c3_{jbk3}$ – cost of railway transportation between j and b on the price level $k3$ [cost/price];
$cp2_{k2i}$ – maximum number of cargo units [payloads] for $k2$ [units of cargo];
$cp3_{k3i}$ – maximum number of cargo units [payloads] for $k3$ [units of cargo];
$e2_{k2i}$ – minimum number of cargo units [payloads] for $k2$ [units of cargo];
$e3_{k3i}$ – minimum number of cargo units [payloads] for $k3$ [units of cargo];
$p2_{k2}$ – disruption probability for transportation component $k2$;
$p3_{k3}$ – disruption probability for transportation component $k3$.

Variables for decision-making process:

$kx2_{ik2bjt}$ – the number of i units of cargo transferred from b point to j point through transportation route component $k2$ during the period t;
$kx3_{ik3bjt}$ – the number of i units of cargo transferred from b point to j point through transportation route component $k3$ during the period t;
$m2_{k2}$ – number of transportation means available for route component $k2$;
$m3_{k3}$ – number of transportation means available for route component $k3$.
$n2_{k2}$ – minimum required number of TEUs (or total cargo volume) to be transported on maritime route component k_2 in a given time period t (possibly based on service-level agreements, scheduling, or port throughput requirements);
$n3_{k3}$ – minimum required cargo volume (e.g., in TEUs) to be assigned to railway transport component k_3 in time period t, to ensure minimum utilization or meet contractual/service constraints;
Z – binary variable indicating whether cargo is transported on a specific maritime/railway/road route segment in a given period, where $Z = 1$ if assigned, or $Z = 0$ otherwise.

1. Introduction

The multimodal freight transportation involves the coordination and implementation of freight movement through multiple forms of transportation such as rail, sea, air and road, but under a single contractual service provider, ensuring the effective transition of goods from the point of origin to the final point of destination (Bydlinski 1997; Kukulski *et al.* 2023; Kaewfak *et al.* 2024).

This approach unifies the chain of transport responsibilities in the hands of an unique multimodal logistics operator, who will permanently seek to optimize the route and to select the optimum transportation option, in order to identify and to assign a seamless and cost-effective flow of cargo, within the transportation network, crossing the borders and combining the routes, in compliance with the principles established by the *United Nations Convention on International Multimodal Transport of Goods* as implemented from 24 May 1980 (Hoogendoorn-Lanser *et al.* 2006; Xu *et al.* 2024).

In the present study, the authors have analysed the objective capability of detecting the potential hazards associated with the multimodal transports, applied on different segment routes along the chain of transportation. The need for research consists in the aim of defining a mathematical model that can be applied peculiarly for the case of multimodal transport of goods, in the general context of considering the risk analysis applied to this field (Asariotis *et al.* 2019; Cherednichenko *et al.* 2023; Huang *et al.* 2020). The objective of the research has been focused on optimizing the risk analysis of the multimodal transport of goods, by applying a mathematical model that can predict the financial impact of the risks recorded along the multimodal segments of transport in terms of costs on different routes combinations (Li *et al.* 2023). The anticipated results should demonstrate how a coherently applied mathematical model can provide a correct framework for calculation of the costs occurred within the multimodal transport, per each route component (Rausand *et al.* 2020).

The research hypothesis has been developed based on the key elements of risk identified within transportation segments that may contribute to the decision-making process (Xu *et al.* 2024). These key elements will ultimately determine the cost of transporting units through the multimodal transport route components, as land, air or sea.

During the past decades, safety-related constraints have been actively considered in the multimodal transport problem analysis, while the transportation planning processes in regard of the safety aspects have been considered as being significant for logistics companies' activity, impacting the modal or multimodal transportation performance and reliability (Muller 1999). From the literature review has been stated that the multimodal transportation problem should be evaluated by incorporating economic, social, and environmental conditions simultaneously (Bula *et al.* 2017; Guo, Luo 2022). Therefore, the transportation modes and related services, should be assessed critically considering in all operational respects the risks of multimodal transportation. As reflected by several authors as an operational rule, explosions and crashes may occur during the transportation within multimodal or modal channels of goods transferring toward the clients (Cherradi *et al.* 2017; Cieśla *et al.* 2017).

