



National University of Science and Technology Politehnica Bucharest

**Faculty of TRANSPORT
DOCTORAL SCHOOL OF TRANSPORT
Doctoral field
Transport Engineering**

SUMMARY THESIS

**RESEARCH ON RISK MITIGATION IN MULTIMODAL
FREIGHT TRANSPORT SYSTEMS**

**Doctoral Supervisor:
Prof. univ. mat. ec. Doina - Eufrosina CARP**

**PhD Student:
Nicolae – Ovidiu ȘTEFANOV**

**BUCHAREST
2026**

TABLE OF CONTENTS

LIST OF ABBREVIATIONS	VIII
LIST OF FIGURES	X
LIST OF TABLES	XI
CHAPTER 1. INTRODUCTION	1
1.1 The necessity and opportunity of the research	1
1.2 The importance of research for multimodal transport	3
1.3 The state of research in the field of risks associated with multimodal freight transport	5
1.4 General and specific objectives of the research	8
1.5 Research methodology	9
1.6 Structure of the thesis	11
CHAPTER 2. RISKS ASSOCIATED WITH MULTIMODAL FREIGHT TRANSPORT	13
2.1 Definitions and conceptual clarifications	13
2.1.1 Risks in transport	13
2.1.2 Risks in multimodal transport	17
2.1.3 Risks associated with intermodal transport operations	22
2.1.4 Reliability of multimodal transport	23
2.2 Classification of risks in multimodal transport	24
2.2.1 General dysfunctions associated with risks in freight transport	24
2.2.2 Typology of risks in multimodal transport	25
2.2.3 Classification of risks in intermodal transport and transfer terminals	27
2.2.4 Classification of risks by modal components of the multimodal transport route	29
2.2.4.1 Risks manifested in the road component	29
2.2.4.2 Risks associated with the railway component of multimodal transport	30
2.2.4.3 Risks associated with the maritime component of multimodal transport	31
2.2.4.4 Risks associated with inland waterway transport within the multimodal route	32
2.2.4.5 Risks specific to air transport within the multimodal transport route	35
2.3 Legislative framework applicable to risk management in transport	35
2.3.1 National regulations	35
2.3.2 International regulations	36
CHAPTER 3. METHODS FOR RISK ASSESSMENT AND MITIGATION MEASURES IN MULTIMODAL TRANSPORT	39
3.1 Risk management in multimodal transport	39
3.2 Theoretical methods for risk assessment used in multimodal transport	42
3.2.1 FMEA model (Failure Modes and Effects Analysis)	42
3.2.2 Risk assessment scoring model	43
3.2.3 Fault Tree Analysis model (Fault Tree Analysis - FTA)	44
3.2.4 Probabilistic model of Dynamic Fault Tree	47
3.3 Risk reduction solutions in multimodal transport	49
3.3.1 Risk reduction methods in integrated multimodal transport	49
3.3.1.1 Solutions for reducing operational risks	50
3.3.1.2 Methods for reducing technological risks	51
3.3.1.3 Solutions for reducing technical risks	52

3.3.1.4 Methods for reducing human errors	53
3.3.1.5 Application of modelling and simulation for risk reduction	55
3.3.1.6 Methods for reducing risks generated by security threats	58
3.3.2 Risk mitigation solutions for intermodal transport and transfer points	60
3.3.2.1 Solutions applied in intermodal transport	60
3.3.2.2 Risk reduction solutions in transshipment terminals	63
3.4 Case studies regarding the application of risk assessment models	65
3.4.1 Application of the weighted average method in the analysis of multimodal risks ..	65
3.4.1.1 Methodological foundation of the weighted average method	65
3.4.1.2 Working hypotheses and scope of applicability	67
3.4.1.3 Sources used and methodology for assigning weights	67
3.4.1.4 Constraints and limitations of the method	69
3.4.1.5 Application of the weighted average calculation formula in risk assessment	69
3.4.1.6 Determination of the probability of a compound event using the probability of the complementary event	78
3.4.2 Application of the scoring model in the assessment of risks in multimodal transport	79
3.4.2.1 Application hypotheses	79
3.4.2.2 Structure and data sources used	79
3.4.2.3 Treatment of uncertainties and lack of data	80
3.4.2.4 Risk assessment using the scoring method	81
3.4.2.5 Operational constraints and interpretation of results	82
3.4.3 Application of the Dynamic Fault Tree model	89
3.4.3.1 Working hypotheses	89
3.4.3.2 Model structure and data sources used	90
3.4.3.3 Analysis of causal relationships and structural organization of the DFT	91
3.4.3.4 Construction of the adjacency matrix for the collision hypothesis	94
3.4.3.5 Evaluation of DFT logical paths and calculation of probabilities for each hypothesis	95
3.4.3.6 Graphical representation of the DFT	97
CHAPTER 4. RISK MITIGATION SOLUTIONS – CASE STUDIES	99
4.1 Solutions for reducing operational, technical and technological risks in the DP World terminal	99
4.1.1 Description of the problem	99
4.1.2 Alternative routes on the road component of multimodal transport between Constanța South Port and Curtici terminal	101
4.1.3 Identification of operational, technological and technical risks	103
4.1.4 Capacity of transfer interfaces and freight flow bottleneck ratio	107
4.1.5 Evaluation of the effects of risks and of system recovery times of the port operating system through discrete-event simulation – DP World Constanța South	113
4.1.5.1 General considerations regarding the modelling of handling and transport processes within a container terminal	113
4.1.5.2 Development of the simulation model	114
4.1.5.3 Impact of handling equipment reliability on the operational performance of the DP World – Constanța South terminal	122

4.1.6 Conclusions	129
4.2 Risk reduction solutions in multimodal transport on the route Constanța South Port – Curtici terminal	131
4.2.1 Description of the problem	131
4.2.2 Alternative routes on the road component of multimodal transport between Constanța South Port and Curtici terminal	134
4.2.2.1 Analysis of the connectivity structure of the road network and route alternatives	136
4.2.2.2 Application of the SAW method in assessing the risk level of the road component	143
4.2.3 Analysis of risks associated with the operation of the railway component of the multimodal transport route Constanța South – Curtici	149
4.2.3.1 Presentation of freight railway routes and their risks	149
4.2.3.2 Evaluation of railway rerouting in scenarios of segment unavailability	152
4.2.3.3 Determination of risk scores using the SAW method for the railway component	161
4.2.4 Risk mitigation through the improvement of multimodal flows including the inland waterway transport component	165
4.2.5 Conclusions	178
CHAPTER 5. CONCLUSIONS	181
5.1 Final considerations and results	181
5.2 Original contributions	183
5.3 Directions for future research	187
BIBLIOGRAPHY	189
ANNEX 1. Statistics regarding navigation incidents/accidents	200
ANNEX 2. Synthesis of information regarding events and factors that caused maritime incidents and accidents	202
ANNEX 3. Risk mitigation strategies related to the components of multimodal transport	208
ANNEX 4. Logistic characteristics and associated risks for intermodal road routes Constanța South Port – Curtici terminal	209
ANNEX 5. Technical information of the DP World – Constanța South terminal	210
ANNEX 6 A. Risk assessment questionnaire – maritime transport	214
ANNEX 6 B. Risk assessment questionnaire – road transport	215
ANNEX 6 C. Risk assessment questionnaire – railway transport	216

CHAPTER 1

INTRODUCTION

1.1 The necessity and opportunity of the research

In the context of the intensification of commercial exchanges and the integration of international logistics networks, multimodal freight transport has become an essential component of modern transport systems; however, its operation is influenced by multiple categories of risks associated with modal components and transfer operations within multimodal transport routes. Under these conditions, the research is oriented toward the assessment of these risks and toward the identification of solutions for their mitigation within multimodal freight transport systems.

The necessity of the research derives from the fact that technical dysfunctions, traffic blockages, human errors or climatic conditions may affect the operation of each transport mode and, through a propagation effect, may compromise the entire multimodal freight flow, with direct consequences on safety, costs and operational reliability.

The opportunity of the research is determined by the current structure of freight transport in Romania, characterized by the predominance of road transport, limited capacities of railway and port infrastructure, operational congestion in major logistics nodes and insufficient correlation of modal components, a situation which amplifies the risks of discontinuity of transport flows and requires their assessment and the substantiation of solutions for risk mitigation in multimodal freight transport.

1.2 The importance of the research for multimodal freight transport

The importance of the research in the field of multimodal transport is determined by the manner in which risks occurring on individual transport segments are transmitted through transshipment operations to the successive stages of the transport process. In operation, the sequence of loading, unloading and takeover operations between transport modes, as well as the correlation of transport and handling capacities, condition the continuity of the multimodal transport route, while the occurrence of local vulnerabilities at transfer points generates discontinuities with effects on the entire transport route.

1.3 The state of research in the field of risks associated with multimodal freight transport

The specialized literature regarding risks associated with multimodal freight transport mainly addresses risks specific to individual transport segments and risks generated within transshipment processes, while the analysis of risk at the level of the multimodal transport route, considered as an integrated functional system, is treated to a limited extent.

Table 1.1 Synthesizes the relevant specialized literature used in the thesis, constituting the basis for the substantiation of the research framework employed and for the development of the applied model for the assessment and mitigation of risks in multimodal freight transport.

Research direction	Subject analyzed	Types of risks addressed	Representative references
Conceptual foundation and structuring of transport systems	- defining the conceptual framework for risks in transport; - structuring the elements of the transport system used in the analysis.	risks addressed at conceptual and systemic level.	(Raicu, 2007), (Heckmann, 2015), (Abdulahi and Luo, 2020), (Kramberger et al., 2018).
Operation and functioning in multimodal transport	- operational processes under real operating conditions; - mechanisms of propagation of operational deviations.	- operational risks; - technological risks; - risks associated with the human factor.	(Raicu, 2022), (Goel, 2016), (Sellner and Vyslouzilova, 2019), (Bartle, 2021).
Performance and vulnerability in transport networks	- sensitivity of operation to variations in demand and capacity; - vulnerability to disruptions in the network.	- operational risks; - environmental risks.	(Chen, 2023), (Gbadegoye, 2025).
Risks on multimodal transport routes	- manifestation of risks along multimodal routes; - effects on transport continuity.	- operational risks; - technological risks.	(Dini, 2024), (Kengpol, 2014), (Bilato, 2022).
Risks at transshipment interfaces between transport modes	- transshipment processes and coordination between modes; - discontinuities at the transfer interface.	- transshipment risks; - operational risks; - risks associated with the human factor.	(Popa, 2016), (Russo, 2006), (Chang, 2019), (Bínová, Heralová, 2017).
Reliability of handling and transshipment subsystems for loading units	- operation of technical subsystems; - their reliability in operation.	- technical risks; - technological risks.	(Müller, 2020), (Guan, 2013), (Fraga-Lamas, 2017).
Risk management in multimodal transport	- influence of human errors on system operation; - correlation of the human factor with unwanted events.	- risks associated with the human factor; - operational risks.	(Soares, 2001), (Galierikova, Sosedova, 2018), (Ma, 2022), (Bogalecka, 2024).
Risk management in multimodal transport	- influence of environmental conditions on system operation; - effects on transport continuity.	environmental risks.	(Makarova, 2023), (Göçmen, Erol, 2018), (Ferguson, 2025).
Risk management in multimodal transport	- risk quantification; - scoring and ranking of risks.	applicable according to the level of analysis.	(Liao, 2023), (Kaewfak, 2024), (Cieśla, 2018), (Timofeeva, 2023), (Nitsenko, 2020).

The analysis of the specialized literature highlights the predominance of risk assessments conducted at the unimodal level, with limited integration of interdependencies between transport modes at the level of multimodal transport routes.

1.4 General and specific objectives of the research

I. General objective: The general objective of the research consists in the development and application of methods for the assessment and mitigation of risks in multimodal freight transport systems, through their analysis at the level of transport components, transshipment interfaces and the multimodal transport route, in order to ensure the continuity of transport processes under real operational conditions.

II. Specific objectives:

1. Research on vulnerabilities and deficiencies associated with multimodal freight transport, by relating them to the structure of transport processes, to the sequence of operations between modes and to the functioning of transfer interfaces, so that the identified risks are directly correlated with real operational conditions;
2. Identification and classification of relevant risks for multimodal freight transport, by differentiating operational, technical, technological and human risks in relation to transport components and to the stages of the multimodal process, based on statistical data and the technical-operational documentation used in the thesis;
3. Evaluation of the identified risks using the weighted average method, in order to establish the relative risk levels corresponding to the analyzed categories and subcategories, while respecting the conditions of comparability between transport modes and the constraints imposed by the structure of the available data;
4. Application of a scoring-based risk assessment model for quantifying risk exposure generated by vulnerabilities and deficiencies and for evaluating the impact of materialized risks on the continuity of multimodal transport processes, by relating the results to the operation of the analyzed routes;
5. Research on the causal relationships between risk-generating events in multimodal freight transport, by using the Fault Tree Analysis method and the Dynamic Fault Tree model, in order to represent the logical structure of the occurrence of undesired events and to highlight the conditions under which they may lead to disruptions of transport processes;
6. Analysis of specific risks within transshipment and handling activities in a container terminal, through discrete-event modelling and the use of INCI and BOR indicators for evaluating the influence on the degree of resource utilization and operational capacity, in order to substantiate measures for risk mitigation that may affect the continuity of multimodal transfer processes;
7. Research on risks associated with a multimodal transport route, through scoring-based evaluation using the SAW method at the level of road and railway components, in order to substantiate measures for reducing the relative risk exposure generated by the identified vulnerabilities and deficiencies, with impact on the continuity of multimodal transport processes under real operational conditions.

1.5 Research methodology

The methodological framework of the research is based on a combination of quantitative methods and engineering tools for modelling, probabilistic assessment and operational simulation, applied with the purpose of identifying and mitigating risks associated with multimodal transport networks.

The research methodology is structured on three complementary levels:

- Identification and classification of risks relevant for multimodal transport;
- Quantitative evaluation and ranking of these risks through scoring models and multicriteria

methods;

- Analysis of causal relationships and operational simulation in failure scenarios.

Each level provides results used in the subsequent stage, ensuring the internal coherence of the methodological framework and avoiding the isolated application of analytical tools.

A. Methodological foundations:

The research is based on an integrated approach oriented toward the identification, assessment and mitigation of risks that affect the operational performance of multimodal freight transport.

The applied methodology combines quantitative evaluation, logical modelling and dynamic simulation, according to the following directions:

- Quantitative approach to operational, technological, technical and human risks, through the conversion of frequency and severity into measurable numerical indicators (Risk Assessment Scoring Model), in order to objectively quantify the level of risk. The data used originate from official statistical sources, both national and international.
- Logical modelling of causal relationships, for the identification of sequences of critical events and the substantiation of control measures (Fault Tree Analysis – FTA and Dynamic Fault Tree – DFT);
- Operational simulation in failure scenarios, using the discrete-event simulation method, based on statistically validated data sets, with applicability in a transshipment terminal, in order to identify the critical conditions that may generate logistical blockages and to substantiate solutions for risk prevention and mitigation;
- Hierarchical evaluation of risks through multicriteria methods, using a weighted numerical scoring model according to severity, probability and detectability, with the purpose of prioritizing risk mitigation interventions in multimodal transport networks.

B. Methods and techniques used:

- Fault Tree Analysis (FTA) and Dynamic Fault Tree (DFT) were used for investigating the mechanisms of occurrence and propagation of risks in multimodal freight transport, through the modelling of causal relationships between risk-generating events and the identification of the conditions under which they may lead to disruptions in the continuity of transport processes;
- The evaluation of the identified risks was carried out using the weighted average method, in order to determine the relative risk levels corresponding to the analysed categories and subcategories, ensuring the comparability of results between transport modes and consistency with the statistical and technical-operational data used in the thesis;
- The scoring-based risk assessment model was applied for interpreting the effects of vulnerabilities, deficiencies and risks on the performance of multimodal freight transport, in the context of the objective of the thesis regarding the mitigation of their effects on the continuity of transport processes;
- The multicriteria ranking method of the SAW type was used as a comparative analysis tool for the studied alternatives, exclusively to support the evaluation of risks at the level of the multimodal transport route, without formalizing routes as algorithmic calculation or optimization problems;
- Discrete-event simulation, carried out in the Arena Rockwell environment, was used for analysing the activities within the DP World Constanța South container terminal, with the purpose of evaluating the manner in which the failure of handling equipment influences the continuity of transfer operations and generates risks of blockage in the multimodal transport chain;

- The risks associated with the unavailability of handling equipment within the port terminal were characterized through reliability indicators of the MTTF and MTBF type, used to highlight the influence of failures on the operational functioning of the DP World terminal and to substantiate measures for mitigating the effects of technological and operational risks.

C. Instruments and technologies used:

- Arena Rockwell software – used for discrete-event simulation of logistics flows within freight transshipment terminals, allowing the testing of equipment failure scenarios and the evaluation of their impact on operational continuity.

D. Application of the methodology and analysis of results:

The methodology used within the thesis is applied in a coherent and consistent manner throughout the analytical chapters, by correlating the risk assessment methods with the available data and with the specific characteristics of the analysed multimodal transport processes. The application of the methodology aims to demonstrate the adequacy of the methods used for risk assessment, through the interpretation of the results obtained in relation to real operational conditions.

The application of risk assessment methods was carried out by using the scoring-based evaluation model, constructed on values determined through weighted averages and normalized according to the defined analysis criteria. This approach allowed the comparable quantification of the analysed risks and the interpretation of the relative risk levels in relation to the components of multimodal transport and to the stages of the transport process.

The research on causal relationships between risk-generating events was carried out through the application of the Fault Tree Analysis method and the Dynamic Fault Tree model, used for the structured representation of the mechanisms of occurrence and propagation of risks within multimodal transport processes. The obtained results were interpreted in relation to the operational sequence of activities and to the vulnerability points identified within the analysed routes.

The application of the methodology at the level of the multimodal transport route was carried out for the hypothesis of the route Constanța South Port – Curtici Terminal, through the analysis of risks associated with the road and railway components and through the comparison of the studied alternatives from the perspective of the determined relative risk levels. The research aimed to highlight the influence of risk categories on the continuity of transport processes. For the terminal component, the methodology was applied through the modelling of operations carried out within the DP World Constanța South container terminal, using discrete-event simulation in the Arena Rockwell environment. The model was constructed based on the real sequence of handling operations and was used to analyse the effects of equipment failures on operational continuity and the occurrence of blockages in the transfer flow.

The analysis of risks associated with the unavailability of handling equipment was carried out by using the reliability indicators MTTF and MTBF, interpreted in relation to the investigated operating conditions. The indicators used allowed highlighting the influence of failures on the execution of terminal operations and supported the interpretation of results in the context of the objective of the thesis regarding the mitigation of the effects of risks on the continuity of multimodal transport.

CHAPTER 2

RISKS ASSOCIATED WITH MULTIMODAL FREIGHT TRANSPORT

Chapter 2 establishes the conceptual framework used in the research of risks associated with multimodal freight transport, by clarifying the notions, delimitations and classifications adopted in the thesis. The definitions of risk, uncertainty, vulnerabilities and deficiencies are analysed as they are formulated in the specialized literature in the field of transport, in order to establish a unified terminological framework.

The chapter structures the typologies of risks specific to multimodal and intermodal transport in relation to transport components and transshipment processes, constituting the conceptual basis necessary for the application of the quantitative evaluation methods developed subsequently.

2.1 Definitions and conceptual clarifications

2.1.1 Risks in transport

In the field of transport, risk is associated with undesired events for which the probability of occurrence can be estimated, and the consequences can be evaluated in relation to the objectives of safety, continuity and efficiency of the transport system.

Risk represents a future event whose outcomes are uncertain and whose probability of occurrence is non-zero, having a potential negative impact on the analysed system. The Ministry of Transport in Romania treats risk as the possibility of the occurrence of an undesired event associated with transport activities, characterized by a probability of occurrence and an impact on the safety, continuity and performance of the transport system (**Intermodal Transport Strategy in Romania, MT, 2011**).

In the specialized literature an explicit distinction is made between the concepts of risk and uncertainty. Risk refers to events for which outcomes are not known with certainty, but the probabilities of occurrence can be determined or estimated, being associated with negative effects on the performance of transport processes. Uncertainty characterizes situations in which both the outcomes and the corresponding probabilities are unknown, which excludes their treatment through classical probabilistic methods (**Raicu et al., 2022**).

Risks are events known in probability, usually associated with negative outcomes, while uncertainty describes situations or unpredictable outcomes, without determined probabilities and which may influence the performance of supply chains (**Heckmann et al., 2015**).

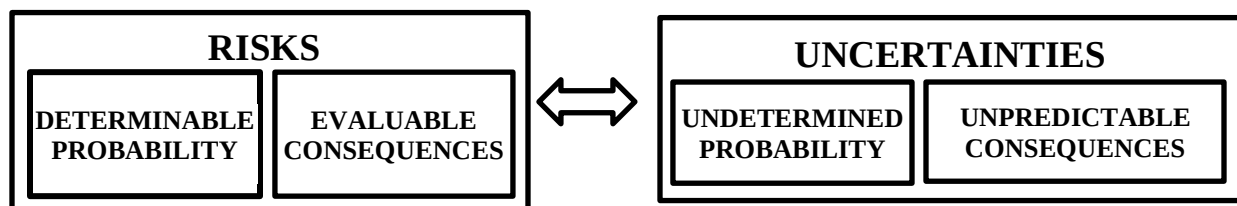


Figure 2.1 Delimitations between risks and uncertainties in the research of multimodal transport systems (Source: Author)

In the field of transport, risk is often defined as a quantitative measure of potential hazard or of the undesired consequences associated with transport activities. This includes the probability of occurrence of adverse events and their impact on the safety and efficiency of the transport system (**Kuznetsov & Sokolov, 2022**).