Furthermore, the study of operational risks of transportation modes during the multimodal optimization processes, is also very important because of each mode characteristics, from all points of views, from technology to the environmental impact (Barnhart, Ratliff 1993). Basically, the road transports are the most preferred meanings throughout the multimodal options, due to its flexibility on door-to-door features, chosen especially for picking, batching, or delivering services in many of the routing options, when short/medium distances and light cargo (Beresford *et al.* 2021). Railway transport mode is often used for heavy goods, on short or medium ranges, with minimum transport costs (Miller, Shaw 2021). On the other hand, the maritime transport is preferred because of its large capacity and reliability, out of the time restriction, being an optimal multimodal option in case of transportation of heavy goods, liquids or bulk cargo, large batch of containers, offering the minimum cost advantages on the principle of economy of scale (Fang *et al*. 2020). Nowadays, considering other externalities as accepted restrictions, because road transportation negative environmental impacts, a modal shift from the road to other modes is seen as more beneficial on sustainable basis (Zhang *et al*. 2020).

For optimizing the total cost of transportation, the process flow is usually designed applying mathematical modelling for identifying the quantitative expression for the risk variables influence against each mode of transportation and for building the respective models of multimodal transportation as optimum result of operational planning (Min 1991; Serper, Alumur 2016). Besides of this approach, other authors centered their studies on the transport modes comparison, seeking to quantify the influence of each mode within the channel of multimodal transfer of goods (Barnhart, Ratliff 1993).

The analysis of multimodal transportation effectiveness and cost optimization, based on risk variables consideration, has been approached by multiple researchers in the literature, the results being valued in difference modelling alternatives of multimodal network optimization (Rausand *et al*. 2020; Huang *et al*. 2020; Guo *et al*. 2021; Chang 2008). In this context, some authors have examined the dangerous materials by considering transport risks variables (Bubbico *et al*. 2004), or have formulated a risk model for railway transport (Glickman *et al*. 2007), while others have developed a bilevel problem for transportation network and proposed a heuristic approach that would lower the network risks (Erkut, Gzara 2008). In the same direction, few authors have developed a model designed to minimize the total risk for multimodal transport (Caramia, Giordani 2009). Verma *et al.* (2012) have studied the dangerous goods transport problem seeking to minimize the total transportation cost and to calculate the share of population who is affected by risky events. Moreover, Reniers & Dullaert (2013) had issued a methodology of transporting dangerous materials by different modes using a transport risk analysis tool for dangerous materials, considering the accidents probability and Guo & Verma (2010) had studied multiple transports of materials by using historical accident data and risk map for the transport of dangerous goods.

In relation with above state of the art in risk modelling and cost optimization developments, the authors of the present study have aimed to contribute by formulating an objective function method designed to optimize the routing decision-making process by considering the risk assessment variables. The main authors' contribution is residing from the novelty of decision-making process approach, considering the risk variables in different combination, facile to be applied professional in multimodal transportation in routing process, when risks are to be considered as significant for process reliability.

2. Methodology

The approach is based on math modelling, focused on a detailed analysis of the variables that influence the risk factors occurrence for each component within the channels of multimodal transportation valuing its impact on cost effectiveness, in different combination of transport routes. In this perspective, the authors aimed to provide a depth analysis about how the variables and the constraints in the mathematical model are related to the probability of the cost influence in relation with operational risks in multimodal transports.

Therefore, in order to assess the operational risks in multimodal transports, the authors have formulated an objective function with the aim of minimizes the sum of total cost of transportation on route components depending on the risk variables, respectively for road, maritime and railway subsystems of multimodal transport, in different combinatorial perspectives. The main objective of this study is to provide a method to value the overall risk assessment based on the defined objective function, considering both the variables that may influence the cost effectiveness and the relevant probabilities for each route component of multimodal transport. In this perspective, the authors have sought to provide practical solutions for decision-making process in multimodal routing, to optimize the costs on different routes and to contribute for decision-making process in routing and transports mode selection. For each proposed combination of routing segments, the authors have tested the model with a practical case study, to reflect the practical importance of such modelling approaches in regular decision-making process.

2.1. Key elements for decision-making process in the enhanced model of multimodal transportation

Multimodal transportation network elements:
- railway and maritime transport, with detailed interconnection points and capacity constraints;
- cost structures derived from real transportation corridors, ensuring alignment with empirical economic data.

Cargo type considerations:
- standardized unit measures for TEU-based intermodal transportation, ensuring consistency across transport modes;
- specific cargo risk profiles, incorporating variability in handling times, security risks, and environmental influences.

Optimal transportation mode selection:
- integration of verified cost/km values from different international routes, adjusted based on operational and infrastructural constraints;
- dynamic adaptation to probability-based risk assessments, optimizing transport efficiency by minimizing disruption impacts.

2.2. Model constraints and limitations

Demand fulfilment requirements:

- ensuring full cargo transport compliance with customer demand, adapting dynamically to congestion and alternative route selection using optimized pathfinding algorithms;
- incorporating network disruptions and infrastructure constraints to simulate real-world operational delays.

Payload capacity constraints:

- adjusting transport capacity models based on verified infrastructure data and fleet specifications for railway and maritime transport;
- factoring in limitations due to handling capabilities at intermodal terminals, optimizing loading and unloading operations to minimize delays.