In the specialized literature, multiple mathematical models are proposed for risk assessment in transport systems, differentiated by the structure of the mathematical relationships used, the typology of the parameters considered and the level of formalization of the analysis methodologies. The comparative analysis of the main approaches highlights the fact that each model uses a distinct conceptual structure for risk quantification, with different degrees of applicability in the assessment and management of risks specific to transport systems.

Table 2.4 *Comparative elements of mathematical models for risk assessment in transport*

Criterion analyzed	Russo et al. (2006)	Finochenko et al. (2021)	Sapori et al. (2014)
Mathematical relation	$R = P \times M$	$R = X_{max} + \sum_{i=1}^n X_i \times \left(\frac{8 - X_{max}}{8(n-1)}\right)$	$R = T \times V \times C$
Parameters used	• Event probability (P); • Consequence magnitude (M).	• Maximum score of dominant variable; • Scores of associated variables; • Normalization coefficient; • Number of variables.	• Trigger probability (T); • System vulnerability (V); • Consequence severity (C).
Treatment of vulnerability	Not introduced explicitly.	Reflected indirectly through the scores of the analyzed variables.	Introduced explicitly as a distinct parameter.
Field of application	General risk assessment in transport.	Assessment of working conditions in railway operations.	Risk assessment in transport systems with systemic exposure analysis.
Structure of input data	• Numerical value of probability; • Numerical indicator for consequences.	• Numerical scores of operational variables; • Upper limit of the scoring scale used in the methodology; • Number of variables analysed.	• Probability of the triggering factor; • System vulnerability; • Magnitude of consequences.

The comparative analysis of the sources shows that each author proposes a different mathematical model for risk assessment, with varying degrees of formalization and practical applicability. The model proposed by (Russo et al., 2006) has an elementary character, defining risk as the product between probability and severity, useful only in preliminary assessments. (Finochenko et al., 2021) formulate a weighted scoring model calibrated for risks associated with the human factor in railway transport, which integrates concrete operational variables and supports the design of protection measures. (Sapori et al., 2014) introduce a conceptual extension by including system vulnerability as a distinct variable, allowing the evaluation of risks also according to the capacity of infrastructure and processes to respond to disruptive events.

2.1.2 Risks in multimodal transport

Risks in multimodal transport manifest within integrated logistics systems characterized by the coordinated sequence of several transport modes under a single operational responsibility.

The specificity of risk in multimodal freight transport derives from the functional interdependence between transport segments, nodes and logistics operations, as well as from the propagation of the effects of a disruptive event across the entire transport route or network.

Within this framework, the structural and operational vulnerabilities of the system components are expressed through operational dysfunctions, and their materialization, under specific conditions, leads to the occurrence of risks at the level of the multimodal transport route.

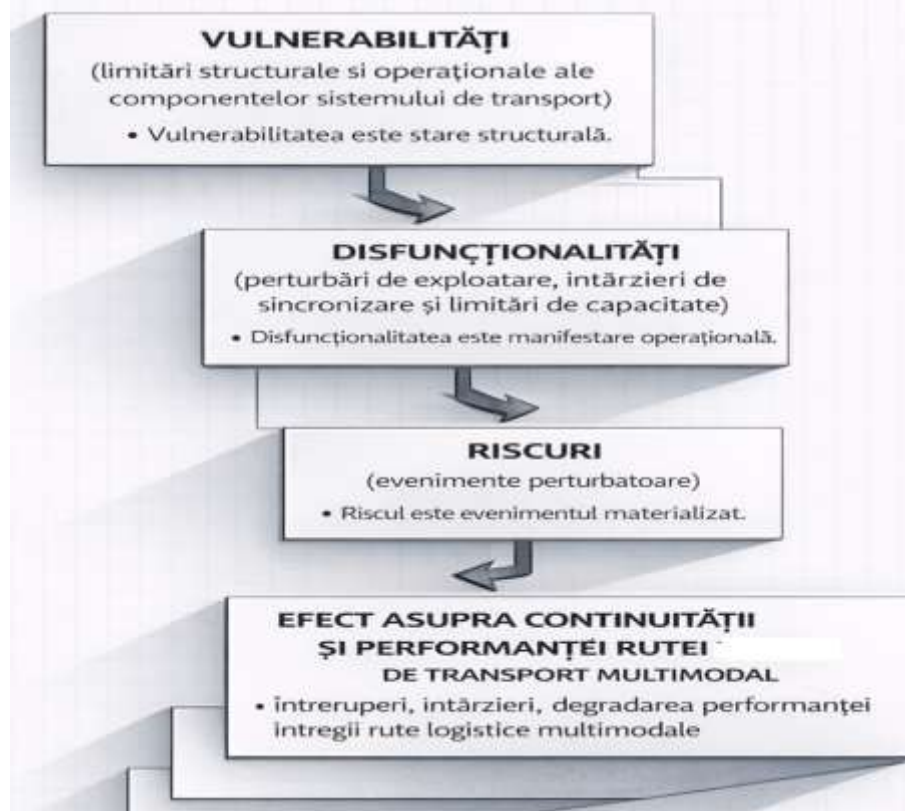


Figure 2.2 Logical representation of the causal chain vulnerability – dysfunction – risk in multimodal freight transport
(Source: Author)

The research of dysfunctions in multimodal and intermodal transport requires the delimitation of the manner in which they manifest in relation to the operational structure of the transport flow and to the particularities of transfer between road, railway, maritime, inland waterway or air transport modes.

Table 2.5 Conceptual delimitation of dysfunctions in multimodal and intermodal transport

Element of analysis	Multimodal transport	Intermodal transport
Transport flow configuration	Sequence of two or more transport modes coordinated under a single responsibility on a continuous origin–destination route.	Sequence of several transport modes using the same loading unit without handling the content.
Operational mechanism	Transfer of goods between modes through distinct loading, unloading and takeover operations.	Transfer of the loading unit between modes through mechanized transshipment operations.
Critical points of occurrence	Multimodal terminals, maritime or inland ports, freight railway stations, road–rail crossing points.	Container terminals, transshipment platforms, container handling installations.
Causes of dysfunctions	• Lack of correlation between circulation schedules of transport modes; • Infrastructure restrictions on a transport segment; • Limitations of handling equipment; • Cumulative delays generated on previously travelled segments.	• Interruption of transshipment operations; • Failure of handling equipment; • Mismatch between circulation schedules of transport modes; • Local congestion in terminals.

Element of analysis	Multimodal transport	Intermodal transport
Effects on the transport route	• Interruption of the continuity of the modal transport sequence; • Increase of the total transport duration; • Forced redistribution of flows to alternative routes.	• Delay in the transfer of the loading unit; • Local blockage in the terminal; • Temporary accumulation of loading units in the transfer area.

(Source: Author)

Relation (2.1) proposed by **(Russo et al., 2006)** may also be extended in the context of multimodal transport: $R = P \times V \times N$, (2.4)
where:

- P: probability of occurrence of the disruptive event;
- V: vulnerability of the multimodal transport chain;
- N: exposure of goods and logistics infrastructure to risk.

According to **(Sapori et al., 2014)**, vulnerability expresses the probability that a component of the logistics network (e.g., railway terminal, port, road node, airport) may be functionally affected by a disruptive event, such as a technical failure, a human error or a severe climatic condition. Therefore, it reflects the degree of structural and operational resistance of the system in relation to an identified threat, while a high level of vulnerability implies an increased potential for interruption of the logistics flow, material losses and blockage in multimodal transport.

During the period of the doctoral research, the probabilistic risk assessment model expressed by relation (2.4) was also applied and detailed in a paper developed together with other authors **(Popa et al., 2025)**, in which the contribution of the author of the present thesis consisted in the development and application of this model for the analysis of operational risks associated with multimodal transport, including human, technical and environmental components.

In the specialized literature, the formalization of risk in multimodal transport may be structured into two distinct methodological types:

- Functional probability–impact model (MF–PI): based on the functional relationship between probability and impact, applied to the stages of the multimodal chain, substantiated in **(Bínová & Heralová, 2017)**;
- Weighted segmental quantitative model (MC–SP): assumes the segmental quantification of risk and the weighted combination of probability – impact – structural coefficient components, addressed by **(Nitsenko et al., 2020)**.

Further, the two formalizations are analysed comparatively in table 2.6:

Research parameters	MF–PI (Bínová & Heralová, 2017)	MC–SP (Nitsenko et al., 2020)
Mathematical structure	$R = f(P, I)$ (2.13)	$R = \sum_{i=1}^n P_i \times I_i \times W_i$, (2.14)
Conceptual structure	Probability (P) × Impact (I)	Segment probability × Economic impact × Structural coefficient
Definition of probability	Probability estimated based on the frequency of events within the transport chain.	Probability statistically estimated for each segment (ratio incidents/trips or adapted probabilistic distributions).
Treatment of uncertainty	Semi-quantitative evaluation based on statistical data and operational analysis.	Stochastic modelling using empirical distributions, fuzzy methods and Monte Carlo simulations.

Research parameters	MF–PI (Bínová & Heralová, 2017)	MC–SP (Nitsenko et al., 2020)
Definition of impact	Impact (I) defined as the effect on the continuity of multimodal transport (delays, additional costs, etc.).	$I_i = C_m \times D_i \times S_m$ (2.15) quantified according to cargo value, additional duration and sensitivity.
Research domain	Critical stages of the multimodal chain (transshipment, handling, intermediate storage).	Individual segment of the multimodal transport route and later aggregation at route level.
Risk composition form	Functional relation between probability and impact, without rigid numerical formalization.	$W_i = w_0 + \delta_t$, (2.16) where w_0 is the base weight and δ_t is a penalty coefficient for operational vulnerability.
Differentiation between transport modes	Risk treated through analysis of functional stages of the multimodal transport chain.	Risk treated through separate evaluation of each segment and application of weighting coefficients (W_i).
Level of formalization	Functional formalization oriented toward operations.	Explicit quantitative model integrable in cost–risk multicriteria analysis.
Decision purpose	Identification and prioritization of critical operational stages to reduce losses and increase reliability.	Selection of multimodal route by integrating risk in a cost–risk objective function: $\min (\lambda_1 \times C_{total} + \lambda_2 \times R_{total})$ (2.17)

(Source: Author)

The comparison of the two models highlights different approaches to the relationship vulnerabilities – dysfunctions – risks within multimodal transport, showing that in the case of the MF–PI model used by (Bínová & Heralová, 2017), the research is conducted at the level of the functional stages of the multimodal chain, focusing on dysfunctions generated at the interface between transport modes. In contrast, in the case of the MC–SP model (Nitsenko et al., 2020), risk is formalized through the determination of probability and impact for each segment of the multimodal transport route, while vulnerability is reflected through structural weighting coefficients.

2.1.3 Risks associated with intermodal transport operations

Within the present research, the analysis of risks associated with intermodal transport is focused on transfer and coordination operations between the involved transport modes. In intermodal transport, risks are generated by uncertainties and dysfunctions occurring at the interface between modes, especially in transshipment nodes, affecting the performance of the transport chain through delays, additional costs and cargo losses. The reduction of handling operations during transfer between modes reduces exposure to these risks and supports the continuity of the integrated logistics chain (European Court of Auditors, 2023).

In order to ensure comparability, the sources presented in Table 2.7 from the specialized literature are structured according to the manner of defining probability and impact, the integration of vulnerability and the mechanism of risk determination in intermodal transport:

Table 2.7 *Comparative elements regarding the treatment of risks in intermodal transport*

Criterion of analysis	A1 (Nitsenko et al., 2018)	A2 (Galierikova and Sosedova, 2018)	A3 (Kramberger et al., 2018)	A4 (Maslarić et al., 2016)
Object of research	Modelling the overall risk of multimodal transport and using it for route and transport mode selection (e.g., combines financial risks and risks associated with transshipment).	Intermodal transport of dangerous goods: legal framework, intermodal flow (road–maritime) and deficiencies leading to risk materialization.	Inland intermodal terminal used as an instrument for extending the port hinterland, based on a port choice model considering port attractiveness and transport distance.	Risk management in the intermodal supply chain; holistic framework for risk identification and classification.
Analyzed systemic structure	• Multimodal system as a set of subsystems (transport modes, UTI transfer points, temporary storage, information support); • Risks evaluated by transport stages and nodes (e.g., ports).	Nodes and interfaces of the intermodal chain (port, terminals) where transshipment activities and controls take place.	• Port–hinterland system (intermodal corridors; inland terminal) analysed through port choice modelling; • Includes sensitivity analysis to container flow fluctuations.	• Intermodal transport as a network of operators–activities–allocated resources; • Specialized loading unit transfer points are the most critical points of the logistics chain.
Risk typology	• Economic risks treated stochastically (tariff variations) and operational transshipment risks treated using fuzzy logic; • Legislative risks in the railway transport stage.	Operational risks associated with modal interfaces: labelling errors of loading units, substance leaks, improper cargo securing, human errors and technical causes.	Economic and operational risks generated by trade imbalances and fluctuations in freight flows affecting the feasibility of intermodal freight transport.	Internal risks (technical, technological, operational) and external risks (natural, security, financial, political) affecting the stability of intermodal transport flows.
Risk assessment methods	Total risk determined by combining risks evaluated separately for stages of intermodal transport, using probabilistic models for economic risks and fuzzy logic models for operational transshipment risks.	Research of incidents reported in transfer nodes correlated with the examination of the regulatory framework and operational causes at the transshipment interface.	Port selection model based on linear programming and the Analytic Hierarchy Process (AHP), integrating sensitivity analysis to freight flow variations.	• Structured literature review within ISCRM (Intermodal Supply Chain Risk Management) with identification and structuring of risks using the PESTEL model (political, economic, social, technological, environmental and legal factors); • Evaluation of each risk based on probability of occurrence, duration of manifestation and severity of impact.

2.2 Classification of risks in multimodal transport

2.2.1 Dysfunctions generating risks in multimodal freight transport

The research of dysfunctions in the transport system aims at identifying operational deviations that may occur along the multimodal freight transport chain and that affect the operating regime and the continuity of flows between transport modes.

Dysfunctions represent the operational level of manifestation of vulnerabilities within the multimodal transport system and constitute the framework for risk assessment, through the

determination of the probability of occurrence and the impact on the operational performance of the transport chain. The classification of dysfunctions (D.1 – D.6) is carried out according to the nature of the processes and resources affected and according to their effects on the operational parameters of multimodal transport.

Table 2.8 synthesizes the categories of dysfunctions relevant for multimodal freight transport, subsequently used within the research and risk assessment stages.

Table 2.8 *Dysfunctions of the multimodal transport chain generating risks*

Code	Type of dysfunction	Description of dysfunctions in multimodal freight transport	Examples of manifestation
D.1.	Operational dysfunctions	Disturbances occurring in the execution of current transport operation processes, affecting the sequence and coordination of operational activities.	Delivery delays, handling errors, dysfunctions in operation planning.
D.2.	Technological dysfunctions	Limitations or failures of technological and information systems used in transport management, affecting the control and monitoring of flows.	IT system failures, software errors, unavailability of communication systems.
D.3.	Technical dysfunctions	Failures of infrastructure and physical equipment leading to degradation of transport capacity or temporary interruption of network operation.	Vehicle failures, deterioration of road or railway infrastructure.
D.4.	Environmentally induced dysfunctions	External influences generated by meteorological conditions affecting the safety and regularity of transport system operation.	Storms, dense fog, extreme temperatures limiting transport operations.
D.5.	Human-factor-related dysfunctions	Errors or inappropriate decisions of personnel involved in transport system operation affecting safety and operational coordination.	Inattention, fatigue, lack of adequate training, wrong decisions in critical situations.
D.6.	Security dysfunctions	Events affecting the integrity of goods, equipment or personnel, influencing the normal execution of transport flows.	Theft, vandalism, acts of sabotage, smuggling.

Source: Adaptation after Kaewfak et al. (2024) and Nitsenko et al. (2020)

Therefore, the categories of dysfunctions (D.1 – D.6) systematized in table 2.8 represent operational manifestations of the limitations associated with the components of the multimodal transport chain, which, under conditions of a certain level of frequency and impact, may lead to the materialization of risks and affect the continuity of multimodal transport routes.

2.2.2 Typology of risks in multimodal transport

The classification of risks in the present research is carried out based on two complementary criteria:

- the nature of the risk (operational, technical, technological, human, legal, economic, environmental);
- the level of manifestation within the transport system (multimodal systemic level, intermodal interface level, modal component level within multimodal transport).

Risks in multimodal transport derive from the structural and organizational vulnerabilities of the system and manifest predominantly in the form of operational, technological, technical, human or environmental risks, at the level of coordination between modes, modal interfaces and the integration mechanisms between transport operators.

Unlike unimodal transport, where risks are associated with the operation of a single transport mode, at the systemic level multimodal transport involves interdependencies between transport modes, infrastructures and resources, which introduces additional constraints related to technical interoperability, operational synchronization and the contractual delimitation of responsibilities.

Table 2.9 synthesizes the typology of risks specific to multimodal transport (R.M.1 – R.M.8), structured according to the mechanisms of generation and the effects on the functioning of the multimodal transport system:

Table 2.9 *Categories of risks associated with multimodal freight transport*

Risk code	Risk typology	Analyzed element	Risk generation mechanisms	System-level operational manifestation
R.M.1	Operational	• Operational coordination risks • Risks in transfer and transshipment operations • Risks generated by operational fragmentation • Risks associated with capacity and congestion in transport nodes	• Uncoordinated synchronization between transport modes • Deficiencies in transfers between transport modes • Incomplete integration of route segments • Overloading of multimodal node infrastructure	• Misalignment of schedules between transport modes • Delays in the transfer of loading units • Discontinuities between route segments • Port congestion and long waiting times for operations
R.M.2	Technical	• Risks associated with technical interoperability • Risks regarding the physical integrity of loading units • Risks related to the availability of critical equipment	• Incompatibilities between infrastructures and equipment • Repeated stresses during mode changes • Unavailability of terminal machinery	• Terminals not adapted for intermodal transfer • Damage to containers and transported goods • Unavailability of cranes or handling equipment
R.M.3	Technological	• Risks related to the technological integration of information and monitoring systems for multimodal transport • Risks regarding the continuity of information systems.	• Incompatibility between information systems • Interruption of management platforms • Inconsistencies in the exchange of operational data between transport operators	• Lack of real-time access to data • Failure of the transport node information system • Discrepancies between the real and reported status of the loading unit
R.M.4	Human	• Risks related to specialized human resources • Risks related to decision-making coordination between operators	• Uneven qualification levels of personnel • Uncoordinated operational decisions • Improper use of logistics systems and equipment	• Improper operation of equipment • Overlapping operational schedules • Incorrect data entry into the system
R.M.5	Legal	• Risks associated with the delimitation of contractual responsibilities • Risks regarding procedural and documentary compliance • Risks regarding operational constraints in terminals	• Inconsistent contractual structuring • Procedures applied differently between transport modes • Local requirements imposed in terminals	• Disputes regarding liability during mode changes • Inconsistent documentation at transfer points

Risk code	Risk typology	Analyzed element	Risk generation mechanisms	System-level operational manifestation
R.M.6	Security	• Security risks in multimodal nodes • Risks regarding the integrity of the cargo chain of custody • Risks related to operational information security	• Vulnerability to deliberate external interventions • Insufficient access control • Compromise of operational data	• Theft in terminals • Unauthorized access to transfer areas • Alteration of real-time transport monitoring data
R.M.7	Economic	• Risks regarding the systemic impact on the costs involved in multimodal transport	• Inefficiencies generated by delays and congestion • Contractual penalties	• Demurrage or waiting costs • Penalties for exceeding contractual deadlines • Increase in the total cost of the transport route
R.M.8	Environmental	• Risks related to compliance with environmental requirements in terminals and on integrated transport segments	• Operational restrictions generated by environmental regulations • Constraints related to emissions and the handling of certain types of cargo	• Access to multimodal infrastructure conditioned by predefined operational windows • Special operating conditions in ports

Source: Adapted from Cieřla (2018) and Bínová & Heralová (2017).

2.2.3 Classification of risks in intermodal transport and transfer points

Within the framework of risk analysis, intermodal transport represents a distinct component of multimodal transport, characterized by the use of the same loading unit across successive segments belonging to different transport modes and by the concentration of critical processes at cargo transfer points and operational interfaces. From this perspective, the risks specific to intermodal transport are predominantly generated by dysfunctions manifested in transshipment processes, operational coordination and technological interfacing between transport modes, rather than by the actual execution of transport activities on each transport segment.

The classification of intermodal risks (R.I.1 – R.I.8) is carried out according to the nature of the dysfunctions that may lead to the materialization of risks at transfer points. This classification has an operational character and provides the basis for the evaluation and quantification stages developed in the following chapters, in accordance with the structure synthesized in table 2.10.

Table 2.10 *Categories of risks occurring in intermodal transport and in transshipment terminals*

Risk code	Risk typology	Analyzed element	Risk description
R.I.1	Operational	• Operational risks at cargo transfer points • Risks related to operational coordination between modes • Risks related to infrastructure and capacity of intermodal nodes	• Transshipment processes generate vulnerabilities related to flow synchronization • Insufficient integration of services affects the continuity of the intermodal chain (Kramberger et al., 2018)
R.I.2	Technical	• Risks associated with handling equipment and modal vehicles • Risks related to technical systems of intermodal infrastructure	• Equipment failures reduce operational capacity • Vehicle unavailability generates transfer delays • Technical dysfunctions affect operational stability (Hilmola & Szekely, 2006)

Risk code	Risk typology	Analyzed element	Risk description
R.I.3	Technological	• Risks regarding interoperability of information systems in terminals • Risks regarding software errors and faulty automation • Cybersecurity risks	• Interoperability deficiencies affect data exchange between modes • Software errors reduce flow visibility • Cyber vulnerabilities disrupt operational control (Göçmen & Erol, 2018)
R.I.4	Human	• Risks generated by operational errors in terminals • Risks related to staff communication and coordination • Risks related to the level of professional training	• Handling errors affect the integrity of transport units • Poor communication generates mismatches between modes • Insufficient training influences operational safety (Galierikova & Sosedova, 2018)
R.I.5	Legal	• Risks related to modal legislative harmonization • Risks related to documentation and contractual responsibilities	• Legislative inconsistencies generate procedural blockages (National Customs Authority, 2023) • Documentary inconsistencies produce delays • Contractual ambiguities favor operational disputes (Flodén, 2007)
R.I.6	Security	• Risks related to physical security in terminals • Risks related to unauthorized access	• Theft or sabotage disrupt operational continuity • Insufficient protection increases exposure to deliberate incidents (Gencer & Gök, 2023)
R.I.7	Economic	• Risks related to operational costs and price volatility • Risks related to tariffs and currency risks	• Cost fluctuations influence the financial structure of the intermodal chain • Tariff instability affects economic predictability (Hilmola & Szekely, 2006)
R.I.8	Environmental	• Risks related to the ecological impact of intermodal operations • Risks related to compliance with environmental requirements	• Emissions and noise pollution generate operational constraints • Compliance requirements influence the organization of intermodal operations (Göçmen & Erol, 2018)

CHAPTER 3

RISK ASSESSMENT METHODS AND RISK MITIGATION MEASURES IN MULTIMODAL TRANSPORT

3.1 Risk management in multimodal transport

Risk management in multimodal transport is approached as an operational process oriented toward identifying, evaluating and mitigating the effects of dysfunctions on transport performance, particularly with regard to delivery times, continuity of flows and the efficient utilization of available capacities. In this context, risk analysis is related to operational processes, the resources used and the operational constraints of the transport system.

Risks manifest as effects of dysfunctions that affect transport flows, infrastructure processing capacity and the coordination of operations between transport modes (**Ouedraogo et al., 2022**).

Figure 3.1 synthesizes the sequence of risk management stages applicable to the freight transport chain, highlighting the cyclical nature of the process and the interdependence between risk identification, evaluation, implementation of mitigation measures and monitoring of results.

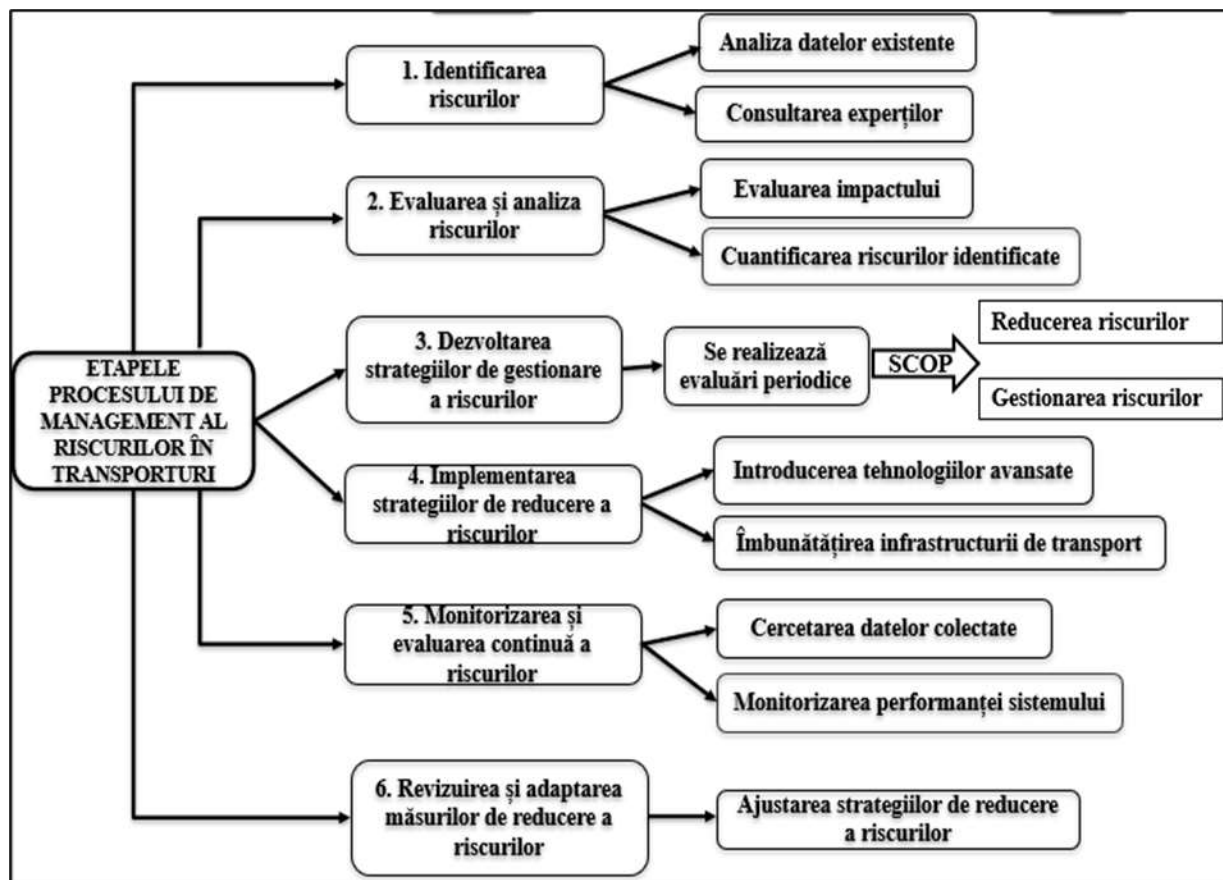


Figure 3.1 Stages of the risk management process in transport
Source: Adapted from Bromiley et al. (2015).

3.2 Theoretical models for risk assessment in multimodal transport systems

Risk assessment in multimodal transport systems is carried out through the use of mathematical and logical models that allow the description of the causal structure of disruptive events, the estimation of the probability of occurrence and the quantification of their impact on the operational parameters of transport.

In this thesis, established models such as Failure Mode and Effects Analysis (FMEA), risk assessment scoring models, Fault Tree Analysis (FTA) and their dynamic probabilistic extensions (Dynamic Fault Tree – DFT) are analyzed.

These models are presented in order to delimit the analytical framework used in the field and to support the selection of the assessment instruments adopted in the research. Within the thesis, the methods are treated differently according to their role: some have a conceptual character and are used to structure risks according to the specialized literature, while others are applied operationally for the quantitative evaluation of risks and for supporting the mitigation measures developed in the case studies.

3.2.2 Risk assessment scoring model

Within the risk assessment stage in multimodal transport, the risk assessment scoring method is used to rank the identified risks numerically according to the probability of occurrence and the impact on the transport system. This method allows the allocation of prevention and mitigation resources proportionally to the level of risk. In the thesis, the method is applied as a static evaluation stage, preceding the detailed structural analyses, with the role of highlighting risks

that have a major impact on the continuity and operational performance of multimodal transport. The source (Tummala & Schoenherr, 2011) proposes an evaluation model structured in the following operational stages:

1. Risk identification: This stage is carried out through technical interviews, document review and the analysis of transport processes. Each vulnerability is recorded in a table together with a clear description (for example: crane failure in a terminal or delivery delay caused by railway congestion).

2. Probability assessment: For each risk, a score P, ranging from 1 to 5, is assigned based on historical data, technical expertise in transport engineering and statistical analysis:

- 1 = below 15% (very unlikely);
- 2 = 15–29% (unlikely);
- 3 = 30–50% (moderately possible);
- 4 = 51–75% (probable);
- 5 = 76–100% (very probable).

3. Impact assessment:

A score I, also ranging from 1 to 5, is assigned according to the severity of the effect:

- 1 = insignificant impact (e.g., delay <1 hour, costs <100 €);
- 2 = minor impact (e.g., slight disturbance of operational routine);
- 3 = moderate impact (e.g., temporary loss of cargo, costs >1,000 €);
- 4 = major impact (e.g., shutdown of a logistics component for several hours);
- 5 = critical impact (e.g., severe damage, disruption of the entire supply chain).

The evaluation is carried out on the basis of observations and quantitative criteria such as costs, delays and operational disruptions.

4. Risk score calculation:

The risk value for each event is determined, with possible values ranging between 1 and 25, using the relation: $R = P \times I$ (3.2)

The probability–impact assessment matrix is structured on ordinal levels 1–5. The values of the risk score R are grouped into three classification intervals (Tummala & Schoenherr, 2011):

- Green zone (score 1–6) → acceptable risk: no immediate measures are required;
- Yellow zone (score 7–12) → moderate risk: monitoring and conditional treatment are required;
- Red zone (score 13–25) → critical risk: immediate prevention and control measures are required.

The classification according to score intervals R allows the prioritization of risks, enabling operational teams to intervene where the efficiency of mitigation measures is highest relative to the severity of the risk.

3.3 Risk mitigation solutions in multimodal transport

3.3.1 Methods for risk reduction in integrated multimodal transport

Risk mitigation methods are designed to reduce both the probability of occurrence of adverse events and the impact generated by them.

3.3.1.1 Operational risk mitigation solutions

The reduction of operational risk at the level of a multimodal transport route, expressed through the probability of exceeding the processing capacity and the admissible transfer time thresholds in transshipment nodes, is achieved through measures aimed at the organization and coordination of transport flows, together with the evaluation of their impact on processing times and on the utilization rate of the operational capacity of the transfer node (number and performance

of handling equipment, availability of operational personnel, and the effective operating schedule) (Popa et al., 2016).

Table 3.6 *Methods for reducing operational risks in multimodal transport*

No.	Operational risk mitigation solutions (R.M.1)	Content
1	Implementation of a digital operations management system for synchronizing activities (European Court of Auditors, 2023)	Use of software applications for planning and coordinating operations along the multimodal transport route, ensuring the alignment of transfers between modes and reducing scheduling conflicts between operations.
2	Periodic staff training and implementation of standardized operating procedures (Popescu, 2016)	Continuous training programs are implemented for personnel, aimed at reducing errors in cargo handling and applying uniform operational standards.
3	Optimization of traffic flows and use of real-time monitoring technologies (mt.ro, 2020)	Monitoring the flows of vehicles and loading units in the transfer nodes of the multimodal route using sensors and video systems in order to reduce processing times.
4	Use of appropriate equipment and implementation of strict handling protocols (UNTRR, 2016)	Ensuring compatibility of equipment used in transfers between modes and applying uniform procedures to increase the reliability of operations.
5	Implementation of track-and-trace systems for real-time monitoring (Publications Office of the European Union, 2023)	Automatic identification technologies (RFID, QR codes) used to track goods during transfers between transport modes.
7	Implementation of truck appointment scheduling systems to avoid congestion and improve efficiency (Gopalakrishnan & Gupta, 2023)	Establishing time windows for access to multimodal route nodes in order to control flows and prevent exceeding processing capacity.
8	Use of Transport Management Systems (TMS) for the integration and coordination of different transport modes (Rocket Consulting, 2024)	A software platform is used to coordinate multimodal flows, ensuring visibility and synchronization between road, rail and maritime transport within the terminal.

3.3.1.2 Methods for reducing technological risks

The mitigation of technological risks (R.M.3) in multimodal freight transport is achieved through measures that act on the way technological and information systems are used and integrated within the transport process, as well as on the control, monitoring and digital coordination mechanisms that support its operation.

The mechanism for reducing technological risks consists in interrupting the propagation chain between the occurrence of technological dysfunctions (D.2) at the level of control systems and the emergence of functional unavailability of the transport process, through the early identification of informational deviations and by maintaining system operation under controlled technological regimes. Through these measures, the risk is reduced by limiting the probability that a technological dysfunction (D.2) will evolve into a disruption of multimodal freight transport.

Table 3.7 *Methods for reducing technological risks in multimodal freight transport*

No.	Technological risk reduction methods (R.M.3)	Description
1	Advanced automation	Implementation of automated systems to reduce operational errors by taking over command and control functions and limiting variations generated by non-uniform digital sequences (Jithin & Antriksh, 2021).

No.	Technological risk reduction methods (R.M.3)	Description
2	IoT monitoring	Integration of sensors for early detection of operational deviations and reduction of the time between the occurrence of a dysfunction and its identification (Goel et al., 2016).
3	Cybersecurity systems	Protection of the integrity and availability of operational data through encryption and continuous monitoring, reducing the probability of information loss or unauthorized access (Disk.com, 2023).
4	Fleet management software	Real-time monitoring of transport vehicles to maintain information coherence and prevent decisions based on incomplete or asynchronous data (Yilma, 2014).
5	Documentation digitalization	Electronic archiving and processing of documents to eliminate informational discontinuities associated with physical records and to reduce data inconsistencies.
6	Predictive analytics	Correlation of historical data with operational parameters in order to anticipate technological failures and transform them into manageable situations (Chang et al., 2019).
7	Predictive maintenance systems	Estimation of failure probability based on monitored technological parameters and intervention before operational continuity is affected (Kostrzewski et al., 2021).
8	Software updates	Maintaining compatibility and functional stability of information systems through controlled updates, reducing technological vulnerabilities (Fraga-Lamas et al., 2017).
9	Technological interoperability	Ensuring coherent and continuous data exchange between different software platforms in order to prevent informational fragmentation within the multimodal flow.
10	Energy efficiency	Implementation of intelligent energy management systems to stabilize the power supply of digital infrastructure and reduce the probability of functional interruptions (Goel et al., 2016).

3.3.1.3 Solutions for reducing technical risks

The reduction of technical risks (R.M.2) in multimodal freight transport is achieved through interventions applied to the technical vulnerabilities of transport infrastructure and equipment, which manifest through dysfunctions (D.3) of mechanical, electrical or functional nature within operational processes.

The mitigation mechanism consists in controlling the technical condition and functional availability of infrastructure and equipment, through which the probability of failures is limited and the risk that a technical dysfunction (D.3) will materialize into a failure affecting the continuity of the transport process is reduced.

Table 3.8 *Methods for reducing technical risks in the multimodal transport process*

No.	Methods for reducing technical risks (R.M.2)	Content
1	Maintenance and inspection	Application of structured verification and maintenance programs to maintain equipment in operating conditions compliant with the manufacturer's technical specifications, reducing the probability of uncontrolled functional failures.
2	Use of equipment and infrastructure compliant with technical standards	Selection and operation of equipment designed for the mechanical and functional demands specific to multimodal flows, increasing structural reliability and reducing the rate of structural failures (Janic, 2017).
3	Functional redundancy	Implementation of configurations with backup components (power supply, communications, handling equipment) to ensure operational continuity in the event of failure of an individual component.

No.	Methods for reducing technical risks (R.M.2)	Content
4	Training of personnel operating freight terminals or transport equipment	Reduction of failures generated by improper operation through personnel qualification regarding the use, adjustment and maintenance of technological equipment.
5	Continuous monitoring of operating parameters	Permanent supervision of critical variables (vibration, temperature, load, pressure) in order to identify deviations from the established technical regime and intervene before functional degradation occurs.
6	Preventive maintenance adapted to the real operating regime	Correlation of maintenance intervals and types of technical interventions with the actual condition of equipment and operational history, reducing the probability of premature failures or accelerated wear.
7	Periodic technical audit of equipment and infrastructure	Systematic evaluation of the structural and functional compliance of equipment and infrastructure, identifying latent defects and eliminating them before failures materialize.

(Source: Author)

3.3.1.4 Methods for reducing human errors

The reduction of risks associated with human errors (R.M.4) in multimodal freight transport is achieved through interventions applied to human vulnerabilities identified in operational, supervision and control processes. These vulnerabilities manifest through dysfunctions (D.5) in the execution of tasks, the interpretation of operational information and the compliance with working procedures.

Table 3.9 *Methods for reducing human errors*

No.	Methods for reducing human errors (R.M.4)	Content of measures
1	Standardization of procedures	• Detailed specification of task execution, sequence and conditions under which tasks must be performed; • Implementation of efficient operating procedures along the entire supply chain regarding container handling, loading, unloading and transport.
2	Implementation of automation and technological integration	• Use of advanced technologies (AI and machine learning) to automate repetitive tasks and minimize human errors; • Automation also reduces human involvement in hazardous areas, improving safety (Cruz & Marques, 2012).
3	Training and development of professional competences	• Acquisition of the necessary skills by personnel involved in order to manage their tasks efficiently and safely.
4	Predictive analytics	• Artificial intelligence (AI) technologies and machine learning algorithms predict possible errors before they occur; • By analyzing historical data and identifying patterns, these systems can alert operators to potential problems, enabling preventive actions.
5	Effective communication	• Each party involved must understand its roles and responsibilities and have access to updated information; • Blockchain technology provides a secure record of transactions and interactions between the parties involved.
6	Quality control and assurance	• Early detection of errors and their prevention; • Regular audits and inspections ensure compliance with operating procedures.

No.	Methods for reducing human errors (R.M.4)	Content of measures
7	Safety culture	• Encouraging employees to report potential safety issues through regular safety training meetings.
8	Prevention of operational staff fatigue	• Ensuring adequate rest periods and monitoring workload prevent fatigue-related errors.
9	Continuous improvement of procedures	• Regular review of procedures; • Learning from errors; • Updating systems and processes based on lessons learned.

(Source: Author)

3.3.2 Risk reduction solutions for intermodal transport and transshipment points

3.3.2.1 Solutions applied in intermodal transport

Risk mitigation solutions in intermodal transport (R.I.1 – R.I.8) are based on the analysis of loading unit transfer processes and on the operational coordination between the transport modes involved, since discontinuities and performance losses occur predominantly at the points where the transport mode changes. The operational stability of intermodal transport depends on the correlation of reception, handling and dispatch capacities, as well as on the temporal synchronization of the operations associated with each transport mode.

In this context, risk reduction measures are defined as technical and operational interventions applied to the sequence of transfer operations, to the planning and scheduling of operational resources used at transshipment points (handling equipment and operational personnel), and to the information systems supporting management and operational control.

These interventions aim to limit dysfunctions generated by capacity mismatches, variations in resource availability and synchronization deficiencies, thereby reducing the probability of risk events affecting the continuity of intermodal transport:

1. Standardization of the sequence of technological operations for loading unit transfer;
2. Determination and allocation of the required handling equipment and operational personnel based on the transfer cycle time of loading units;
3. Control of access to the transfer point of loading units according to the service capacity;
4. Introduction of an operational time margin in transfer scheduling and control of time variability;
5. Use of operational parameters specific to the transport system components in intermodal transfer planning;
6. Information system support for coordinating transfers, ensuring loading unit traceability and operational updates;
7. Technical control of resources and operational competence for critical transfer functions.

3.3.2.2 Risk reduction solutions in transshipment terminals

In transshipment terminals, risk reduction is achieved through measures applied directly to the operational processes of handling, temporary storage and transfer of loading units between the served transport modes. From an operational perspective, these measures aim at configuring and controlling internal traffic flows, correlating handling capacities with traffic volumes and coordinating the use of technical and human resources involved in operations.

The interventions are formulated at the local terminal level and act on the sequence of transshipment operations, on the allocation of handling equipment and operational personnel, and on the operational regime of terminal infrastructure. By applying these measures, the occurrence

of operational and technical dysfunctions is limited, thereby reducing the probability of human and operational risks affecting the continuity of intermodal transfer.

1. Control of the operational capacity of terminal interfaces;
2. Control of the sequence of handling operations;
3. Adaptation of equipment utilization to operational workload;
4. Organization of internal circulation and separation of operational flows;
5. Integration of temporary storage of loading units into the terminal operational flow;
6. Configuration of the operational regime of critical terminal resources;
7. Technical control of handling equipment;
8. Monitoring of terminal operations and control of deviations from operational planning.

3.4 Case studies regarding the application of risk assessment models

3.4.1 Application of the weighted average method in the analysis of multimodal risks

3.4.1.1 Methodological foundation of the weighted average method

The quantitative evaluation of risks in multimodal freight transport (R.M.1 – R.M.8) requires the processing of a significant volume of data originating from technical, institutional and statistical sources, which are not always comparable in terms of accuracy, reporting frequency or data collection methodology. In this context, it is necessary to apply a scientific method capable of ensuring the uniform processing of numerical values originating from heterogeneous sources within a controlled methodological framework.

The data sources used cover different time intervals, as a consequence of the specific reporting and updating practices characteristic of each institution or specialized study. This temporal heterogeneity is inherent to safety analyses in transport systems and is managed through selection and weighting criteria without affecting the relative comparability of results.

For this purpose, a numerical processing method based on the weighted average has been adopted, allowing the differentiated assignment of a relevance coefficient to each data source, determined according to the degree of methodological compatibility between the source and the requirements of the research.