2.3. Methodology of mathematical model. Definition of scientific hypothesis

As scientific hypothesis for the proposed operational analysis, the authors have formulated a mathematical model, following the mathematical values (indices and parameters) mentioned in Notation section. Then, in the 1st stage of conducted research, a mathematical model has been built, considering on the basics of its content the next elements, variables, and restrictions within the study scenario.

Key elements for decision-making process in the conceived model:

- the elements from the multimodal transportation network;
- the cargo type used in the transportation model;
- the choice of a transportation medium along the multimodal transportation chain.

Limits of the model:

- the requirement of integral demand fulfilment of considered clients;
- the limited payload capacity of each chosen transportation medium along the multimodal transportation chain.

The limitations of the model are defined by the requirement to fully satisfy the demand, but especially the limited payload capacity of each transport medium chosen along the multimodal transport chain. The mathematical model is strictly applied to maritime and railway components, excluding road transport, as per the scope of this research.

3. The mathematical modelling of multimodal risks' occurrence costs. Research results and interpretations for decision-makers

3.1. Modelling solutions for multimodal risks' assessment

To assess the operational risks impact along multimodal routes in order to disclose the modal cost influence, a probabilistic approach has been applied considering the probability rate of occurrence extracted from historical statistical data and expert evaluations, as synthesized in Table 1. These risk parameters were used as sample in quantifying the total risk occurrence costs, considering the assessment of the impact of each potential failure event (Cherednichenko *et al.* 2023; EMSA 2024; UNCTAD 2024).

In the following risk analysis formulas, each variable (e.g., *a*, *b*, etc.) refers to a distinct operational risk event within the multimodal transport system – such as congestion, equipment failure, or weather disruption. While the risk scenarios *a* (moderate congestion) and *b* (critical technical failures) are illustrated in detail in the next section to demonstrate the application of risk importance measures, the remaining scenarios in Table 1 – namely *c* (severe weather conditions), *d* (equipment malfunctions), *e* (security risks), and *f* (poor coordination) – have been evaluated using the same mathematical procedures and formulas. Then, for each of these scenarios, the associated parameters probability of occurrence *P*, impact in hours *I*, and total risk *R* – were estimated based on historical incident data and expert judgment sourced from maritime safety databases (e.g., EMSA 2024, UNCTAD 2024). These values were then used to compute the next 4 importance measures: Birnbaum importance I_B, Fussell–Vesely importance I_{FV}, risk reduction worth I_{RRW} and risk achievement worth I_{RAW}. The values presented for scenarios c–f in Table 1 are the result of applying these formulas to their respective risk data. Although the complete step-by-step derivation is not detailed for all scenarios, these were computed using the same methodology as outlined for scenarios *a* and *b* in Section 3.2, this consistent application ensuring the comparability across all risk factors considered in the multimodal transport system. For example, in subsequent examples: *a* corresponds to moderate congestion and *b* corresponds to critical technical failure.

The risk evaluation process has considered several probabilistic modelling techniques as following:

1. *FTA (Ruijters, Stoelinga 2015):*

- is used as facile method to break down the complex failure events, to analyse their contributing causes and the chain of consequences;
- may be enabled to quantify the disruption probabilities by analysing the chain of failures in logistics workflow;
- the probability of risk occurrence for each failure event is determined based on historical data and expert assessments;

2. *risk quantification methods (Miziuła, Navarro 2019; Mou et al. 2021):*

- Birnbaum importance I_B: evaluates how the probability variance of an individual event may affect the total system risk (Miziuła, Navarro 2019):

$$I_B = \frac{\partial R}{\partial P} = a, \tag{1}$$

it reflects the rate of change of the system's total risk-based on variations in the probability of an event *P* (examples: congestion in the Suez Canal, re-routing via the Cape of Good Hope);

Table 1. Risk analysis using importance measures in multimodal transport

Risk scenario	Probability P	Impact I [h]	Total risk R	Importance			
				I_B	I_{FV}	I_{RRW}	I_{RAW}
a: moderate congestion (maritime traffic)	0.12	24	0.49	0.8	0.19	1.24	2.42
b: critical technical failures	0.02	48	0.41	0.5	0.02	1.02	2.19
c: severe weather conditions	0.05	12	0.41	0.3	0.03	1.03	1.69
d: equipment malfunctions	0.03	12	0.21	0.4	0.05	1.06	2.83
e: security risks	0.10	72	0.36	0.6	0.16	1.20	2.50
f: poor coordination	0.07	10	0.27	0.3	0.07	1.08	2.03

Source: data collected and processed by authors from literature review (Cieśla *et al.* 2017; Kukulski *et al.* 2023; Kaewfak *et al.* 2024; Basallo-Triana *et al.* 2021; AGCS 2022; UNCTAD 2024; EMSA 2024).