The method aims to obtain comparable numerical values that can be used in risk analysis for the purpose of relative ranking and comparative evaluation of risk subcategories, without assigning to these values the meaning of probabilities of occurrence defined in a strict probabilistic sense. This methodological delimitation ensures interpretative coherence and clearly separates the stage of statistical aggregation from the subsequent stage of probabilistic modelling.

From a theoretical perspective, the use of the weighted average is fully grounded in statistics, being recognized as a formal extension of the arithmetic mean in situations where observations do not have the same relevance or representativeness. This approach is presented and validated in reference works such as (Hogg et al., 2019) and (Neter et al., 2005) and is explicitly applied in risk analysis of complex transport systems (Sauerberg et al., 2024).

The weighted average calculation model is based on the mathematical relation (3.13) used by (Popa et al., 2025) and aims to determine an aggregated numerical value for each risk subcategory, expressed as a percentage and adjusted according to the methodological compatibility of the data sources used.

This method allows the controlled combination of percentage values reported for the same risk subcategory originating from different sources, without interpreting them as probabilities of occurrence, thus ensuring a coherent numerical basis for the comparative analysis of risks.

The percentage values corresponding to each subcategory are processed through the application of the weighted average, where the weight w_i reflects the level of technical and methodological adequacy of the source relative to the research objective, according to the following relation:

$$M = \frac{\sum_{i \in V} (v_i \times w_i)}{\sum_{j \in W} (w_j \times f(w_j))}, \text{ (Popa et al., 2025)} \quad (3.13)$$

where:

- M = weighted average of the percentage values;
- v_i = percentage value of each subcategory;
- w_i = weighting factor assigned to the sources according to the extent and accuracy of the data provided by each source;
- n = number of identified sources (e.g., for the maritime component $n \in 1, \dots, 16$);
- V = set of sources that mention the analyzed risk subcategories (e.g., for the maritime component, $V \subseteq \{S1, \dots, S16\}$);
- W = set of distinct weights (w_j);
- frequency of w_j : $f(w_j)$ = number of sources associated with each distinct weight (w_j).

Unlike methods based on simple averages, which assign the same weight to all sources, the method used ensures a controlled weighted aggregation of percentage values, by applying a weighting function w_i determined according to predefined criteria: institutional recognition, academic indexing, data recency, methodological rigor and the degree of direct applicability in the research context. Each weight corresponds to a frequency of occurrence within the dataset, denoted $f(w_j)$, which is used exclusively to balance the numerical contributions of the sources in the structure of relation (3.13), as reflected in tables 3.14, 3.16 and 3.18.

3.4.1.3 Sources used and methodology for assigning weights

Each source was assigned an **engineering-justified score**, expressed as an integer weighting coefficient $w_i \in \{1, 2, 3, 4, 5\}$, according to an evaluation grid that considers the following criteria:

- Direct thematic relevance to the analyzed risk category (priority being given to sources that address the specific risk rather than general references);
- Institutional recognition of the source (national or international agency, university, or industry organization) and scientific indexing (Web of Science, Scopus, or other relevant databases);
- Timeliness of the information, assessed with reference to an operationally acceptable time interval;
- Level of methodological detail and structure of the data (disaggregated by risk types rather than aggregated values).

3.4.1.5 Application of the weighted average formula in risk evaluation

At this stage of the analysis, the mathematical relation for calculating the weighted average (relation 3.26) is applied in order to determine aggregated numerical indicators corresponding to each risk subcategory associated with the maritime, road, and rail components of multimodal freight transport.

The purpose of applying this relation is to obtain comparative percentage values that reflect the relative contribution of risk-generating factors, depending on the reporting frequency and the methodological adequacy of the data sources used.

A. Identification and treatment of risks in the maritime component:

For the maritime component, the analyzed risks are quantified based on the values, determined through a weighted average according to relation (3.13), where the weight assigned to each source reflects its methodological and institutional adequacy, and the percentage values used represent the relative frequencies of risk-generating factors reported in the analyzed studies.

Furthermore, the same weighted average method was applied to the other risk subcategories within the maritime component, resulting in the values presented in table 3.14.

Table 3.14 Percentage indicators calculated using the weighted average method for subcategories of risk-generating factors associated with maritime accident case studies

Main risk	Risk subcategories	Source scores and risk percentages	Weighted average $M = \frac{\sum_{i \in V} (v_i \times w_i)}{\sum_{j \in W} (w_j \times f(w_j))}$
Technical (means of transport) R.M.2	M.2.1: Inadequate maintenance	S1 (5): 65.0%; S2 (5): 57.02%; S3 (5): 48.33%; S13 (4): 18.6%; S15 (4): 38.3%.	46.93 %
	M.2.2: Technical failures	S2 (5): 62.0%; S10 (5): 40.0%; S12 (5): 24.0%; S15 (4): 22.0%.	37.79 %
	M.2.3: Defective design	S3 (5): 30.0%; S10 (5): 66.0%;	48.00 %
	M.2.4: Vessel age	S13 (4): 29.1%; S14 (4): 28.8%; S15 (4): 26.3%; S16 (4): 24.1%.	27.08 %
	M.2.5: Equipment age	S5 (4): 38.95%; S10 (5): 36.1%; S13 (4): 35.6%; S15 (4): 33.6%.	36.06 %
Human factor R.M.4	M.4.1: Human behavior	S1 (5): 53.6%; S2 (5): 51.17%; S3 (5): 61.2%; S4 (4): 42.33%; S5 (4): 41.66%; S6 (4): 45.82%.	49.97 %
	M.4.2: Personnel negligence	S1 (5): 48.12%; S2 (5): 53.48%; S3 (5): 58.19%; S7 (1): 28.0%.	51.68 %
	M.4.3: Inadequate professional training	S1 (5): 37.6%; S2 (5): 45.38%; S7 (1): 21.19%; S8 (2): 26.72%.	37.66 %
	M.4.4: Fatigue	S1 (5): 32.16%; S4 (4): 43.7%; S9 (3): 31.85%; S10 (5): 54.3%; S14 (4): 37.1%.	40.53 %
	M.4.5: Poor communication	S1 (5): 28.32%; S3 (5): 39.92%; S6 (4): 27.16%; S8 (2): 14.81%; S9 (3): 12.08%.	27.14 %
	M.4.6: Violations of rules and procedures	S1 (5): 68.95%; S3 (5): 58.18%; S10 (5): 52.1%; S15 (4): 38.6%.	55.29 %
Environmental R.M.8	M.8.1: Visibility	S1 (5): 46.7%; S7 (1): 16.81%; S8 (2): 19.95%; S11 (2): 8.66%; S15 (4): 6.75%.	32.47 %
	M.8.2: Light conditions	S3 (5): 63.66%; S5 (4): 31.83%; S9 (3): 27.4%; S14 (4): 5.66%; S15 (4): 1.66%.	41.85 %
	M.8.3: Sea state	S1 (5): 70.33%; S3 (5): 48.8%; S6 (4): 37.16%; S10 (5): 3.66%; S15 (4): 1.72%.	49.54 %
	M.8.4: Wind conditions	S2 (5): 64.4%; S8 (2): 31.3%; S11 (2): 20.4%.	47.27 %

Based on the values presented in Table 3.14, the following findings result:

1. The risk subcategories “Vessel age” and “Poor communication” record low percentage values of the weighted average indicators, namely 27.08% and 27.14%, compared to the other subcategories analyzed within the maritime component;

2. The risk subcategories “Personnel negligence” and “Violations of rules and procedures” present high percentage values of the calculated indicators, namely 51.68% and 55.29%, highlighting a relatively higher contribution of the human factor within the analyzed case studies.

B. Identification and treatment of risks in road transport:

The evaluation of risks associated with the road component in multimodal transport is based on the integration of official statistical sources, selected and weighted according to the relevance, timeliness, and methodological comparability of the data (Popa et al., 2025).

This structure for source selection enables the consistent use of statistical information in the process of assessing the impact of road transport risks, ensuring a coherent database for the analysis and ranking of risks within the multimodal transport system.

By applying the weighted average calculation formula (3.13), weighted average values are determined for each risk subcategory related to freight road transport, based on the relevance weights assigned to the sources and the frequency of occurrence within the analyzed dataset.

Table 3.16 Weighted average values of risks associated with road transport

Risk category	Risk subcategory	Code	Sources and risk percentages (%)	Weighted average $M = \frac{\sum_{i \in V} (v_i \times w_i)}{\sum_{j \in W} (w_j \times f(w_j))}$
Operational R.M.1	Traffic overload / congestion	R.1.1	S1=38; S2=35; S3=32; S4=30.	34.18
	Lack of adequate signaling	R.1.2	S1=30; S2=32; S3=28; S4=25.	29.06
Technical R.M.2	Technical and mechanical vehicle failures	R.2.1	S1=50; S2=48; S3=44; S4=42.	46.47
	Brake system failures	R.2.2	S1=35; S2=30; S4=28.	31.21
Technological R.M.3	Degraded infrastructure	R.3.1	S1=32; S2=30; S3=27; S4=25.	28.88
	Inadequate infrastructure design	R.3.2	S1=30; S2=25; S3=25; S4=27.	26.94
	Quality of construction materials	R.3.3	S1=25; S2=20; S3=20; S4=23.	22.18
	Poor infrastructure maintenance	R.3.4	S1=40; S2=35; S3=30; S4=28.	33.94
Human factor R.M.4	Human errors in vehicle operation	R.4.1	S1=60; S2=55; S3=50; S4=48; S5=25; S6=28.	49.75
	Driver age (22–30 years)	R.4.2	S1=50; S2=40; S3=30; S4=28.	38.35
	Driver age (30–50 years)	R.4.3	S1=30; S2=25; S3=20; S4=18.	23.94
	Driver age (over 50 years)	R.4.4	S1=40; S2=35; S3=32; S4=30.	34.76
	Driver experience (0–5 years)	R.4.5	S1=60; S2=45; S3=50; S4=40.	49.12
	Poor driver health condition	R.4.6	S1=80; S2=25; S3=20; S4=22; S5=31.	38.68
Environmental R.M.8	Adverse weather	R.8.1	S1=34; S2=30; S3=28; S4=26.	29.88
	Difficult traffic conditions	R.8.2	S1=35; S2=30; S3=25; S4=27.	29.85
	Reduced visibility	R.8.3	S1=28; S2=25; S3=22; S4=22; S6=18.	24.28

(Source: Author)

The analysis of the weighted average values presented in Table 3.16 indicates that the risk subcategories with the highest percentage values of the calculated indicator within the road component are associated with the human factor, namely errors in vehicle operation (49.75%) and lack of driver experience (49.12%).

C. Identification and treatment of risks in rail transport:

The evaluation of risks associated with the rail component is based on a set of official european and national data sources, used for quantifying the risk subcategories related to railway infrastructure and operation (Popa et al., 2025).

Table 3.18 presents the weighted average values calculated for the main risk subcategories associated with freight rail transport, structured by risk categories and subcategories.

Table 3.18 Values of risks and sub-risks associated with the rail component

Risk Category	Risk Subcategory	Code	Sources and Risk Percentages (%)	Weighted Average (%) $M = \frac{\sum (v_i \times w_i)}{\sum_{j \in W} (w_j \times f(w_j))}$
Operational risks R.M.1	Degraded infrastructure	F.1.1	S1: 40; S2: 38; S3: 35; S4: 33.	37.14
	Deficiencies in operational safety management	F.1.2	S1: 50; S2: 45; S3: 42; S4: 40.	45.21
	Train collisions	F.1.3	S1: 25; S2: 22; S3: 20.	22.58
Technical risks R.M.2	Brake system failures	F.2.1	S1: 35; S2: 30; S3: 28.	31.42
Technological risks R.M.3	Rail wear	F.3.1	S1: 35; S2: 32; S3: 30; S4: 28.	31.93
	Deficiencies in maintenance of bridges and tunnels	F.3.2	S1: 30; S2: 28; S3: 27; S4: 25.	28.00
	Technical failures of rolling stock	F.3.3	S1: 45; S2: 40; S3: 38.	41.42
Human factor R.M.4	Human error (vehicle operation errors)	F.4.1	S1: 55; S2: 50; S3: 48; S4: 45.	47.20
	Driver age (over 50 years)	F.4.2	S1: 35; S2: 32; S3: 30.	32.58
	Lack of driver experience (0–5 years)	F.4.3	S1: 45; S2: 40; S3: 38.	41.42
Environmental R.M.8	Adverse weather conditions	F.8.1	S1: 30; S2: 28; S3: 25; S5: 5.	26.08
	Reduced visibility – weather conditions	F.8.2	S1: 25; S2: 23; S3: 22.	21.85

(Source: Author)

3.4.2 Application of the risk assessment scoring model in the evaluation of risks in multimodal transport

The evaluation of risks associated with the maritime (R.M.2, R.M.4, R.M.8), road (R.M.1, R.M.2, R.M.3, R.M.4, R.M.8), and rail (R.M.1, R.M.2, R.M.3, R.M.4, R.M.8) components of a multimodal transport route is carried out by applying the Risk Assessment Scoring Model, proposed by (Tummala & Schoenherr, 2011), based on a probability–impact grid used for risk ranking.

Table 3.19 Risk scores for maritime, road, and rail transport

Mode of transport	Main risk code	Risk category	Risk subcategory code	<i>p</i> (%)	<i>P</i>	<i>I</i>	<i>R</i>	Zone
Maritime	R.M.2	Technical	M.2.1	46.93	3	4	12	Yellow
			M.2.2	37.79	3	4	12	Yellow
			M.2.3	48.00	3	3	9	Yellow
			M.2.4	27.08	2	3	6	Green
			M.2.5	36.06	3	3	9	Yellow
	R.M.4	Human factor	M.4.1	49.97	3	4	12	Yellow
			M.4.2	51.68	4	4	16	Red
			M.4.3	37.66	3	3	9	Yellow
			M.4.4	40.53	3	4	12	Yellow
			M.4.5	27.14	2	3	6	Green
			M.4.6	55.29	4	4	16	Red
	R.M.8	Environmental	M.8.1	32.47	3	3	9	Yellow
			M.8.2	41.85	3	3	9	Yellow
			M.8.3	49.54	3	4	12	Yellow
			M.8.4	47.27	3	3	9	Yellow
Road	R.M.1	Operational	R.1.1	34.18	3	4	12	Yellow
			R.1.2	29.06	2	3	6	Green
	R.M.2	Technical	R.2.1	46.47	3	4	12	Yellow
			R.2.2	31.21	3	4	12	Yellow
	R.M.3	Technological	R.3.1	28.88	2	3	6	Green
			R.3.2	26.94	2	3	6	Green
			R.3.3	22.18	2	2	4	Green
			R.3.4	33.94	3	4	12	Yellow
	R.M.4	Human factor	R.4.1	49.75	3	4	12	Yellow
			R.4.2	38.35	3	3	9	Yellow
			R.4.3	23.94	2	2	4	Green
			R.4.4	34.76	3	3	9	Yellow
			R.4.5	49.12	3	3	9	Yellow
			R.4.6	38.68	3	3	9	Yellow
	R.M.8	Environmental	R.8.1	29.88	2	3	6	Green
			R.8.2	29.85	2	3	6	Green
			R.8.3	24.28	2	2	4	Green
Rail	R.M.1	Operational	F.1.1	37.14	3	4	12	Yellow
			F.1.2	45.21	3	4	12	Yellow
			F.1.3	22.58	2	5	10	Yellow
	R.M.2	Technical	F.2.1	31.42	3	4	12	Yellow
			F.3.1	31.93	3	3	9	Yellow
	R.M.3	Technological	F.3.2	28.00	2	3	6	Green
			F.3.3	41.42	3	4	12	Yellow
			F.4.1	47.20	3	4	12	Yellow
	R.M.4	Human factor	F.4.2	32.58	3	3	9	Yellow
			F.4.3	41.42	3	3	9	Yellow
	R.M.8	Environmental	F.8.1	26.08	2	3	6	Green
			F.8.2	21.85	2	2	4	Green

(Source: Author)

3.4.2.5 Operational constraints and interpretation of results

The analysis of the risk scores obtained for each transport mode highlights the need to adopt specific risk mitigation measures, formulated to effectively reduce the probability of occurrence and/or the impact of risks within the multimodal transport system.

Table 3.20 Risk scores and mitigation measures for the maritime component of multimodal transport

Evaluated risk code	Risk score	Risk mitigation measure	Technical application (operational description)	Influenced score component
M.4.1 Human behavior	12	Periodic training; operational supervision	Define responsibilities; post-maneuver evaluation; observation log	<i>P</i>
M.4.2 Personnel negligence	16	Checklists; compliance control	Pre-arrival checks; verification; cross-checking	<i>P</i>
M.4.3 Inadequate training	9	Training programs; competence evaluation	Defined topics; exercises; retraining	<i>P</i>
M.4.4 Fatigue	12	Shift planning; rest verification	Shift scheduling; rest log; duty confirmation	<i>P</i>
M.4.5 Poor communication	6	Communication discipline; standard messages	VHF channel; pilot-master checklist	<i>P</i>
M.4.6 Procedure violations	16	Internal checks; incident analysis	Audits; reporting; procedure revision	<i>P</i>
M.8.1 Reduced visibility	9	Operational thresholds; enhanced watch	Visibility checks; observation posts; records	<i>I</i>
M.8.2 Lighting conditions	9	Operational lighting; equipment checks	Lighting verification; replacement; checklist	<i>I</i>
M.8.3 Sea state	12	Weather control; restrictions	Weather checks; port limits	<i>I</i>
M.8.4 Wind conditions	9	Wind control; maneuver adjustment	Wind verification; restrictions	<i>I</i>
M.2.1 Inadequate maintenance	12	Planned maintenance; checks	Scheduling; testing; restriction if needed	<i>P</i>
M.2.2 Technical failures	12	System testing; corrective actions	Steering test; alarms; repair	<i>P</i>
M.2.3 Defective design	9	Compliance checks	Documentation; acceptance tests	<i>P</i>
M.2.4 Vessel age	6	Maintenance planning; inspections	Additional checks; repair prioritization	<i>P</i>
M.2.5 Equipment age	9	Replacement planning; inspections	Inventory; replacement; records	<i>P</i>

(Source: Author)

In the column “Influenced score component”, the markings P and I indicate the variable within the scoring model on which the risk mitigation measure acts, namely P for the reduction of the probability of risk occurrence through the control of triggering conditions (organization, procedures, verification processes, competencies, technical compliance, maintenance, and testing), and I for the reduction of impact through the imposition of operational thresholds, operational restrictions, and consequence-limitation measures.

The presentation model used in Table 3.20, based on the correlation between the risk score, mitigation measures, their technical application, and the influenced score component, is maintained in a similar manner for the road component (table 3.21) and the rail component (table 3.22) of multimodal freight transport.

3.4.3 Application of the Dynamic Fault Tree model

3.4.3.1 Working hypotheses

The modeling using the Dynamic Fault Tree (DFT) method aims to evaluate the collision scenario between the container vessel MSC ANDRIANA III and another vessel located in berth 123 of the Port of Constanța, during a berthing maneuver assisted by the tug BSV Rusia, by integrating the human, technical, and environmental factors identified in the study, namely crew fatigue (M.1.4), poor communication (M.1.5), functional failure of tug assistance during maneuvering (M.3.1), failures of the vessel steering system (M.3.2), reduced visibility (M.2.2), and adverse wind conditions (M.2.5).

The main objective consists in estimating the probability of the precursor event by means of a logical modeling of multiple causes, dependent both temporally and logically, using dynamic gates specific to the Dynamic Fault Tree methodology.

3.4.3.2 Model structure and data sources used

The Dynamic Fault Tree (DFT) method is used to represent the dynamic and conditional relationships between basic events such as: human errors (fatigue – M.1.4 or insufficient personnel training – M.1.3), technical failures (failure of the steering system of the container vessel – M.3.2), extreme weather conditions (storm – M.2.5, reduced visibility – M.2.2), and the failure of coordination with the tug due to poor communication (M.1.5), which leads to improper tug assistance to the container vessel during the berthing maneuver (functional failure of maneuvering assistance – M.3.1).

Table 3.23 *Types of logical gates used in the DFT analysis of the case study*

Logical Gate	Graphic Symbol	Interpretation in the Study	Example
OR		Represents alternative risks, any of which can lead to the precursor event.	Negligence (M.1.2) or lack of personnel training (M.1.3); alternatively, reduced visibility (M.2.2) or adverse wind conditions (M.2.5) may cause deviation from the maneuver trajectory.
AND		Represents simultaneous risks that must occur together.	Fatigue (M.1.4) and poor communication (M.1.5); simultaneously, wind conditions (M.2.5) may act as environmental amplifying factors.
PAND		Represents risks in strict critical sequence.	Fatigue (M.1.4) followed by poor communication (M.1.5), as degraded vigilance precedes incorrect transmission/reception of orders.
FDEP		Activation of a triggering event automatically activates a dependent event.	Trigger event: poor communication (M.1.5); dependent event: functional failure of tug assistance (M.3.1), where push/pull commands are misinterpreted, leading to ineffective maneuver control.