- Fussell–Vesely importance I_{FV}: determines the fractional contribution of a specific event to the total risk (Mou *et al.* 2021):

$$I_{FV}=\frac{a\cdot P}{R}=\frac{a\cdot P}{a\cdot P+b}, \quad (2)$$

it measures the fractional contribution of an event to the system's total risk;
- risk reduction worth I_{RRW}: measures the decrease in total system risk if a particular event is completely mitigated (Vrbanic, Basic 2024):

$$I_{RRW}=\frac{R}{R(P=0)}=\frac{a\cdot P+b}{b}, \quad (3)$$

indicates how much the system's total risk would be reduced if the probability of a risk event were eliminated (P = 0) and refers to the impact value that reducing or increasing a specific risk has on the system's total risk;
- risk achievement worth I_{RAW}: assesses how much total system risk increases if a particular risk event is guaranteed to occur (Vrbanic, Basic 2024):

$$I_{RAW}=\frac{R(P=1)}{R}=\frac{a+b}{a\cdot P+b}, \quad (4)$$

indicates the increase in risk if the risk event is guaranteed (P = 1);

3. ***mathematical modelling of total risk:***
- the total risk function was defined in accordance with (Huang *et al.* 2020):

$$R=a\cdot P+b,$$

where: R represents the total system risk; $a\cdot P$ accounts for scenarios where a specific risk event occurs; b accounts for all other contributing risk scenarios.

3.2. Model's applications in decision-making-process for multimodal routes combinations

As application of proposed model, by using empirical risk data from Table 1, the following steps must be followed and next values will be obtained:

- select 2 events – in the following calculations, a and b represent risk events selected from Table 1, where a refers to moderate congestion and b refers to critical technical failures in the maritime transport component:
  - moderate congestion: $P_1=0.12$, $R_1=0.49$;
  - critical technical failures: $P_2=0.02$, $R_2=0.41$;
  - calculate the probability for event a referring to moderate congestion: $a=\frac{R_1-R_2}{P_1-P_2}=0.8$; (5)
  - calculate the probability for event b referring to critical technical failures: $b=R_1-a\cdot P_1=0.394$; (6)
- compute importance measures:
  - $I_B=\frac{\partial R}{\partial P}=0.8$; (7)
  - $I_{FV}=\frac{a\cdot P}{R}=\frac{a\cdot P}{a\cdot P+b}=0.19$; (8)
  - $I_{RRW}=\frac{R}{R(P=0)}=\frac{a\cdot P+b}{b}=1.24$; (9)
  - $I_{RAW}=\frac{R(P=1)}{R}=\frac{a+b}{a\cdot P+b}=2.42$. (10)

The impact of congestion risk in the maritime component of multimodal freight transport (for example in case of Suez Canal), in terms of delays, is quantified based on the probabilistic model derived from Table 1. According to different sources, the probability of congestion is $P=0.12$ (AGCS 2022; UNCTAD 2024; Basallo-Triana *et al.* 2021).

The expected delay impact due to congestion is derived from historical shipping data and operational reports, where past congestion events have resulted in delays ranging from 12 to 24 h. Given the statistical data from Table 1, the estimated impact for moderate congestion is $I=24$ h.

This impact is used in the I_B and I_{FV} measures to quantify how congestion contributes to the overall risk of the maritime segment. The integration of probabilistic delay modelling allows for improved rerouting decisions and cost estimation in the multimodal transport network (Kukulski *et al.* 2023; Kaewfak *et al.* 2024).

These equations were applied to multiple risk scenarios, using data extracted from Table 1 to ensure accuracy in quantifying risk impacts. Applying these methodologies, the impact of each risk event on total system risk was quantified, allowing for better mitigation planning and optimization of multimodal logistics flows. This structured approach ensures that risk modelling in the transport network is both systematic and data-driven, providing valuable insights for improving operational resilience.

Considering the study hypothesis and the enounced methodology, the minimization function structures will result, for maritime (Equation (11)) and railway (Equation (12)) route components. Then, following the general approach of cost minimization under risk constraints, the total transportation cost for each subsystem of the multimodal route is modelled as an objective function.

For the maritime component, the minimization function is defined as follows, aiming to minimize the total transportation cost across all indices of cargo type *i*, regions *b*, route components *k*, demand points *j*, and time periods *t*:

$$\min z = \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} kx2_{ik2bjt} \cdot c2_{jbk2} \cdot m2_{k2} \cdot p2_{k2}. \quad (11)$$

Similarly, for the railway component, the minimization function is defined as follows:

$$\min z = \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} kx3_{ik3bjt} \cdot c3_{jbk3} \cdot m3_{k3} \cdot p3_{k3}. \quad (12)$$

Equations (11) and (12) define 2 sub-objective functions that are structurally similar, each minimizing the total cost for a specific transport mode (maritime and rail), both functions integrate operational risk variables through the probability coefficients $p2_{k2}$ (for maritime route) and $p3_{k3}$ (for railway route), allowing the overall multimodal optimization model to evaluate and select the most cost-effective and risk-resilient route combination.

Then, the objective function is minimizing the sum of total cost of transportation on route components, considering the operational risks factors impact, as processed from different risk assessment methodologies including FTA results, like following, depicted on each mode of transportation within the multimodal considered route (Kaewfak *et al.* 2024; Li *et al.* 2023).

3.2.1. The case of maritime transportation component through the multimodal transportation route

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} kx2_{ik2bjt} \le \sum_{i=1}^{I} cp2_{k2i} \cdot m2_{k2},$$
$$k_2 \in K,\ t \in \{1, T\}. \quad (13)$$

The restriction regarding the transport capacity is modelled as following:

$$\sum_{i=1}^{I} cp2_{k2i} \cdot m2_{k2} -$$
$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx2_{ik2bjt} \cdot Z \ge \sum_{i=1}^{I} e2_{k2i} \cdot m2_{k2},$$
$$k_2 \in K,\ t \in \{1, T\}, \quad (14)$$

where: Z is a binary decision variable defined as $Z = 1$ if cargo is allocated to a specific maritime transport leg during time period *t*; $Z = 0$ otherwise. It is used to enforce the condition that minimum payload constraints are only activated when transport is actually scheduled.

This constrain assures a low number of risks as expressed below:

$$\sum_{b=1}^{B}\sum_{k=1}^{K} kx2_{ik2bjt} = a_{jbit},$$
$$j \in J,\ t \in \{1, T\},\ i \in \{1, I\}. \quad (15)$$

This constrain assures the following cargo demand:

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} n2_{k2} \cdot kx2_{ik2bjt} \ge m2_{k2},$$
$$k_2 \in K,\ t \in \{1, T\}. \quad (16)$$

The computation of these equations may ensure the decision takers that the maritime transport component operates within capacity limitations, meeting the cargo assignments' demand volumes, and maintaining a low risk levels.

For a clear representation, the authors have applied as exemplification, the data proposed in Table 2, to validate the model assessing the risk impact against the maritime transportation costs, as application of the method in decision-making process, using the available data on online maritime business platforms (*https://www.marinevesseltraffic.com*).

Therefore, to validate the proposed model, the authors have considered the following scenario:

- a client for transportation places a shipping order of 56000 TEUs, to relocate cargo consignments from a given port to another port of calling, with available maritime capacity constraints;
- considering the ships capacity, the constraint is fully satisfied fixing 4 vessels to operate at full capacity with a payload of 14000 TEUs each;
- given the vessels' available and their carrying capacity.

As conclusion, the model will process the following results, the capacity constraint holds, ensuring feasible transport of the requested TEUs within the available vessel fleet:

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx2_{ik2bjt} = 50000;$$
$$m2_{k2} = 4;\ cp2_{k2i} = 14000 \text{ TEUs}. \quad (17)$$

Table 2. Maritime transportation capacity and cost data

Parameter	Description	Value	Unit
$cp2_{k2i}$	maximum cargo capacity per vessel	14000	TEU
$e2_{k2i}$	minimum cargo capacity per vessel	8000	TEU
$m2_{k2}$	number of available vessels	4	units
$c2_{jbk2}$	cost per TEU per km (Zhang *et al.* 2020)	1.2	$/km
$p2_{k2}$	disruption probability (maritime)	0.08	–

Source: authors' processed data using the specialized portal: *https://www.marinevesseltraffic.com*

Since:

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx2_{ik2bjt} =$$

$$50000 \leq 4 \cdot 14.000 = 56000 \text{ TEUs}. \quad (18)$$

This confirms the model's effectiveness in handling real-world maritime transportation constraints.

3.2.2. The case of railway transportation component through the multimodal transportation route

For the study purpose, the authors have focused the analysis on the railway component of the Trans-Caspian Corridor and Iran–Turkey railway route. The objective is to evaluate the transportation costs in relation with any associated operations risks, as delays, technical failures, infrastructure bottlenecks or weather conditions that may occur in the railway route, using real-world data extracted from documented sources (Pineda-Jaramillo, Viti 2023).

The following variables are defined for proposed model:

- i = 1, 2, ..., I (cargo types);
- b = 1, 2, ..., B (regions of origin);
- j = 1, 2, ..., J (demand points);
- t = 1, 2, ..., T (time periods);
- k = 3 (railway component in multimodal transport).