(Source: Author)

3.4.3.3 Analysis of causal relationships and structural organization of the DFT tree

General formulation for the OR gate between two independent events:

$$P_{OR}(A,B) = P(A) + P(B) - P(A) \times P(B) \quad (3.17)$$

Within this structure, risks M.1.4 and M.1.5 are modeled using OR and PAND gates, the dependency between M.1.5 and M.3.1 is represented through the FDEP gate, while the combination of risks M.3.2, M.2.2, and M.2.5 is achieved through the AND gate, so that the model reflects the sequence, conditionality, and simultaneous interaction of events leading to the collision scenario.

The combination of risks within the DFT structure was performed by modeling the logical relationships between the basic events M.1.4, M.1.5, M.3.1, M.3.2, M.2.2, and M.2.5. Events M.1.4 and M.1.5 were associated through an OR gate to define the intermediate event M1, resulting in a probability of $P(M1) = 0,57$, while the critical sequence M.1.4 $\rightarrow$ M.1.5 was modeled using a PAND gate, leading to $P_{PAND} = 0,11$. The functional dependency between M.1.5 and M.3.1 was represented using an FDEP gate, with a probability of $P_{FDEP} = 0,12$, while the simultaneous combination of risks M.3.2, M.2.2, and M.2.5 was modeled using an AND gate, resulting in $P_{AND} = 0,05$.

The aggregated event associated with the collision scenario was determined through an OR gate applied to the three mechanisms E1, E2, and E3, resulting in $P_{total} = 0,257$, respectively approximately 0,26. This result indicates that the analyzed scenario is determined by the combined action of risks M.1.4, M.1.5, M.3.1, M.3.2, M.2.2, and M.2.5, with cumulative contribution of human sequences, functional dependency, and techno-environmental conditioning factors.

3.4.3.4 Evaluation of DFT logical paths and probability calculation for each hypothesis

The objective of this stage is to determine the probability of occurrence of the precursor event (collision) by evaluating the dynamic logical paths within the DFT tree structure, using the risk values from table 3.14, dynamic gates (PAND, FDEP, AND), and mathematical relations for event combinations.

The evaluation of DFT logical paths was performed through the independent calculation of hypotheses E₁, E₂, and E₃, based on the values associated with risks M.1.4, M.1.5, M.3.1, M.3.2, M.2.2 and M.2.5.

For E₁, the critical sequence M.1.4 $\rightarrow$ M.1.5 was modeled using the PAND gate:

$$P_{PAND} = P(M.1.4) \times P(M.1.5) = 0,11 \quad (3.28)$$

For E₂, the functional dependency M.1.5 $\rightarrow$ M.3.1 was evaluated using the FDEP gate:

$$P_{FDEP} = P_{trigger} \times P_{dependent} = P(M.1.5) \times P(M.3.1) = 0,27 \times 0,46 = 0,12 \quad (3.29)$$

where:

$P_{trigger}$: represents the probability that the triggering event occurs;

$P_{dependent}$: represents the probability of the dependent event occurs in the absence of the trigger.

For E₃, the simultaneous combination M.3.2 $\wedge$ M.2.2 $\wedge$ M.2.5 was modeled using the AND gate:

$$P_{AND} = P(M.3.2) \times P(M.2.2) \times P(M.2.5) = 0,37 \times 0,32 \times 0,47 = 0,05 \quad (3.30)$$

Total collision probability: The complete relation associated with the OR logical gate between independent events is used to determine the total collision probability, being justified in the context of distinct logical paths without major structural overlap.

The OR-type relation enables final probabilistic integration in a coherent formulation, under conditions of logical independence and absence of temporal correlations (**Vesely et al., 1981**):

$$P_{total} = 1 - \prod_{i=1}^3 (1 - P_i) = 1 - (1 - 0,11)(1 - 0,12)(1 - 0,05) = 1 - 0,73 = 0,27 \quad (3.31)$$

Conclusion: The obtained result represents a composite numerical value integrating the contributions of the risk manifestation mechanisms modeled through the Dynamic Fault Tree logical gates used in the analysis, namely the PAND gate for the combination of human factors (crew fatigue (M.1.4) and poor communication (M.1.5)), the FDEP gate for the functional dependency between communication (M.1.5) and tug availability (M.3.1), and the AND gate for

the combination of technical risk and environmental conditions (loss of steering control (M.3.2), reduced visibility (M.2.2), and lateral wind (M.2.5).

3.4.3.6 Graphical representation of the DFT tree

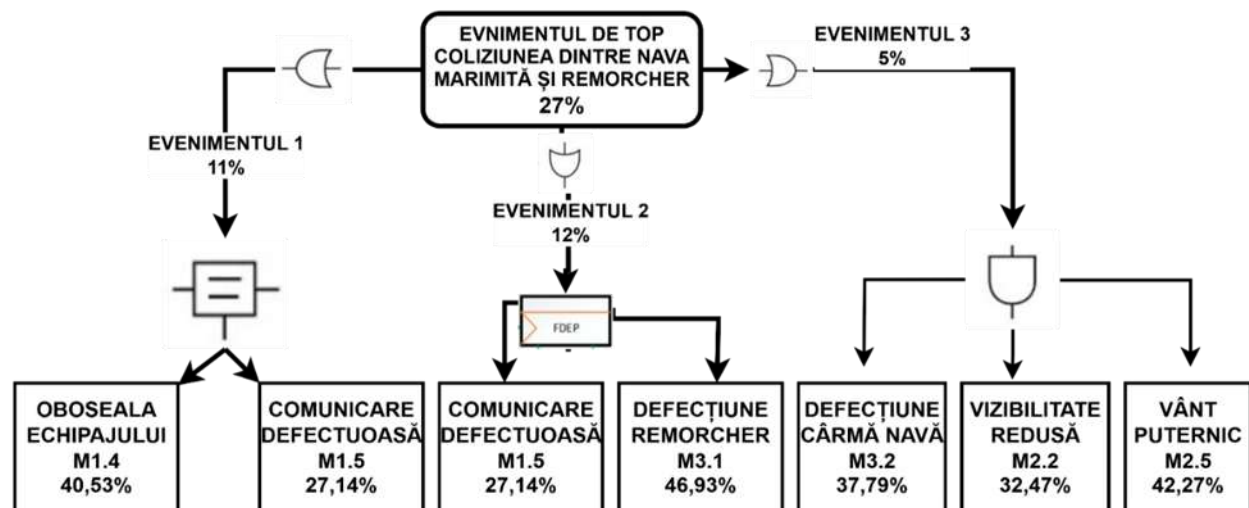


Figure 3.8 Dynamic Fault Tree (DFT) for the final event – collision between a maritime vessel and a tug during the berthing maneuver in the DP World terminal – Port of Constanța Sud
(Source: Author)

CHAPTER 4 RISK MITIGATION SOLUTIONS – CASE STUDIES

4.1 Solutions for reducing operational, technical, and technological risks in the DP World terminal

4.1.1 Problem description

The DP World Constanța Sud terminal represents an intermodal and multimodal transfer node, acting as an interface between maritime flows in the Black Sea and land and inland waterway connections integrated into the European transport network.

The operation of the terminal depends on the continuous coordination of equipment, resources, and operational sequences, which leads to the occurrence of distinct categories of risks, namely operational risks (R.I.1), technical risks (R.I.2), technological risks (R.I.3), and meteorological risks (R.I.8), each having a direct impact on the continuity of the logistic flow.

Under these conditions, the identification of mitigation measures for risks R.I.1, R.I.2, R.I.3, and R.I.8 is necessary in order to limit operational disruptions and to maintain the functional continuity of the terminal.

4.1.3 Identification of operational, technological, and technical risks

In the case of the DP World Constanța Sud terminal, system vulnerabilities are associated with the operational configuration of the quay-side operating area, the availability and reliability of handling equipment, as well as the manner in which these are functionally integrated into the terminal operating system. These vulnerabilities manifest through dysfunctions in the sequence of

vessel loading and unloading operations (D.1), through mismatches between quay crane productivity and the capacity to receive and evacuate containers from temporary storage areas (D.2), as well as through inefficient utilization of operational resources (D.3).

Under conditions where quay crane productivity is not correlated with the handling and transfer capacity of temporary storage areas, local accumulations of loading units occur, leading to operational dysfunctions (D.1) and limiting the effective operational capacity of the vessel. This generates operational risks (R.I.1) with direct impact on berth time and on the continuity of the multimodal transport process. At the same time, technological risks (R.I.3) and technical risks (R.I.2) are associated with the performance and reliability of quay cranes, which have a determinant role in the overall operational capacity of the terminal.

4.1.4 Transfer interface capacity and cargo flow bottleneck ratio

The methodological framework for evaluating the capacity of transfer interfaces within the DP World Constanța Sud transshipment terminal is based on identifying the limiting section of an interface, where the effective capacity of the interface (berth–vessel, storage platform–rail transport mode, and platform–road component) is lower than the capacities of adjacent subsystems (quay, container storage platform, road gate, rail ramp), thereby limiting total throughput and increasing the risk of congestion and delays (Notteboom & Rodrigue, 2022).

In order to evaluate the level of utilization of port infrastructure and to identify areas susceptible to becoming bottlenecks, quantitative indicators are used, including the Berth Occupancy Ratio (BOR), which measures the degree of utilization of berthing infrastructure (ABPmer, 2019), the analysis of physical constraints regarding the number of cranes that can operate simultaneously on the same vessel, generated by the non-crossing constraint (Lu et al., 2012), as well as a comparative indicator between the capacity of evacuation interfaces and the operational rate at the berth. The Berth Occupancy Ratio (BOR) expresses, in percentage terms, the effective utilization level of berthing infrastructure over a defined time interval, by relating the total time during which the berth is operationally occupied to the total time available for operation within the analyzed period.

$$BOR = \frac{T_0}{T_t} \times 100\% , \text{ (ABPmer, 2019)} \quad (4.1)$$

where: T_0 represents the effective time during which the berth is occupied (from berthing to departure, including formalities carried out by authorities if performed at the berth), while T_t represents the total available time of the berth within the selected period (e.g., 24 h/day or 8,760 h/year).

For a single berth, the BOR indicator highlights two distinct operational situations. Under the assumption of a continuously occupied operating day, the result is BOR = 100 %, which indicates full utilization of the berth and a potential risk of waiting time for berthing in the case of traffic increase. Conversely, at a weekly level, an occupation of 24 hours out of 168 hours results in BOR = 14.29 %, reflecting a low level of utilization and the existence of significant available capacity.

Intermodal Interface Capacity Index (INCI): In the continuation of the modeling process, the value of the Intermodal Interface Capacity Index (INCI) is determined, defined as the ratio between the capacity of the analyzed interface (cargo transfer area) and the maximum operational rate at the berth, in accordance with the concept of capacity alignment between port subsystems (adapted from Rodrigue, 2020).

$$\text{The relation used is: } INCI_x = \frac{C_x}{C_{berth,maxim}}, \quad (4.4)$$

where: C_x represents the capacity of the analyzed interface (containers/hour), determined from real operational data; $C_{berth,max}$ represents the maximum operational capacity at the berth (containers/hour), calculated based on quay crane productivity and physical operating constraints; $INCI$ is dimensionless (without measurement unit), as it represents a ratio of capacities.

Interpretation of results: Values of the indicator $INCI < 1$ indicate that the analyzed interface has a capacity lower than the maximum operational capacity at the berth and, therefore, may constitute a bottleneck in the cargo flow. Values $INCI \geq 1$ indicate that the interface has a capacity at least equal to that of the berth and does not represent a limiting factor.

For the comparative evaluation of port interfaces (rail and road) relative to the berth operating area, it is necessary to first determine the maximum operating rate at the berth and the average handling rate per call, using real operational data.

The reference berth handling rate is 54 cont./h (2 QC cranes $\times$ 27 cont./h/QC), while the average handling rate per call, considering 20 hours of effective operation out of 24 hours of berth occupancy, is 45 cont./h. The simultaneity of cranes operating on the same vessel is limited by geometric and safety constraints (DP World Romania, 2024; Lu et al., 2012).

Rail interface: Is equipped with 2 RMG units $\times$ 15 cont./h, resulting in 30 cont./h. This leads to an indicator value of $INCI_{rail} = \frac{30}{54} = 0,56$, with a capacity gap relative to the berth of 24 cont./h, indicating a tendency of accumulation within the storage platform.

Road interface: Is evaluated based on the effective gate capacity (trucks/hour under real operating conditions) and compared with the average berth handling rate per call. The normalized interface indicator ($INCI$) is calculated explicitly using the base relation (4.67). For the operational data of the terminal, achieving equilibrium without accumulation in the storage area requires a road flow of approximately 15 cont./h (approximately 300 – 330 cont./day at 20–22 hours/day), corresponding to a minimum threshold $INCI_{road,min} \approx 0.28$. Below this value, inventory accumulation and increased waiting times occur, while above this threshold, the road flow is aligned with vessel operations.

Table 4.5 Technical measures for risk mitigation, by transfer categories, in the DP World terminal

Transfer category	Main risks	Risk mitigation measures
Maritime vessel → berth operating area (quay)	• Inadequate bay sequencing generates simultaneous flow exceeding capacity (R.I.1); • Unavailability of a quay crane STS/QC prolongs berth time (R.I.2); • Adverse weather conditions suspend quay operations (R.I.8); • Delays of lashing/de-lashing teams slow operational cycles (R.I.4); • Quay platform congestion limits ITV vehicle circulation and increases operational risk (R.I.1); • Misalignment between vessel stowage plan and hinterland connections generates terminal blockages (R.I.1).	• The vessel planner optimizes bay sequence for uniform flow towards the terminal; • Dispatch allocates redundant STS/QC and activates MHC in case of failure; • Terminal management applies adverse weather procedures and reschedules connections; • Quay supervisor synchronizes lashing/de-lashing and hatch cover handling with crane schedule; • Traffic coordinator defines one-way ITV routes;

Transfer category	Main risks	Risk mitigation measures
Berth operating area → rail transport component	• Yard congestion blocks rail lanes (R.I.1); • Failure to meet rail windows delays train departure (R.I.1); • Additional RTG moves increase preparation time (R.I.1); • Overloading of RMG cranes reduces reliability (R.I.2); • Documentation inconsistencies delay wagon loading (R.I.3); • Incomplete rail maneuvers block loading front.	• Planning team establishes rail windows immediately after berth operations start; • Terminal organizes pre-staging by wagon and position; • Supervisor assigns dedicated RTG feeder; • Maintenance schedules RMG servicing outside windows; • Parallel rail lines used where possible.
Berth operating area → road transport component	• Gate congestion and yard blockages due to uncontrolled access (R.I.1); • Uneven truck flow generates yard overload (R.I.1); • Repetitive RTG moves increase cycle time (R.I.1); • Flow desynchronization (R.I.1); • Internal traffic incidents in high-density areas (R.I.4).	• Truck appointment system synchronized with berth operations; • Pre-gate filtering and priority lanes; • Extended gate hours; • Truck-first zones near gates; • Dedicated RTG during peak hours.
Storage yard management	• Excessive stack occupancy reduces mobility (R.I.1); • High number of repetitive moves increases risk (R.I.1); • Long RTG/RS routes increase cycle time (R.I.1).	• Operational thresholds and phased clearance plans; • Yard reconfiguration; • Separation by transport modes and destinations.

(Source: Author)

4.1.5 Evaluation of risk effects and system recovery times of port operations through discrete-event simulation – DP World Constanța Sud terminal

For the development of the discrete-event simulation model, the Arena Rockwell software application was used, a platform designed for process simulation, with the capability to generate and manage simulation entities interacting with resources, including those associated with service stations (Roșca et al., 2025). The proposed model represents a discrete-event simulation of container terminal operations at vessel arrival, reproducing the flow vessel → berth → storage yard → exit flows as a discrete, stochastic system with limited resources. Processes and interdependencies are formalized through logical blocks, while resources include berths, quay cranes, and internal vehicles, using primary data from C.S.C.T. – DP World Constanța Sud.

The simulation in Arena (Rockwell) maps the operational processes, runs based on inputs calibrated with real data, and enables the implementation of control policies in a reproducible framework (Kelton, Sadowski & Zupick, 2015; Law, 2015). The reliability of quay cranes is modeled as an alternation between the availability state (“up”) and the unavailability state (“down”), governed by the following indicators: $F(t)$ – failure function, $R(t)$ – reliability function, $\lambda(t)$ – failure rate, MTBF – mean time between failures, and MTTR – mean time to repair (Târcolea et al., 1989). This modeling captures transitions between steady-state and transient regimes, as well as the effect of repair processes on throughput.

The verification and validation process uses established tests for stationarity and convergence (Schruben et al., 1983; Heidelberger & Welch, 1983; Geweke, 1992). The reported indicators, representing the outputs of the discrete-event simulation model (Arena Rockwell), executed on the defined scenarios and calibrated using operational data from the DP World

Constanța Sud terminal, include: berth handling flow (containers/hour), queue size (vessels/containers), and waiting times of vessels/TEUs.

Table 4.10 *Simulation scenarios*

Scenario ID	Description
S00	All quay cranes are operational. The simulation duration is 365 days. The warm-up period, during which no data is recorded, is 5 days.
S11	Same as S00. After 30 days, one quay crane becomes unavailable/failed for 24 hours.
S17	Same as S00. After 30 days, one quay crane becomes unavailable/failed for 7 days.
S114	Same as S00. After 30 days, one quay crane becomes unavailable/failed for 14 days.
S21	Same as S11. After 30 days, another quay crane becomes unavailable/failed for 24 hours.
S27	Same as S11. After 30 days, another quay crane becomes unavailable/failed for 7 days.
S214	Same as S11. After 30 days, another quay crane becomes unavailable/failed for 14 days.

(Source: Author)

The time series of vessel waiting times and its corresponding density distribution are illustrated in Figure 4.5:

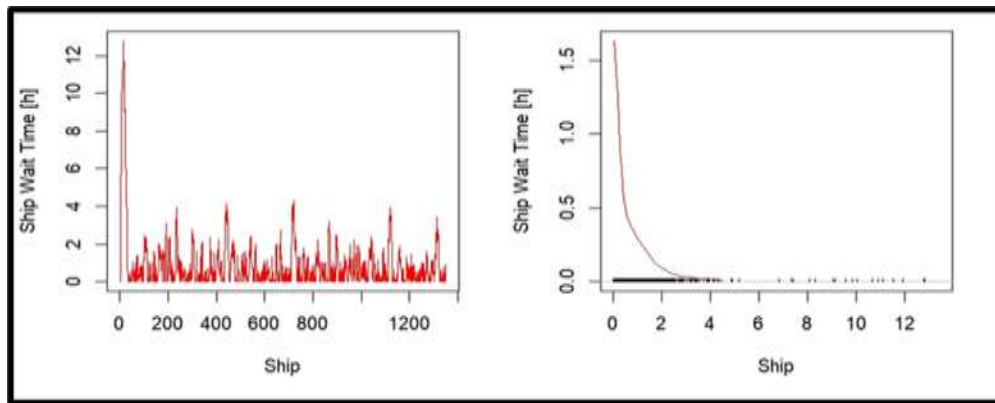


Figure 4.5 *Time series of vessel waiting times (values and density)*

(Source: Author)

The effect of QC crane unavailability is as follows: when one QC crane is out of service for 7 days, the time series becomes stationary after approximately 102 vessels; when one QC crane is out of service for 14 days, stationarity is reached after approximately 418 vessels; when two QC cranes are out of service for 14 days, the series is non-stationary (Heidelberger–Welch test value, $p = 0.02$, representing the probability, under the null hypothesis of stationarity, of obtaining data at least as extreme; $p < 0.05$ indicates rejection of the stationarity hypothesis for the vessel waiting time series at berth) and requires a longer simulation run in order to reach equilibrium of the analyzed system.

For different scenarios, in which a variable number of cranes are unavailable for different time intervals, the results are illustrated in figures 4.7 – 4.12:

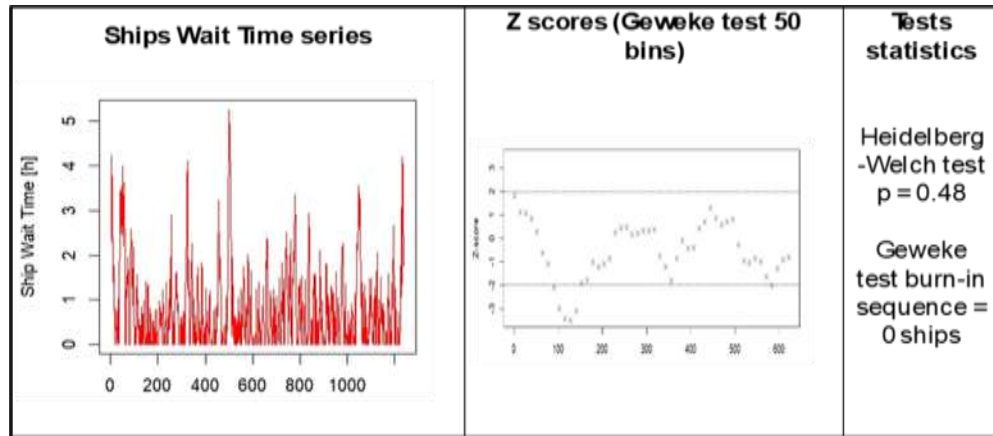


Figure 4.7 Time series of vessel waiting times for the failure of one quay crane – one-day interruption

(Source: Author)

These results quantitatively demonstrate how the reduction in QC crane availability shifts the system from the steady-state regime (SS) to transient states (TS1–TS3) and increases vessel waiting times, providing the basis for operational risk mitigation measures (yard storage allocation planning, resource reconfiguration, preventive maintenance).