Based on documented sources from specialized platforms addressed to decision-makers, the following values have been identified for the selected railway routes (Table 3).

While the previous calculations focused on transport costs computation based on standard cost parameters per TEU/km for each segment, the following section refines these estimates by integrating risk-based modelling. The next computing step incorporates probabilistic disruptive factors to assess their impact on the overall transport cost, ensuring a more comprehensive evaluation of multimodal logistics efficiency for decision-makers.

The total railway transport cost is calculated using the following equation:

$$C_{total\ railway} = \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J}\sum_{t=1}^{T}\left(\left(kx3_{ik3bjt} \cdot c3_{jkb3}\right) \times m_3 k_3 \cdot \left(1 + p3_{k3}\right)\right), \quad (19)$$

where: $kx3_{ik3bjt}$ – transported freight volume [TEU]; $c3_{jbk3}$ – transport cost per TEU/km for the railway segment; m_3k_3 – number of trains operating on the railway route; $p3_{k3}$ – probability of railway transport disruptions.

Applying the real-world values:

$$C_{Bandar\ Abbas - Tabriz} = 3633 \cdot 0.06 \cdot 10000 = \$2179800; \quad (20)$$

$$C_{Tabriz - Istanbul} = 1635 \cdot 0.04 \cdot 10000 = \$654000; \quad (21)$$

$$C_{total\ railway} = 2179800 + 654000 = \$2833800. \quad (22)$$

The railway segments considered are:

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{k=1}^{K}\sum_{j=1}^{J}\sum_{t=1}^{T} kx3_{ik3bjt} \leq \sum_{i=1}^{I} cp3_{k3i} \cdot m3_{k3},$$

$$k_3 \in K,\ t \in \{1, T\}. \quad (23)$$

The restriction regarding the transport capacity is modelled as following:

$$\sum_{i=1}^{I} cp3_{k3i} \cdot m3_{k3} - \sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J} kx3_{ik3bjt} \cdot Z \geq \sum_{i=1}^{I} e3_{k3i} \cdot m3_{k3},$$

$$k_3 \in K,\ t \in \{1, T\}, \quad (24)$$

where: $cp3_{k3i}$ – maximum freight capacity per train [TEU]; $e3_{k3i}$ – minimum required freight volume per train to ensure operational efficiency.

Using data from listed sources collected from specialized portals (*https://www.openrailwaymap.org*) following results will be obtained:

- for Bandar Abbas – Tabriz railway route: $cp3_{k3i} = 2000$ TEU, $e3_{k3i} = 150$ TEU;
- for Tabriz – Istanbul railway route: $cp3_{k3i} = 2000$ TEU, $e3_{k3i} = 150$ TEU.

This constrain assures a low number of risks as expressed below.

To quantify potential disruptions, the authors have used the probabilistic failure model (Di Francesco *et al.* 2022):

$$P(F) = 1 - \prod_{i=1}^{N}\left(1 - P(F_i)\right), \quad (25)$$

where: $P(F_i)$ represents the probability of individual risk factors affecting the railway route.

Using the collected the following values will be obtained:

- for Bandar Abbas – Tabriz railway route: $P(F) = 0.035$ (risks considered: technical failures, infrastructure bottlenecks, weather conditions);
- for Tabriz – Istanbul railway route: $P(F) = 0.018$ (risks considered: weather conditions, customs delays).

Table 3. Data table for railway transport parameters

Segment	Distance [km]	Average speed [km/h]	Transport cost [$/TEU/km]	Logistics delay [h]	Weather risk delay [h]
Bandar Abbas (Iran) – Tabriz (Iran)	3633	20...30	0.06	5...12	3...6
Tabriz (Iran) – Istanbul (Turkey)	1635	30...40	0.04	4...10	10...15

Source: authors' processed data using the specialized portal: *https://www.openrailwaymap.org*

Therefore, the total probability of railway transport failure for both segments:

$$P\left(F_{railway}\right)=1-\left(1-0.035\right)\cdot\left(1-0.018\right)= 0.0527\left(5.27\%\right); \quad (26)$$

$$\sum_{b=1}^{B}\sum_{k=1}^{K}kx3_{ik3bjt}=a_{jbit},$$

$$j\in J,\ t\in\left\{1,T\right\},\ i\in\left\{1,I\right\}.$$

This constrain assures the following cargo demand:

$$\sum_{i=1}^{I}\sum_{b=1}^{B}\sum_{j=1}^{J}n3_{k3}\cdot kx3_{ik3bjt}\geq m3_{k3},$$

$$k_3\in K,\ t\in\left\{1,T\right\}. \quad (27)$$

3.2.3. The case of maritime and railway routes combination as multimodal transportation solution

As result, a set of values may be created satisfying both the identified constraints and the established requirements, for both routes on maritime and rails modes, that will be further applied in the objective function, while considering the established constraints in order to calculate the total costs of transportation under risk impact, in the decision-making process. Consequently, a hypothetical set of values will be defined for variables' definition in decision-making process:

- b = 2 (2 regions);
- j = 3 (3 demanding points);
- i = 4 (4 types of cargo payloads);
- k = 2 (2 components of multimodal transportation route – railway and maritime);
- t = 2 (2 periods).