Interpretation of simulation results: A short-term failure of a single crane has a moderate effect, with the port system recovering within a limited operational horizon. A prolonged unavailability (14 days) of one crane increases waiting times, while the system maintains the capacity to reach a stabilized regime. When two cranes are unavailable for 14 days, the vessel waiting time series exhibits non-stationary behavior; in the absence of corrective measures, vessel queues accumulate and container flows become constrained.

With regard to equipment reliability, the calculation of MTBF/MTTF indicators and the use of distribution functions allow the modeling of failures in accordance with operational conditions. A higher MTBF value reflects a lower failure probability. These reliability indicators are used to establish preventive maintenance schedules and repair durations for each crane.

4.1.6 Conclusions

The model was implemented in the ARENA Rockwell simulation environment and focused on quay cranes, which represent critical equipment for container handling, evaluating the system transition between equilibrium conditions and transient states generated by failures. In addition to discrete-event simulation, the BOR method and the INCI indicator were applied in order to quantify berth utilization and to assess the alignment of capacities across critical interfaces.

The results demonstrate that quay crane failures have a significant impact on vessel waiting times and on the continuity of port operations.

For short-duration failures, the system returns to equilibrium conditions, while for interruptions of 14 days, the system does not reach stationarity within the analyzed simulation horizon, requiring prompt corrective measures to avoid operational disruption. The Heidelberg–Welch and Geweke tests confirm the conditions under which the system stabilizes or remains affected by major disturbances, while BOR and INCI values highlight the exceedance of berth saturation thresholds and the transformation of rail and road interfaces into capacity-constraining points.

4.2 Solutions for risk reduction in multimodal transport on the route Constanța Sud Port – Curtici terminal

4.2.1 Problem description

The multimodal transport route between Constanța Sud Port and the Curtici terminal operates based on the integration of road and rail land components, whose operation is conditioned by the capacity of the infrastructure used and by the stability of the operational regime along the constituent segments. In this context, route performance is influenced by operational dysfunctions occurring on both components, with direct effects on the continuity of the transport flow.

The identified dysfunctions are generated by functional limitations of the infrastructure, temporary restrictions imposed by maintenance or modernization works, and variable operating conditions, including those determined by environmental factors. These affect the effective traffic capacity and the stability of travel times, both on road and rail segments, depending on the specific characteristics of each component of the multimodal transport system.

4.2.2 Alternative routes on the road component of multimodal transport between Constanța Sud Port and Curtici terminal

Under non-uniform infrastructure operating conditions, the road component of the multimodal transport route Constanța Sud Port – Curtici is affected by operational dysfunctions, technological deficiencies, and structural vulnerabilities which, through propagation at route level, constitute sources of risk for the continuity and efficiency of multimodal transport.

4.2.2.1 Analysis of road network connectivity structure and route alternatives

In order to structurally describe the connectivity of the road network associated with the analyzed alternatives, two standard matrix representations are used: the adjacency matrix and the distance matrix, which allow the explicit formalization of functional links between nodes and provide the analytical support for identifying alternative routes in situations of segment unavailability (R.M.1), as well as for evaluating the effects on route continuity and on risk mitigation options.

For the road component of the multimodal transport route Constanța Sud Port – Curtici terminal, the transport work indicator (TEU·km) was used, allowing the evaluation of the container evacuation mechanism from the terminal to the land network and the identification of how route changes influence the transport activity volume at the level of the entire multimodal transport route.

Table 4.18 Cost analysis and transport performance (TEU·km) for 1 TEU transported

Parameters	Route 1	Route 2	Route 3
Fuel price (RON/litre) (omvpetrom.com , 2024)	6,5	6,5	6,5
Vehicle consumption (litres/km) (IRTU, 2023)	0,3	0,3	0,3
Vehicle depreciation (RON/km) (UNTRR, 2022)	0,5	0,5	0,5
Maintenance and repairs (RON/km) (UNTRR, 2022)	0,4	0,4	0,4
Salaries and benefits (RON/km) (UNTRR, 2022)	0,6	0,6	0,6
Road tolls (RON/km) (IRTU, 2023)	0,3	0,3	0,3
Number of containers (TEU)	1	1	1
Exchange rate (1 Euro = 4.96 RON) (BNR, 2024)	4,96	4,96	4,96
Distance (km) (Google Maps, 2024)	823	854	849
Fuel cost per km (RON): $Cost_{comb./km} = Consum_{vehicul} \left(\frac{litri}{km} \right) \times Pret_{comb.} \left(\frac{lei}{km} \right)$	1,95	1,95	1,95

Parameters	Route 1	Route 2	Route 3
Additional cost per km (RON)	1,80	1,80	1,80
Total cost per km (RON) $C_{\text{mediu total/km (convoi)}} = C_{\text{combustibil/km}} + C_{\text{aditional/km}}$	3,75	3,75	3,75
Total cost per 1 TEU (RON/TEU): $Cost_{TEU,k} = d_k \times C_{t/km}$	3086,25 lei/TEU	3202,50 lei/TEU	3183,75 lei/TEU
Total cost per 1 TEU (EUR/TEU):	622,23 EUR/TEU	645,67 EUR/TEU	641,89 EUR/TEU
Transport performance (TEU·km)	823	854	849

4.2.2.2 Application of the SAW method in assessing the risk level of the road component

In the continuation of the analysis of risks associated with the multimodal transport chain Port of Constanța South – Curtici Terminal, the multicriteria method Simple Additive Weighting (SAW), also known as the Weighted Sum Method (WSM), proposed by (Sigalingging et al., 2024), is applied in order to obtain the risk indicator for each alternative road route.

The SAW method calculates a composite risk coefficient specific to each route alternative, based on the average values of the five risk categories defined for the road segment, namely operational R.1, technical R.2, technological R.3, human R.4 and environmental R.8, previously presented in table 3.16.

The source (Sigalingging et al., 2024) proposes the following relation for aggregating normalized scores, where the total risk score for an alternative route i is obtained as the weighted sum of normalized scores corresponding to each risk category:

$$V_i = \sum_{j=1}^n w_j \times r_{ij} \quad (4.30)$$

where:

- V_i : aggregated value (total risk score) for alternative route i ;
- r_{ij} : normalized value of the assessed risk for criterion j (risk category: operational, technical, technological, human, environmental) for route i ;
- w_j : weight assigned to criterion j , determined based on the weighted average values resulting from the previous risk analysis (presented in table 3.16 for the road segment);
- n : number of criteria (5 risk categories: operational, technical, technological, human, environmental).

Each route between the Port of Constanța South and Curtici Terminal is considered an alternative i , and the initial values $X_{i,j}$ represent the percentage levels of risk for criterion j , taken from table 3.16.

The transformation of the initial risk values, expressed in percentages for each route and criterion, into a comparable format on a common scale is performed by applying the relation proposed by (Vafaei et al., 2022) and (Taherdoost, 2023):

$$r_{ij} = \frac{X_{\max,j} - X_{i,j}}{X_{\max,j} - X_{\min,j}} \in [0, 1] \quad (4.32)$$

The result is expressed on a standardized scale ranging between 0 and 1, where: the value 1 corresponds to the route with the most favorable situation (the lowest risk relative to the other alternatives); the value 0 corresponds to the route with the least favorable situation (the highest risk among the analyzed alternatives).

In each case, the extreme values $X_{\min,j}$ and $X_{\max,j}$ are explicitly determined in order to ensure full traceability of the modeling process.

Table 4.19 Normalized values r_{ij} for the three road routes and the five criteria (risk types)

Criterion (j) / Risk	Route i	$X_{i,j}$ (Risk value %)	$X_{max,j}$	$X_{min,j}$	ΔX_j	r_{ij}
Operational (Traffic congestion/blockage) R.1.1	X_1	38	38	32	6	0
	X_2	35	38	32	6	0,50
	X_3	32	38	32	6	1,00
Technical (Vehicle mechanical failures) R.2.1	X_1	50	50	44	6	0
	X_2	48	50	44	6	0,33
	X_3	44	50	44	6	1,00
Technological (Poor infrastructure maintenance) R.3.4	X_1	40	40	30	10	0
	X_2	35	40	30	10	0,50
	X_3	30	40	30	10	1,00
Human (Human errors in vehicle operation) R.4.1	X_1	60	60	50	10	0
	X_2	55	60	50	10	0,50
	X_3	50	60	50	10	1,00
Environmental (Adverse weather conditions) R.8.1	X_1	34	34	28	6	0
	X_2	30	34	28	6	0,66
	X_3	28	34	28	6	1,00

(Source: Author)

In the continuation of applying the SAW (Simple Additive Weighting) method, the parameter w_j (the weight assigned to the risk factor criterion j) is determined, namely the relative importance of each of the five risk types in the final score.

The methodological procedure is as follows: first, for each risk category (operational, technical, technological, human, environmental), the weighted average values of the risk subcategories are extracted from table 3.16, and their arithmetic mean is calculated, resulting in a single value $\overline{M}_j$ for each risk category.

Subsequently, the five values $\overline{M}_j$ are transformed into weights through normalization to a total sum equal to 1:

$$w_j = \frac{\overline{M}_j}{\overline{M}_{op.} + \overline{M}_{technic} + \overline{M}_{technologic} + \overline{M}_{uman} + \overline{M}_{mediu}}, \text{ (Hwang \& Yoon, 1981; Taherdoost, 2023)} \quad (4.37)$$

where: each w_j is between 0 and 1 and represents the proportion of the total assigned to category j ;

$$\overline{M}_j = \frac{\sum M_{risk\ subcategories}}{N_{risk\ subcategories}} \quad (4.38)$$

where: $\sum M_{risk\ subcategories}$ is the sum of the values of the risk subcategories for risk category j and $N_{risk\ subcategories}$ is their number (extracted from table 3.12).

Further, the weighting is expressed by the relation:

$$w_j = \frac{\overline{M}_j}{\sum_k \overline{M}_k}, \quad (4.39)$$

where: k represents all considered risk categories (operational, technical, technological, human, environmental);

- $\sum_k \overline{M}_k$ is the sum of the mean values of all risk categories k ;
- $\overline{M}_k$ is the mean value of the risk subcategories within category k (expressed in percentages).

Table 4.20 Weights w_j calculated for each risk category based on the mean values of their subcategories

Risk Category	$M_{subcateg.}$ (%)	$N_{subcateg.}$	$\bar{M}_j = \frac{\sum M_{risk\ subcategories}}{N_{risk\ subcategories}}$	$\sum_k \bar{M}_k$	$w_j = \frac{\bar{M}_j}{\sum_k \bar{M}_k}$
Operational	34.18; 29.06	2	31.62	165.54	0.19
Technical	46.47; 31.21	2	38.84	165.54	0.23
Technological	33.94; 28.88; 26.94; 22.18	4	27.985	165.54	0.16
Human	49.75; 38.35; 23.94; 34.76; 49.12; 38.68	6	39.10	165.54	0.23
Environmental	29.88; 29.85; 24.28	3	28.0033	165.54	0.16

(Source: Author)

In the final stage of applying the SAW (Simple Additive Weighting) method, the total score V_i is determined for each analyzed road route using relation (4.30), based on the normalized values $r_{i,j}$ and the corresponding weights $w_{i,j}$ for each risk category.

This step allows the identification of the route with the lowest aggregated level of risk (total weighted risk value) and the establishment of the final ranking, necessary for decision-making regarding the mitigation of specific risks associated with the analyzed routes.

Table 4.21 Total scores V_i and ranking of road routes according to the SAW method

Route	$V_i = \sum_{j=1}^n w_j \times r_{ij}$	Ranking according to SAW method
X₁	0	3
X₂	0,48	2
X₃	1,00	1

(Source: Author)

The obtained results show that route X₃ achieves the best score ($V_i = 1,00$), indicating that, after applying the weights and normalizing the risk values, it has the lowest total weighted risk value among all alternatives. Route X₂ is positioned at an intermediate level ($V_i = 0.48$), while route X₁ presents the highest total weighted risk value ($V_i = 0$).

4.2.3 Analysis of risks associated with the operation of the railway component of the multimodal transport route Constanța South – Curtici

4.2.3.1 Presentation of freight railway routes and their associated risks

The analyzed railway component is treated as an integral part of the multimodal transport route between the Port of Constanța South and Curtici, having the role of taking over containerized cargo flows after the completion of transshipment operations in the DP World Constanța South terminal.

In this context, the railway system ensures the continuity of the transport flow between the maritime–land interface and the final inland destinations, its operational performance directly influencing the overall outcome of the multimodal transport route.

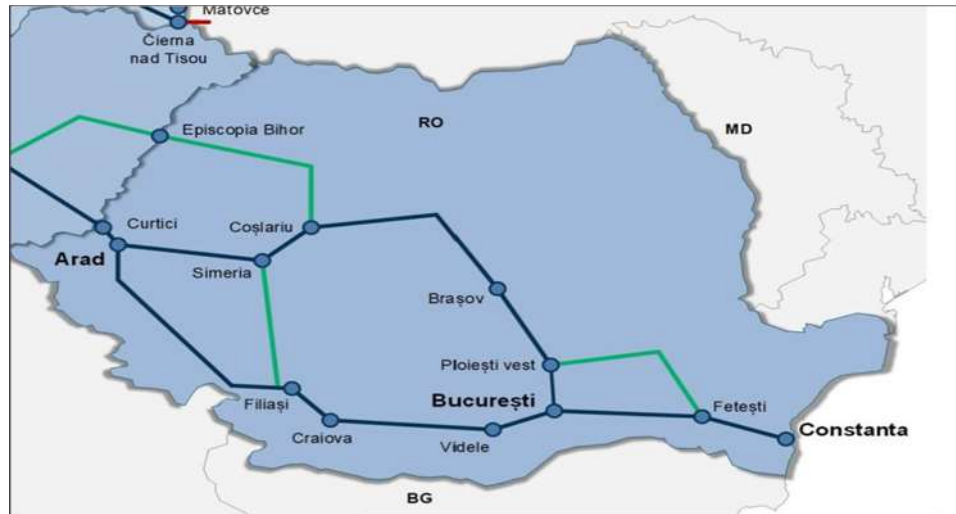


Figure 4.13 Railway transport routes between the Port of Constanța South and Curtici terminal (Arad)

(Source: Author)

Route 1: Constanța South (A) – Bucharest North (B) – Brașov (C) – Sighișoara (D) – Teiuș (E) – Simeria (F) – Arad (G) – Curtici (H);

Route 2: Constanța South (A) – Bucharest North (B) – Roșiori North (I) – Craiova (J) – Drobeta Turnu Severin (K) – Caransebeș (L) – Timișoara (M) – Arad (G) – Curtici (H) .

Table 4.24 Vulnerabilities, deficiencies, risks and mitigation mechanisms for the railway component of the multimodal transport route Constanța South – Curtici

Risk Category	Vulnerabilities	Deficiencies	Risk mitigation measures	Technical effect
Operational (traffic delays, loss of capacity) R.F.1	• sensitivity to variations in railway infrastructure capacity; • dependence on available time slots for freight trains, defined by the timetable; • limited capacity for rescheduling freight train operations.	• temporary line restrictions; • limited railway capacity in intermediate stations; • additional waiting times during operation.	• scheduling freight trains according to available infrastructure capacity; • aligning departure times from the port terminal with railway network access windows; • operational adjustment of the timetable.	• reduction in travel time variability; • increased stability of railway operations.
Technical (rolling stock failures) R.F.2	• dependence on the technical condition of rolling stock; • lack of traction redundancy on freight routes.	• unplanned technical stops during operation; • temporary unavailability of the assigned locomotive.	• operational technical checks before dispatch; • planning traction resources with operational reserve.	• increased reliability of railway operations; • continuity of rail transport.
Technological (infrastructure limitations) R.F.3	• dependence on track superstructure condition; • presence of permanent speed restriction sections.	• limitation of commercial rail speed; • increased effective travel time on affected segments.	• allocation of freight trains on predefined routes with limited capacity; • introduction of operational time buffers.	• maintaining travel times within timetable limits; • increased predictability of arrival times.

Risk Category	Vulnerabilities	Deficiencies	Risk mitigation measures	Technical effect
Human (operational errors) R.F.4	- dependence on interaction between human factor and traffic control systems; - dependence on real-time information flow.	- delays due to uncoordinated decisions; - local disruptions caused by improper procedures.	- keeping decisions within staff responsibilities; - timely communication of operational changes.	- reduction of additional dwell times; - limitation of unjustified delays.
Environmental (weather conditions) R.F.8	exposure of railway infrastructure to severe weather and extreme temperatures.	- temporary traffic restrictions; - reduced operational speed.	- aligning train operations with weather forecasts; - adapting timetable on exposed sections.	limiting unplanned travel time variations.

(Source: Author)

4.2.3.2 Evaluation of railway rerouting in scenarios of segment unavailability

For the railway component of the route between the DP World terminal and the Curtici terminal, route alternatives are defined through an ordered sequence of operational points corresponding to railway stations and transit nodes.

Each railway segment between two consecutive points iii and jjj is associated with a distance d_{ij} (km), such that the total length of each route alternative results from the summation of its component segment distances.

For the railway component, transport performance (TEU·km) allows the quantification of the transport activity volume carried out through the railway network within the multimodal transport route and enables the integration of this transport segment into the overall evaluation of the system operation between the DP World Constanța terminal and the Curtici terminal.

Table 4.26 Determination of time, costs and specific cost relative to transport performance for railway route 1 (calculation for 1 TEU transported)

Segment	Distance (km)	Speed (km/h)	Time (hours)	Transport performance (TEU·km)	Cost (euro)	Operating condition cost (euro/TEU) π_{ij}	Total cost (euro)
1. Constanța – București	225	16	14,06	225	562,50	56,25	618,75
2. București – Brașov	166	16	10,38	166	415,00	41,50	456,50
3. Brașov – Sighișoara	129	16	8,06	129	322,50	32,25	354,75
4. Sighișoara – Teiuș	123	16	7,69	123	307,50	30,75	338,25
5. Teiuș – Simeria	73	16	4,56	73	182,50	18,25	200,75
6. Simeria – Arad	134	16	8,38	134	335,00	33,50	368,50
7. Arad – Curtici	46	16	2,88	46	115,00	11,50	126,50
Total Ruta 1	896	–	56,00	896	2240,00	224,00	2464,00

(Source: Author)

According to table 4.26, the determination of time and costs across railway segments highlights the concentration of a significant share of the total time and total route cost on a limited number of segments, characterized by long distances and extended travel durations.

This concentration indicates segments with increased operational sensitivity, where the occurrence of traffic restrictions generates both cumulative delays and corresponding increases in total transport cost due to the accumulation effect.

The obtained values delineate the critical segments from the perspective of operational performance, contributing to the implementation of risk mitigation solutions through rerouting and by limiting the propagation of delays and cost increases at the route level.

Table 4.27 Determination of time, costs and specific cost relative to transport performance for railway route 2 (calculation for 1 TEU transported)

Segment	Distance (km)	Speed (km/h)	Time (hours)	Transport performance (TEU·km)	Cost (euro)	Operating cost (euro) π_{ij}	Total cost (euro)
1. Constanța South – București North	225	16	14,06	225	562,50	56,25	618,75
2. București North – Roșiori North	101	16	6,31	101	252,50	25,25	277,75
3. Roșiori Nord – Craiova	118	16	7,38	118	295,00	29,50	324,50
4. Craiova – Drobeta Turnu Severin	109	16	6,81	109	272,50	27,25	299,75
5. Drobeta Turnu Severin – Caransebeș	132	16	8,25	132	330,00	33,00	363,00
6. Caransebeș – Timișoara	95	16	5,94	95	237,50	23,75	261,25
7. Timișoara – Arad	54	16	3,38	54	135,00	13,50	148,50
8. Arad – Curtici	46	16	2,88	46	115,00	11,50	126,50
Total Route 2	880	–	55,00	880	2200,0	220,00	2420,00

(Source: Author)

Within the multimodal transport route between the DP World Constanța terminal and the Curtici terminal, the railway component ensures the transfer of container flows over medium and long distances, while transport performance represents the reference parameter for quantifying the volume of transport carried out on the railway network.

Risk reduction mechanisms for the railway component are analyzed through the identification of rerouting alternatives on different segments of the network, accompanied by the redistribution of container flows to routes with available capacity. The evaluation of these solutions is carried out by analyzing their ability to sustain the same transport performance of the railway route under conditions of traffic restrictions or operational disruptions, without interrupting the railway transfer to the Curtici terminal.

Modeling of blockages and use of alternative railway routes:

Following the determination of distances, times and costs associated with the analyzed railway components, the structure of each route is formally represented using graph theory and a multi-flow model (D'Ariano & Hemelrijk, 2006), in order to describe the connectivity relationships between operational points and to analyze the possibilities for maintaining transport continuity under conditions of railway traffic disruptions.

This approach involves a dynamic analysis of risks, focusing on the mechanisms of their generation and propagation within the network, without assuming prior knowledge of their occurrence. In the event of the blockage of an edge, rerouting is performed by selecting an alternative sequence of edges existing in the graph, for which the parameters of distance, time and cost are already defined.