Random values will be generated for above variables, applying a simple *JavaScript* code, as following:

- a_{jbit} = [[[random within the range (1, 10) for t in the rage (1, 2)] for j within the range (1, 3)] for i within the range (1, 4)];
- $c2_{jbk2}$ = [[[random within the range (1, 10) for t within the range (1, 2)] for j within the range (1, 3)] for i within the range (1, 4)];
- $c3_{jbk3}$ = [[[random within the range (1, 10) for t within the range (1, 2)] for j within the range (1, 3)] for i within the range (1, 4)];
- $cp2_{k2i}$ = [[random within the range (50, 100) for i within the range (1, 4)] for k within the range (1, 3)];
- $cp3_{k3i}$ = [[random within the range (50, 100) for i within the range (1, 4)] for k within the range (1, 3)];
- $e2_{k2i}$ = [[random within the range (1, 10) for i within the range (1, 4)] for k within the range (1, 3)];
- $e3_{k3i}$ = [[random within the range (1, 10) for i within the range (1, 4)] for k within the range (1, 3)];
- $p2_{k2}$ = [random within the range (0.01, 0.1) for k within the range (1, 4)];
- $p3_{k3}$ = [random within the range (0.01, 0.1) for k within the range (1, 4)].

Then, these values will be applied in the objective function considering the constraints established by the decision makers, to calculate the total costs for transportation, depending on the impact of the identified risks in routing process. The random values used above represent just an example and could be adjusted depending on the real distribution of data for peculiars of analysis context.

The decision variables of pursued analysis will be considered unchanged (B = 2, J = 3, I = 4, K = 3, T = 2), next narrowing and customizing the values for parameters.

4. Case study for multimodal routes combinations on Middle East region. Results interpretation

To validate the analysis of multimodal combination for Middle East transportation corridors, the authors have conducted a sample of study of modelling for both maritime and railway components of multimodal transport, using alternatively, the Abu Dhabi – Suez Canal maritime segment, and the Bandar Abbas – Tabriz railway segment (3622 km) as case studies, 2 viable alternatives in the multimodal routing. This approach allows, in the case of other route modelling scenarios, the standardization of the methodology and its extension to similar transport corridors, providing a generalized framework for cost and risk analysis in intermodal logistics.

Based on the parameters previously established in above subchapters, the modelling may be continued in case of routes combination as following:

- total cost for transportation for maritime route component k_2:

$$k_2=kx2_{ik2bjt}\cdot c2_{jbk2}\cdot m2_{k2}\cdot\left(1+p2_{k2}\right). \quad (28)$$

The parameters are equal:

- $kx2_{ik2bjt}=10000$ TEU;
- $c2_{jbk2}=1.2$ \$/TEU/km;
- $m2_{k2}=4$ (maritime transport means, vessels);
- $p2_{k2}=0.08$.

Assumed maritime distance = 4407 nm (nautical miles; for the Abu Dhabi – Suez Canal maritime route segment), then $4047\ \text{nm}\cdot 1.852=7492.1\ \text{km}$ (source: https://www.marinevesseltraffic.com):

$$k_2=10000\cdot 1.2\cdot 4\times \left(1+0.08\right)\cdot 7492.1=\$388388064; \quad (29)$$

- total cost for transportation for railway route component $k3$:

$$k_3=kx3_{ik3bjt}\cdot c3_{jbk3}\cdot m3_{k3}\cdot\left(1+p3_{k3}\right). \quad (30)$$

The parameters are equal:

- $kx3_{ik3bjt}=10000$ TEU;
- $c3_{jbk3}=0.06$ \$/TEU/km;
- $m3_{k3}=25$ (railway transport means);
- $p3_{k3}=0.0527$.

Then considering the analysed railway segment Bandar Abbas – Tabriz for the railway route, which has a distance of 3622 km (source: https://www.openrailwaymap.org), the result will be:

$$k_3 = 10000 \cdot 0.06 \cdot 25 \times \left(1 + 0.0527\right) \cdot 3622 = \$57211691. \quad (31)$$

Therefore, by applying the specific values of the parameters, it will be permitted to replace the variables with the exact data, allowing the calculation of the total transport costs for each specified route component (maritime and railway), based on the information adapted to different contexts. These amounts will provide to the decision makers a numerical basis for evaluating the costs associated with each route segment of the multimodal transportation solution.

Analysing these total costs, the authors are proposing by present research a comparison instrument can be applied by the decision-makers in multimodal transportation, to determine the cost effectiveness performance of each route segment, in relation with the potential risks of incidents ($p2_{k2}$, $p3_{k3}$). As applied in practice in Section 3.3 for Middle East multimodal corridor, the cost analysis highlighted a significant difference between maritime and railway transportation alternatives, with maritime transport incurring a total cost of million $388.39, compared to million $57.21 for rail. This discrepancy is primarily due to longer distances in maritime transport (7492 km) compared to railway (3622 km) and higher operational risks impacting the route alternative at sea.

Both calculations are based on 10000 TEU transported per mode, with a cost per TEU/km of $1.2 for maritime and $0.06 for railway. Despite the lower unit cost of maritime transport, the increased distance and risk factors resulted in substantially higher total expenses. In contrast, railway transport remains more cost-effective, particularly for medium-haul routes, making it a strategic choice in multimodal logistics, very useful in this case for optimum routing process.

Reducing maritime transport disruption probability from 8% to 5% could lower costs by approximately 10…15%, minimizing delays and improving efficiency. Similarly, enhancing risk mitigation in railway transport can stabilize costs and optimize multimodal logistics planning. These insights emphasize the importance of risk reduction strategies in multimodal freight transport, enabling cost optimization and increased operational reliability.

The total cost for each route component of multimodal transport, represents part of the objective function of the analysis, aiming to minimize this sum and to identify the optimal combinations of transports for total costs optimization. Lowering the calculated values in the model, will provide lower total costs, which would be satisfying the objectives established by the decision-makers in the performed analysis.

The result of the mathematical modelling of the total cost demonstrates how the associated risks can influence the overall costs of multimodal transport (De Witt, Clinger 2000; Cherednichenko *et al.* 2023). Moreover, if the total costs are higher, it may indicate that the anticipated or occurred risks have had a more significant impact on the transport system, as already sustained by other conducted researching (Bandyopadhyay, Bhatnagar 2023).

The mathematical model has been projected by the authors for further developments in managerial process with the possibility of applying it in other risk assessment studies, not only for the one dedicated to multimodal transportation field but in other decision-making process applications. Further studies can be detailed even more by including the river, road, and air component of the multimodal transportation system (Batarlienė 2020). In the same time, similar studies can be focused on logistics hubs and ports, using the existing mathematical models (Liu *et al.* 2022; Xu *et al.* 2024; Cherednichenko *et al.* 2023; Kukulski *et al.* 2023).

5. Conclusions

The relevance of mathematical model is emphasized by the application of computational methodologies and analytical techniques, providing 3 main categories of deductions as suggested by the conducted research and by the literature review (Liu *et al.* 2022; Xu *et al.* 2024; Cherednichenko *et al.* 2023; Kukulski *et al.* 2023; Basallo-Triana *et al.* 2021; Kaewfak *et al.* 2024):

- from the perspective of multimodal transportation logistics (Guo *et al.* 2021; Kukulski *et al.* 2023, Basallo-Triana *et al.* 2021):
  - the assessment of risks associated with accidents in the case of maritime route component within the multimodal transportation, highlights their significant influence against the costs and the cargo volumes limits in contracted payloads;
  - the total shipping costs for maritime route of multimodal transportation depends on the load capacity and in direct variance with the type of maritime meaning of transportation selected;
  - the interaction between maritime and railway transport capacities shapes the volume of transported cargo and related costs;
- from mathematical modelling the perspective (Cherednichenko *et al.* 2023; Kaewfak *et al.* 2024):
  - the major objective of the proposed mathematical model is to minimize the objective function, in order to optimize the transportation costs and to effectively manage the associated risks of maritime transportation route within the multimodal transport;
  - the constraints of the model reflect the limitations of transport capacity and the specific requirements of the demand for cargo, suggesting practical ways to optimize;
  - in regard of decision-making process, the optimal allocation of decision variables reveals the most efficient quantities of cargo and transportation methods to reduce the costs and to meet the logistics needs;

- from the probability analysis (Di Francesco *et al.* 2022; Liu *et al.* 2022):
  - the application of math modelling facilitates the systematic identification and control of the risks of incidents or failures;
  - the mathematical model builds a formal structure of interdependencies between decision variables, imposed constraints and relevant risks;
  - by using the proposed model in the simulation and optimization processes informed decisions will be promoted, improving the risk management tools for multimodal transport effectiveness.

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