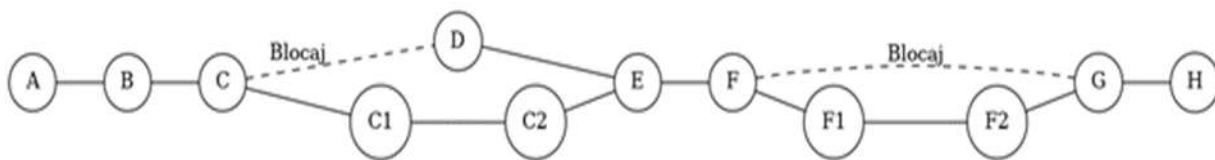


Figure 4.14 Graph of route 1 with alternative paths in case of edge blockages

(Source: Author)

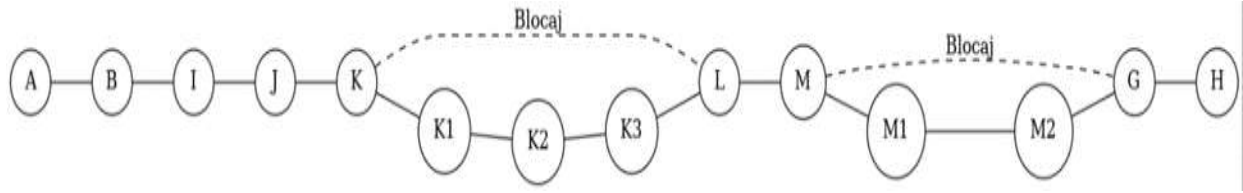


Figure 4.15 Graph of route 2 with alternative paths in case of edge blockages
(Source: Author)

In order to evaluate risk mitigation solutions associated with the blockage of railway segments within the analyzed multimodal transport route, the connectivity structure of the railway component is described using adjacency and time matrices. These instruments allow the formulation of infrastructure availability states and the translation of vulnerabilities and operational deficiencies into changes in network connectivity and travel times.

Adjacency matrix for route 1: The adjacency matrix $V = [v_{ij}]$ describes the connectivity relationships between the operational points of route 1.

If there is a direct connection between two stations i and j , the element v_{ij} takes the value 1; otherwise, it is 0 (absence of connection or blockage of the corresponding segment). In addition to the nodes on the main route (A, B, C, ... H), the matrix also includes additional nodes corresponding to deviation alternatives introduced in blockage scenarios. Nodes C_1 and C_2 represent operational points associated with the branching in the Sibiu – Vințu de Jos area, while F_1 and F_2 are intermediate points on the deviation towards Deva – Timișoara.

Time matrix T for route 1: The travel time matrix $T_{Route\ 1} = T_{ij}$ enables the translation of railway infrastructure vulnerabilities and deficiencies into measurable indicators at the route level. Assigning each railway segment $i \rightarrow j$ travel time T_{ij} reflects the actual operating conditions, including capacity limitations, speed restrictions, and dependence on freight train time windows.

Delay calculation in case of blockage on route 1 (Brașov – Sighișoara segment): In the case of the unavailability of the Brașov–Sighișoara railway segment, operational continuity of the railway component is maintained by activating the alternative route Brașov–Sibiu–Vințu de Jos–Teiuș.

The blockage is associated with operational deficiencies generated by modernization works and infrastructure restrictions, amplified by environmental vulnerabilities, namely landslides and severe weather conditions, leading to the materialization of the operational risk of loss of traffic continuity on the analyzed segment.

The alternative route has a length of 246 km and results in a travel time of 15.38 hours, compared to 129 km and 8.06 hours on the initial route, leading to a total delay of $\Delta T = 7,32$ ore hours, corresponding to an increase in transport duration of approximately 90.82%. This result highlights the direct impact of the blockage on the continuity of the railway flow and justifies the introduction of the alternative route as a risk mitigation measure for reducing the operational risk effect.

4.2.3.3 Determination of risk scores using the SAW method for the railway component

The comparative evaluation of alternative railway routes is carried out by applying the SAW method, using exclusively the two railway routes previously defined and analyzed.

The method is used as a decision-support synthesis tool, with the role of integrating, into a single value, the levels of risk exposure corresponding to each route, in relation to the objective of risk reduction in multimodal transport.

Table 4.29 Determination of normalized risk values for each risk criterion and railway route

Criterion (sub-risk)	Route	X_{ij} (%)	$X_{max.}$	$X_{min.}$	ΔX	r_{ij}
Operational (F3: safety management deficiencies)	X ₁	50	50	45	5	0,00
	X ₂	45	50	45	5	1,00
Technological (F2: rolling stock failures)	X ₁	45	45	40	5	0,00
	X ₂	40	45	40	5	1,00
Technical (F2.1: braking system failures)	X ₁	35	35	30	5	0,00
	X ₂	30	35	30	5	1,00
Human (F4: operational errors)	X ₁	55	55	50	5	0,00
	X ₂	50	55	50	5	1,00
Environmental (F5: adverse weather conditions)	X ₁	30	30	28	2	0,00
	X ₂	28	30	28	2	1,00

(Source: Author)

The total score V_i for each railway route is determined according to relation (4.30), resulting in $V_{X1} = 0$ and $V_{X2} = 1$.

Interpretation of results: The obtained results indicate clear differences between the two railway routes in terms of cumulative risk exposure. Route X₂ records higher normalized values for all analyzed criteria, reflecting a lower exposure to operational, technical, technological, human, and environmental vulnerabilities and deficiencies. Route X₁ is characterized by higher levels of risk exposure, mainly associated with infrastructure deficiencies, a higher frequency of technical failures, and increased vulnerability to operational disruptions.

Table 4.30 Vulnerabilities, deficiencies and risks across the components of the Constanța South – Curtici route

Analyzed elements	DP World Terminal	Road Component	Rail Component	Curtici Terminal
Vulnerabilities	- Concentration of port handling completion within a short time interval (units simultaneously available for dispatch); - Variability of quay unloading rate.	- Variability of travel times on the road segment; - Local traffic disturbances along the route; - Dependence on the technical condition of the road vehicle in operation; - Limitation in adjusting arrival time.	- Punctuality of the dispatch time window set by the timetable; - Capacity limitations for shunting and train formation; - High shunting times during train formation; - High occupancy duration of railway lines allocated.	- Sensitivity of train formation process to road arrivals; - Limited temporary storage capacity; - Limited occupancy capacity of railway lines allocated for train shunting.
Deficiencies	- Time gap between completion of port handling and initiation of inland transport (D.1); - Deviation of gate-out time from planned time (D.1); - Non-uniform utilization of terminal gate outflow (D.1).	- Deviation of actual arrival time at Curtici from the terminal reception window (D.1); - Non-recoverable delays on the road segment (D.1); - Temporary technical unavailability of the road vehicle during transit (D.3).	- Loss of scheduled dispatch slot due to incomplete train formation/loading (D.1); - Increase in shunting times and prolonged occupation of formation lines (D.1); - Non-uniform utilization of line occupancy/release capacity (D.1).	- Accumulation of intermodal transport units in transfer and temporary storage area (D.1); - Exceeding maximum allowable occupation times (D.1); - Increased dwell times beyond operational limits (D.1).

Specific risks	• R.I.1: temporal mismatch between port handling and inland dispatch; • R.I.2: accumulation of intermodal units in yard/temporary storage; • R.I.3: delay propagation to road and rail segments; • R.I.4: prolonged occupation of transfer resources; • R.R.1: exceeding scheduled road pickup window.	• R.R.1: variability of travel times and exceeding Curtici reception window; • R.R.2: route interruption due to vehicle technical failure; • R.R.3: coordination system malfunctions; • R.R.8: temporary restrictions due to weather; • R.I.3: transfer of delays to rail dispatch; • R.I.3: traffic disturbances due to works / incidents.	• R.F.1: loss of scheduled rail dispatch; • R.F.2: rolling stock unavailability or locomotive failure; • R.F.3: signaling/control system failures; • R.F.8: weather-related restrictions; • R.I.1: mismatch between road arrival and rail slot; • R.I.2: accumulation in transfer/storage.	• R.I.1: mismatch between road arrivals and train formation; • R.I.2: accumulation in storage; • R.I.3: delay transmission to rail dispatch; • R.F.1: loss of dispatch slot; • R.F.1: prolonged line occupation; • R.F.2: rolling stock unavailability; • R.R.1: exceeding reception window.
Risk mitigation mechanisms	• Allocation of road departures correlated with destination and rail connection; • Uniform distribution of gate outflow; • Synchronization of handling completion with inland transport.	• Departure planning relative to terminal reception windows; • Rerouting under restrictions; • Preventive maintenance; • Time buffers at departure.	• Operational time buffers; • Flexible train formation sequence; • Line allocation based on transfer sequence; • Sizing traction resources according to flow.	• Transfer organization based on occupancy times; • Limiting occupation times; • Introducing buffer intervals.
Effect on capacity	• Reduction of sudden inflow variations; • Limitation of initial delays.	• Stabilization of inflow at Curtici; • Reduced probability of exceeding capacity.	• Increased ability to absorb deviations; • Reduced accumulation and dwell.	• Maintaining effective transfer capacity; • Avoiding accumulation and increased dwell.

(Source: Author)

4.2.4 Risk reduction through the improvement of multimodal flows including the inland waterway transport component

Within this subchapter, multimodal freight transport flows that integrate the inland waterway transport component on the Constanța Sud – Giurgiu route are analyzed, as well as the corresponding road and rail connections. The transport network between the DP World Constanța Sud terminal and the Curtici terminal is formalized by representing it as a directed graph, and the evaluation of transport configurations is carried out by defining an adjacency matrix and a time matrix, used within an objective function for minimizing the total duration.

The network nodes and the corresponding distances of the route segments are presented in table 4.31.

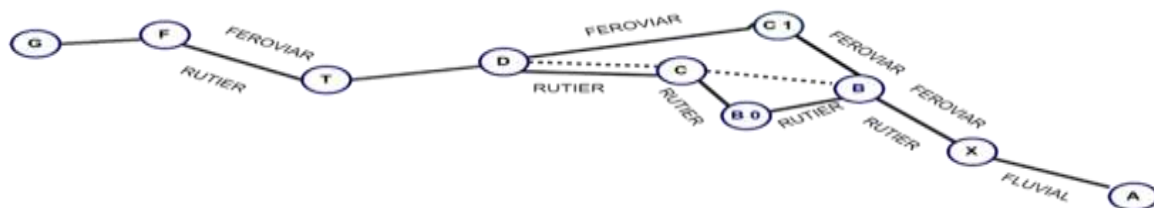


Figure 4.16 Route 1 with blockages (nodes B – C) and alternative routes

(Source: Author)

Table 4.31 Distances for each transport segment of the route between Constanța Sud Port and the Curtici terminal:

Segment	Distance (km)
Constanța Sud Port – Giurgiu Port (inland waterway) A→X	355 km
Giurgiu Port – Bucharest (road) X→B	63 km
Bucharest – Pitești (road) B→C	110 km
Pitești – Sibiu (road) C→D	172 km
Sibiu – Timișoara (road) D→T	233 km
Timișoara – Arad (road) T→F	87 km
Arad – Curtici (road) F→G	60 km
Total road distance / route	725 km / 1080 km
Segment	Distanță (km)
Giurgiu – Bucharest (rail) X→B	65 km
Bucharest – Pitești (rail) B→C	112 km
Pitești – Sibiu (rail) C→D	175 km
Sibiu – Timișoara (rail) D→T	238 km
Timișoara – Arad (rail) T→F	118 km
Arad – Curtici (rail) F→G	45 km
Total rail distance / route	753 km / 1108 km

Source: Adapted from Ministry of Transport (2022), CNAIR (2022) and CFR Marfă (2021).

Under the assumption of a complete graph representation of the network, in which each arc (i, j) is associated with a duration $t_{i,j}$, the Travelling Salesman Problem (TSP) model (Ding, 2020) is used. The purpose of the TSP modeling is to determine an optimal sequence for traversing the nodes of the network such that the total travel duration along the route is minimized, with each node being visited exactly once.

Binary decision variables $x_{i,j}$ are introduced, defined as follows:

$$x_{i,j} = \begin{cases} 1, & \text{if arc } (i, j) \text{ is included in the tour} \\ 0, & \text{otherwise} \end{cases} \quad \forall (i, j) \in A \quad (4.54)$$

$$\text{Parameterization of travel times on arcs: } t_{i,j} = \frac{d_{i,j}}{v_m} \quad \forall (i, j) \in A \text{ belonging to mode } m. \quad (4.55)$$

The objective function of the model selects the combination of segments for which the sum of durations is minimized, under the condition that each node has exactly one incoming and:

$$\min Z = \sum_{(i,j) \in A} t_{i,j} x_{i,j} \quad (4.56)$$

The model is subject to the following structural constraints, which ensure the existence of a unique route from node A (Constanța Sud Port) to node G (Curtici), with each intermediate node being traversed exactly once:

- For the origin node A:

$$\sum_{j:(A,j) \in A} x_{Aj} = 1, \quad \sum_{i:(i,A) \in A} x_{iA} = 0 \quad (4.57)$$

Relation (4.57) indicates that there is a single departure from node A and no return to node A.

- For the destination node G:

$$\sum_{i:(i,G) \in A} x_{iG} = 1, \quad \sum_{j:(G,j) \in A} x_{Gj} = 0 \quad (4.58)$$

Relation (4.58) indicates that there is a single arrival at node G and no departure from node G.

Modeling of blockages on route segments: For the analysis of blockages occurring on road segments along major routes, considering their dynamic occurrence, the formalization based on

graph theory is used, by representing the network as a directed graph. The determination of rerouting with minimum delay is carried out by defining an adjacency matrix and a time matrix, constructed on the same arc selection structure used in TSP-type modeling (**adapted after Ding, 2020**).

Blockage on the Bucharest – Pitești road segment: The blockage modeling is performed by redefining the time on the affected arc as $t_{Blockaj\ BC} = \infty$ and by recalculating the objective function, starting from the general relation for minimizing the total duration (4.56) $\min Z_T = \sum t_{ij}x_{ij}$, which leads to the particularized form:

$$\min Z_{T\ Blockaj} = \infty \times x_{BC} + t_{BB0} \times x_{BB0} + t_{B0C} \times x_{B0C} \quad (4.76)$$

The deactivation of the blocked arc $x_{BC} = 0$ results, along with the selection of the alternative route $x_{BB0} = 1$, with the associated duration $Z_{T\ Blockaj} = 2,21$ hours, a value that results directly from the application of relation (4.70).

Cost analysis for the inland waterway–road and inland waterway–rail routes along the route between Constanța Sud Port and the Curtici terminal:

Further, the total transport cost is determined for each route, based on the unit costs specific to each transport mode and the corresponding distances of the selected segments. The total cost of a route is expressed as the sum of the costs on the arcs, to which the transshipment cost activated at node X is added (**Li et al., 2023**):

$$C_T = \sum_{(i,j) \in A} \alpha_{m(i,j)} d_{i,j} x_{i,j} + \beta_x z_x \quad (4.94)$$

where:

- $\alpha_{m(i,j)}$ = unit cost for the transport mode of arc (i, j) (€/TEU · km);
- $d_{i,j}$ = distance of each route segment (km);
- β_x = transshipment cost for 1 TEU at node X (€/TEU);
- $z_x \in \{0, 1\}$ = activation of transshipment at node X, defined by the following relation:

$$z_x = \sum_{j:(X,j) \in A} x_{Xj}, \quad z_x \in \{0, 1\} \quad (4.95)$$

where, if the route departs from node X on the inland component, the transshipment is activated only once.

It follows that the total values presented in table 4.32 represent the direct numerical application of relation (4.94) for predefined variants, with $x_{ij} \in \{0, 1\}$ and $z_x = 1$:

Table 4.32 Determination of costs per segment for inland waterway–road and inland waterway–rail routes (€/TEU)

Route	Segment	α [€/TEU·km]	d [km]	β [€/TEU]	Cost segment [€/TEU]
Route 1 (Inland waterway + Road)	Inland waterway Constanța – Giurgiu	0,08	355	–	28,4
Route 1 (Inland waterway + Road)	Transshipment at Giurgiu port	–	–	80	80,0
Route 1 (Inland waterway + Road)	Road Giurgiu – Curtici	0,12	725	–	87,0
Total			1080		$C_T = 195,4$
Route 1 (Inland waterway + Rail)	Inland waterway Constanța – Giurgiu	0,08	355	–	28,4

Route	Segment	α [€/TEU·km]	d [km]	β [€/TEU]	Cost segment [€/TEU]
Route 1 (Inland waterway + Rail)	Transshipment at Giurgiu port	–	–	80	80,0
Route 1 (Inland waterway + Rail)	Rail Giurgiu – Curtici	0,05	753	–	37,65
Total			1108		$C_T = 146,05$

(Source: Author)

Based on the results obtained in table 4.32, the indicators of the two route alternatives are determined, as presented in table 4.33:

Table 4.33 Comparative synthesis of the inland waterway–road and inland waterway–rail routes between Constanța Sud and Curtici

Route	Distance (km)	Time (hours)	Cost (€/TEU)	Transport performance (TEU·km)
Inland waterway–road route	355 + 725	22,19 + 10,36	28,4 + 80 + 87,0	
Total	1080 km	32,55 hours	$C_T = 195,4$ €/TEU	1080 (TEU·km)
Inland waterway–rail route	355 + 753	22,19 + 9,41	28,4 + 80 + 37,65	
Total	1108 km	31,6 hours	$C_T = 146,05$ €/TEU	1108 (TEU·km)

(Source: Author)

Note: The transport performance (W) was determined as the product of the transported quantity (Q) and the total distance traveled (D), according to the relation $W = Q \times D$, for $Q = 1$ TEU.

Based on the values determined in table 4.32 and summarized in table 4.33, it results that the inland waterway–rail route alternative presents a lower total transport cost compared to the inland waterway–road alternative. The total transport cost for 1 TEU on the inland waterway–rail alternative is 146.05 €/TEU, compared to 195.4 €/TEU for the inland waterway–road alternative, which leads to a difference of 49.35 €/TEU in favor of using rail transport on the inland segment.

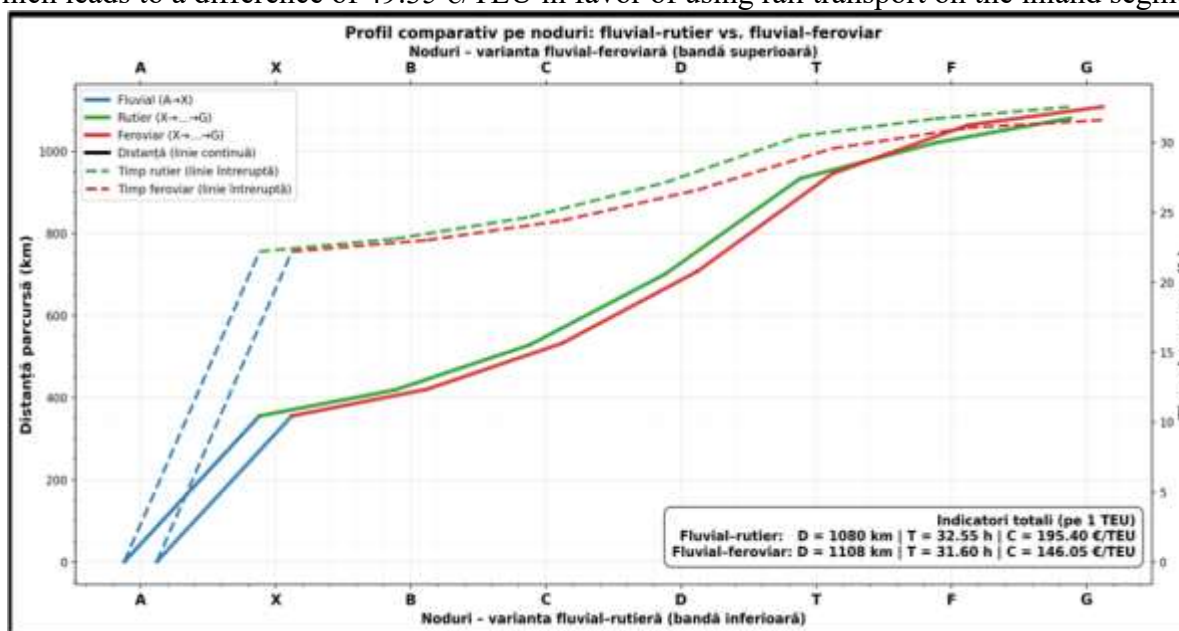


Figure 4.17 Comparative representation of the inland waterway–road and inland waterway–rail routes between Constanța Sud and Curtici

(Source: Author)

Table 4.34 *Risks associated with the multimodal transport route Constanța Sud – Curtici and technical mechanisms for their mitigation*

Risk code / Risk type	Risk mitigation measures	Operational implementation methods
R.M.1 – multimodal operational risk: loss of continuity of the multimodal transport flow due to mismatch of capacities between inland waterway, road and rail components	• redistribution of transport flows through activation of inland ports Cernavodă, Medgidia and Drobeta Turnu Severin; • use of alternative TEN-T network routes; • alignment of modal transport capacities.	• coordination of flows by logistics operators and infrastructure managers; • scheduling multimodal transport in operating time windows; • use of logistics planning platforms.
R.M.2 – multimodal technological risk: malfunctions of coordination and information exchange systems between transport modes	• implementation of electronic data exchange systems; • integrated multimodal monitoring systems; • use of transport management systems.	• operation of IT systems by logistics operators; • use of container transport monitoring platforms; • integration of logistics management.
R.M.3 – multimodal environmental risk: reduction of transport capacity due to hydrological variations of the Danube	• dredging works to maintain navigable depth; • redistribution to alternative inland ports; • adaptation of convoy capacity.	• execution of dredging by river authorities; • navigation coordination via dispatch centers; • convoy reorganization depending on water level.
R.I.1 – intermodal operational risk (Giurgiu terminal): operational blockage in transshipment area	• reorganization of container handling flows; • scheduling transshipment operations; • increasing handling capacity.	• coordination by terminal operator; • planning via terminal dispatch; • mobilization of additional equipment.
R.I.2 – intermodal technical risk (Giurgiu terminal): failure of handling equipment	• preventive maintenance; • backup equipment usage; • reliability monitoring.	• maintenance programs; • technical interventions; • monitoring failure-free time and repair duration.
R.I.3 – intermodal operational risk: accumulation of units in storage area	• expansion of storage areas; • redistribution to alternative ports; • increased evacuation rate.	• reorganization of storage areas; • coordination of road and rail transport; • use of alternative terminals.
R.R.1 – road operational risk (unimodal): traffic congestion on critical sections	• diversion of freight traffic; • dedicated freight time windows.	• routing decisions by CNAIR; • temporary signaling; • monitoring via traffic management centers.
R.F.1 – rail operational risk (unimodal): interruption of freight train circulation	• rerouting trains; • timetable reorganization; • use of overtaking lines.	• rescheduling by CFR Infrastructure; • timetable updates; • coordination via traffic control centers.
R.Fl.1 – inland waterway climatic risk (unimodal): reduction of navigable depth	• dredging works; • modernization of locks; • redistribution of flows.	• dredging by river authorities; • lock modernization programs; • navigation coordination.

(Source: Author)

CHAPTER 5

CONCLUSIONS

5.1 Final considerations and results

Chapter 1 establishes the research framework by defining the objectives, hypotheses, data set, and evaluation criteria, as well as by synthesizing the methods used for the analysis and mitigation of risks in multimodal transport.

Chapter 2 presents the theoretical basis through the definition and classification of risks (operational, technical, technological, human) in relation to infrastructural vulnerabilities, operational constraints, and external conditions, as well as the regulatory framework used in the analysis.

Chapter 3 addresses risk assessment in relation to vulnerabilities and deficiencies, establishing the sources of risk and the rules for quantifying exposure. The weighted average is used for aggregating values across components (maritime, rail, road), the scoring model is used for comparing exposure indicators, and DFT is applied for modeling a collision event, by defining PAND, FDEP, and AND gates and the associated probabilities.

Chapter 4 applies the methodology to case studies, following the logic of the transport chain between the DP World Constanța Sud terminal and the Curtici terminal, using the results of one stage as input data for the subsequent stage.

The DP World terminal is analyzed as a transfer interface, through the integration of multicriteria evaluation with simulation (Arena), and the results are used to formulate measures regarding the reduction of recovery times, the improvement of equipment allocation, and the introduction of redundancy for critical equipment. Based on simulation, the INCI and BOR methods are applied for evaluating resource utilization and sizing operational reserves.

The transport network is modeled using adjacency, distance, and time matrices, and route configurations are analyzed through the TSP model for determining sequences of segments with reduced duration and cost.

The SAW evaluation is applied for the road and rail components, through inverse min–max normalization and weighted aggregation, resulting in the ranking of route alternatives according to risk exposure.

The mitigation solutions target the temporal correlation of flows: scheduling road departures in relation to terminal capacities, synchronizing arrivals with the reception windows in Curtici, introducing time buffers in rail timetables, and limiting the occupation times of lines and equipment, with effects on reducing dwell times and discontinuities at the road–rail interface.

5.2 Original contributions

In Chapter 1, a synthesis table structured by domains, risk types, and validated methods is developed, used as a methodological selection tool. Based on this, evaluation methods (scoring, DFT, multicriteria evaluation, discrete simulation) are selected and adapted, resulting in a unified methodological framework, with defined risk criteria and replicable processing procedures.

In Chapter 2, parameters and evaluation procedures are formalized through the coherent definition of risk categories (operational, technical, technological, human, climatic) and the establishment of a normalization and weighting procedure, which allows comparability between transport modes and integration of results in subsequent research.

Chapter 3 develops a unified methodological basis by correlating quantitative assessment with dynamic logical modeling. The results of the scoring method are used as input parameters in the DFT model, allowing the identification of risk exposure levels and critical sequences of events.

In Chapter 4, the sequential application of methods on correlated case studies is carried out, in which the results of one stage are used as input data for the next stage. The research is structured along the transport chain between DP World Constanța Sud and Curtici, treating the port interface and the propagation of risks across inland components in an integrated manner. For the DP World Constanța Sud terminal, the integration of risk assessment with discrete simulation is achieved, by translating the vulnerability–deficiency–risk relationship into operational indicators (waiting times, resource utilization, capacity). The Arena Rockwell simulation model is used to quantify the effects of operational, technical, and technological risks on waiting times, resource utilization, and handling capacity, and the results are used through the INCI and BOR indicators to support measures aimed at reducing recovery times and ensuring the continuity of transshipment operations in the terminal.

For the Constanța Sud – Curtici route, the road and rail components are evaluated using the SAW method, based on the defined risk criteria, and measures are formulated to limit the increase in travel times, capacity losses, and discontinuities at the road–rail interface. For configurations that include the inland waterway component, the TSP model is used to determine the sequence of nodes along the route and to compare route alternatives on the Constanța Sud – Giurgiu – Curtici relation.

The research results are disseminated through publications in international journals and conferences, confirming the methodological relevance and applicability in multimodal freight transport.

The published articles reflect the main directions of the thesis and are presented below:

- “Modelling solutions for cost optimization in multimodal transports considering the operational risk variables”, Popa et al. (2025), *Transport*, Vilnius Gediminas Technical University (WoS, SCIE, Q2), referenced in the thesis bibliography at number 134, addresses risk reduction in multimodal transport through an integrated methodology of probabilistic evaluation of operational and financial risks, combined with mathematical cost modeling;
- “Assessing the influence of equipment reliability over the activity inside maritime container terminals through discrete-event simulation”, Roșca et al. (2025), *Systems* (WoS, Q1), referenced at number 147, analyzes the impact of equipment reliability through discrete-event simulation;
- “A Hybrid Fault Tree – Fuzzy logic model for risk analysis in multimodal freight transport”, Popa et al. (2025), *Systems* (MDPI, WoS, Q2), referenced at number 138, addresses risks through a Fault Tree–Fuzzy Logic integrated model;
- “Risk-based optimization of multimodal oil product operations through simulation and workflow modeling”, Popa et al. (2025), *Logistics* (MDPI, WoS, Q2), referenced at number 139, provides a quantitative evaluation of operational risks;
- “Case study of risk assessment in maritime operations applying the fault tree analysis method”, Ștefanov et al. (2025), *Transport* (WoS, Q2), referenced at number 164, applies the FTA method for maritime operations;
- “Multimodal livestock operations analysis using the business process modelling. Case study of Romanian Black Sea ports”, Popa et al. (2025), *Economies* (MDPI, WoS, Q2), referenced at number 133;
- “Environmental risk assessment in the background of armed conflict in the Black Sea area”, Ștefanov & Rauca (2023), *TransNav* (WoS, Q3), referenced at number 165;

- “Study of the risk analysis associated with multimodal maritime transport”, Ștefanov et al. (2022), *Technium* (BDI), referenced at number 166;
- “Considerations for risk mitigation in the international carriage of goods by sea”, Ștefanov & Apetroaei (2021), *SEA-CONF* (BDI), referenced at number 164;
- “Multimodal transport – Risk and environment”, Ștefanov et al. (2021), *Technium* (BDI), referenced at number 168.

5.3 Limitations and directions for future research

The research is conducted on the multimodal transport route Constanța Sud Port – Curtici Terminal and on the transshipment operations within the DP World Constanța Sud terminal. Under these conditions, the results are valid for the analyzed configuration and are not directly transferable to other routes, where infrastructure, regulations, and operating conditions may differ.

The scoring-based evaluation method and the Dynamic Fault Tree (DFT) model are applied based on statistical and technical data from validated sources. The structure of relationships between events is constructed through assumptions regarding the independence or logical sequence of risks, which conditions the level of model accuracy in situations where these assumptions are not respected in operation.

The simulations performed in the Arena platform are developed based on defined data sets and scenarios, without including major unplanned variations, such as extreme weather conditions, infrastructure failures, or simultaneous blockages at multiple critical points of the system.

The models are calibrated for the current infrastructure and regulatory conditions in Romania, and legislative, technological, or operational changes require updating the parameters and assumptions used. Based on this, future development directions aim at extending the methodological framework through the integration of international data sets for comparing risk management practices, the use of digital technologies for monitoring and control of operations, and the development of predictive models for anticipating traffic variations and disruptions, with validation under real operating conditions.

BIBLIOGRAPHY

- [1] Abdulahi E., Luo F., (2020), "*Literature review of multimodal transportation risk management system*", International Journal of Academic Multidisciplinary Research, 4(11), 119–127;
- [2] ABPmer, (2019), "*Berth Occupancy Study: Port of London*", Section 4.1, pp. 10–11;
- [3] Acebes F., González-Varona J. M., López-Paredes A., Pajares J., (2024), "*Beyond probability-impact matrices in project risk management: A quantitative methodology for risk prioritisation*", Humanities and Social Sciences Communications, 11(670), pg. 3-5;
- [4] Administrația Porturilor Maritime Constanța, (2023), Raport anual de activitate 2023, Constanța, <https://www.portofconstantza.com>
- [5] Allianz Global Corporate & Specialty, (2023), "*Safety and Shipping Review 2023*", <https://commercial.allianz.com/content/dam/onemarketing/commercial/commercial/reports/AGCS-Safety-Shipping-Review-2023.pdf>
- [6] Ambrosino D., Sciomachen A., (2018), "*Shipping liner company stowage plans: an optimization approach*", EWGT/EURO -2016. AISC, vol. 572, pp. 405–420. Springer;
- [7] American Bureau of Shipping, (2003), "*Guide for Risk Evaluations for the Classification of Marine-Related Facilities*", Houston, TX: American Bureau of Shipping, <https://ww2.eagle.org>
- [8] APM Terminals, (2024), "*Poti Sea Port container terminal specifications*", <https://www.apmterminals.com/poti>
- [9] Autoritatea Navală Română, (2024), "*Raport privind evenimentele de navigație aferent anului 2023*", <https://portal.rna.ro/despre-noi/rapoarte-%C8%99i-studii>
- [10] Autoritatea Națională a Vămirilor, (2023), "*Lista amenințărilor, riscurilor și soluțiilor posibile*", https://www.customs.ro/assets/pdf/gabim/Lista_amenintari_riscuri_si_solutii_posibile_vf.pdf
- [11] Banca Mondială - World Bank Water Data, (2019), "*World Bank Water Data 2019*", Washington, DC: World Bank, <https://databank.worldbank.org/source/water>
- [12] Bartle J. R., Lutte R. K., Leuenberger D. Z., (2021), "*Sustainability and Air Freight Transportation: Lessons from the Global Pandemic*", Sustainability, 13(7), 3738. <https://doi.org/10.3390/su13073738>
- [13] Banca Națională a României, (2024), <https://www.cursbnr.ro/arhiva-curs-bnr-2024-04-05>
- [14] Bilato G. A., Rocco C. D., Azevedo A. T., (2022), "*Planning routes in road freight minimizing logistical costs and accident risks*", <https://doi.org/10.48550/arXiv.2208.09728>
- [15] Bínová H., Heralová D., (2017), "*Risks in transportation of items in multimodal transport*", , pp. 229–242, <https://www.researchgate.net/publication/316281124>
- [16] Bo L., Xi M., Hongman L., Deyang C., Hongbo D., (2023), "*Challenges of decarbonizing global maritime container shipping toward net-zero emissions*", NPJ Ocean Sustainability, 2, 11. <https://doi.org/10.1038/s44183-023-00018-6>
- [17] Bogalecka M., (2024), "*Collision and Contact – Analysis of accidents at sea*", TransNav, The International Journal on Marine Navigation and Safety of Sea Transportation, 18(1), 75-85;
- [18] Bromiley P., McShane M., Nair A., Rustambekov E., (2015), "*Enterprise risk management: review, critique, and research directions*", Long Range Planning;
- [19] CFR, (2024), "*Raport de activitate Compania Națională de Căi Ferate pentru anul 2023*", pag. 33-35;
- [20] CFR, (2021), "*Strategia de dezvoltare a infrastructurii feroviare 2021 - 2025, Anexa 10*", Compania Națională de Căi Ferate CFR SA., pag. 38 - 40;
- [21] Chang C.H., Xu J., Zaili Y., (2019), "*Selection of effective risk mitigation strategies In container shipping operations*", Maritime Business Review, Vol. 4. No. 4, pp. 413-431;
- [22] Chang T., Lee Y., Park J., (2021), "*Discrete event simulation for port terminal operations*", Journal of Logistics Research, 10(2), 45-63. <https://doi.org/10.1016/j.logres.2021.04.005>
- [23] Charlebois P., Griffiths W., (2024), "*FSO SAFER oil spill risk Addressing the threat of a deteriorating super tanker*", International Oil Spill Conference Proceedings, 2024 (1), 176. <https://doi.org/10.7901/2169-3358-2024.1.176>

- [24] Chen X., Yu M., Lin Y., (2023), *"Resilience improvement and risk management of multimodal transport logistics in the post-covid-19 era: The case of tir-based sea-road multimodal transport logistics"*, Sustainability, 15(7), 6041, <https://doi.org/10.3390/su15076041>
- [25] Chen Y., Zhang L., (2023), *"Risk assessment of marine accidents with Fuzzy Bayesian Networks and causal analysis"*, Ocean & Coastal Management, 232;
- [26] Chowdhury M. N., Shafi S., Arzaman A. F. M., Teoh B. A., (2024), *"Navigating human factors in maritime safety: A review of risks and improvements in engine rooms of ocean-going vessels"*, International Journal of Safety and Security Engineering, 14(1), 1-14. <https://doi.org/10.18280/ijssse.140101>
- [27] Christidis P., Ibáñez Rivas J. N., (2012), *"Measuring Road Congestion"*, Luxembourg: Publications Office of the European Union, <https://doi.org/10.2791/15282>
- [28] Christopher M., (2015), *"Logistics & Supply Chain Management: Creating value-adding networks"*, FT Press, 3rd Edition;
- [29] Cieśla M., (2018), *"Multimodal Transport Risk Assessment with Risk Mapping"*, ResearchGate;
- [30] Comisia Europeană, (2023), *"Transport in the European Union: Current Trends and Issues. Directorate-General for Mobility and Transport"*, <https://transport.ec.europa.eu>
- [31] Comisia Europeană, (2024), *"Road Safety Report 2024: Progress and Challenges"*, Brussels: European Commission, https://ec.europa.eu/transport/road_safety
- [32] Comitetul Național pentru Supravegherea și Dezvoltarea Feroviară (CNSDF), (2021), *"Viteza comercială în transportul multimodal: Analiză și statistici"*, <https://www.cnsdf.ro/rapoarte/viteza-comerciala-transport-multimodal-2021.pdf>
- [33] Compania Națională de Administrare a Infrastructurii Rutiere, (2024), CNAIR, *"Raport de evaluare privind activitatea directorilor"*, <https://www.mt.ro/web14/documente/interes-public/rapoarte/2024/Raport%20evaluare%20activitate%20directori%20CNAIR.pdf>
- [34] Consiliul Concurenței – CNSDF & CSDN, (2025), *"Transportul multimodal de mărfuri în România – potențial ridicat, utilizare redusă"*, Economica.net., https://www.economica.net/transportul-multimodal-de-marfuri-in-romania-are-un-potential-ridicat-dar-in-prezent-utilizarea-este-redusa-studiu-consiliul-concurenteiei_831031.html
- [35] Cruz C.O., Marques R.C., (2012), *"Risk-sharing in seaport terminal concessions"*, Transport Reviews Journal, Vol. 32, No. 4, pp. 455-471;
- [36] Curtea de Conturi Europeană, (2023), *"Raportul special 08/2023: Transportul intermodal de marfă"*, Luxembourg: Oficiul pentru Publicații al Uniunii Europene;
- [37] D'Ariano A., Hemelrijk R., (2006), *"Designing a Multi-Agent System for Cooperative Train Dispatching"*, IFAC Proceedings, <https://pdf.sciencedirectassets.com/314898/1-s2.0-S1474667015X60800/1-s2.0-S1474667015359188/main.pdf>
- [38] Derse O., Göçmen P. E., (2019), *"Risk assessment in multimodal transportation: a case study"*, Bitlis Eren Üniversitesi Fen Bilimleri Dergisi, 8(2), 629-642. <https://dergipark.org.tr>
- [39] Det Norske Veritas, (2022), DNV, *"Maritime Safety Report 2012-2022"*, <https://www.dnv.com/maritime/publications/maritime-safety-report-2012-2022-download/>
- [40] Ding L., (2020), *"Multimodal transport information sharing platform with mixed time window constraints based on big data"*, IEEE Access, 8, 36388–36402. <https://doi.org/10.1109/ACCESS.2020.2975295>
- [41] Dini N., Yaghoubi S., Bahrami H., (2024), *"Route selection of periodic multimodal transport for logistics company: An optimisation approach"*, Transportation Research Procedia, 74, 259-274, <https://www.researchgate.net/publication/379662047>
- [42] Disk.com, (2023), *"Logistics automation trends: Opportunities and uncertainties in 2024"*, [Disk.com/Logistics automation trends: opportunities and uncertainties in 2024/2023](https://www.disk.com/logistics-automation-trends-opportunities-and-uncertainties-in-2024/2023)
- [43] DP World, (2020), *"DP WORLD Constanța - Terminal Presentation"*, DP World Constanța, <https://www.dpworld.com/constantat>
- [44] DP World, (2023), *"Annual report for 2022"*, <https://www.dpworld.com/constantat>
- [45] Dugan J. B., Bavuso S. J., Boyd M. A., (1992), *"Dynamic fault-tree models for fault-tolerant computer systems"*, IEEE Transactions on Reliability, 41(3), 363–377, <https://doi.org/10.1109/24.159800>

- [46] Economedia, (2024), "*CNAIR ratează legătura „cap-coadă” Craiova – București pe drum de mare viteză și în 2024: ultimii 12 kilometri ai Drumului Expres Craiova – Pitești, abia în prima parte din 2025*", Economedia, <https://economedia.ro/cnair-rateaza-legatura-cap-coada-craiova-bucuresti-pe-drum-de-mare-viteza-si-in-2024-in-ciuda-promisiunilor-repetate-ultimii-12-kilometri-ai-drumului-expres-craiova>
- [47] Elsayed A., Elsayed D., (2012), "*Reliability Engineering*", Wiley, Chapter 2;
- [48] European Environment Agency - EEA, (2021), "*European Maritime Transport Environmental Report*", Publications Office of the European Union, <https://www.eea.europa.eu/en/analysis/publications/maritime-transport>
- [49] European Environment Agency, (2023), "*Impact of weather on transport infrastructure in Eurasia*", European Climate Report, p. 45, <https://www.eea.europa.eu>
- [50] European Maritime Safety Agency, (2020), "*Safety analysis of data reported in EMCIP: Analysis on marine casualties and incidents involving container vessels*", <https://www.emsa.europa.eu/publications/item/4276-safety-analysis-of-data-reported-in-emcip-analysis-on-marine-casualties-and-incidents-involving-container-vessels.html>
- [51] European Maritime Safety Agency, (2022), "*Safety analysis of EMCIP data – Navigation accidents – Summary report*", (V1.0), EMSA, <https://www.emsa.europa.eu/accident-investigation-publications/safety-analysis.html​>
- [52] European Maritime Safety Agency, (2023), "*Annual overview of marine casualties and incidents 2023*", <https://www.emsa.europa.eu/publications/item/5052-annual-overview-of-marine-casualties-and-incidents.html​>
- [53] European Parliament and Council of the European Union, (2013), Regulation (EU) No 1315/2013 of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU, Official Journal of the European Union, L 348, 20.12.2013, pp. 1–128;
- [54] European Railway Agency, (2023), "*Annual Report on Railway Safety and Interoperability in the EU 2023*", https://www.era.europa.eu/content/annual-report-railway-safety-and-interoperability-eu-2023_en
- [55] European Road Safety Observatory – ERSO, (2018), "*Annual Accident Report 2018*", <https://www.scirp.org/reference/referencespapers?referenceid=2671159>
- [56] European Union Aviation Safety Agency - EASA, (2021), "*Key risk areas and safety issues*", European Plan for Aviation Safety (EPAS) 2021–2025, (Vol. III), https://www.easa.europa.eu/sites/default/files/dfu/epas_2021_2025_vol_three_final.pdf
- [57] Eurostat, (2023), "*Road Safety Statistics: Accidents and Mortality in Europe 2023*", Luxembourg: Publications Office of the European Union, <https://ec.europa.eu/eurostat>
- [58] Eurostat, (2025), <https://ec.europa.eu/eurostat/web/products-eurostat-news/w/ddn-20250416>
- [59] Ferguson M., Sharmin A., Camur M., Li X., (2025), "*A Review on Intermodal Transportation and Decarbonization: An Operations Research Perspective*", <https://doi.org/10.4>
- [60] Finochenko T. A., Dergacheva L. V., Yaitkov I. V., (2021), "*Risk Management in Transportation Safety System*", Transportation Research Procedia, https://www.researchgate.net/publication/349936710_Risk_Management_in_Transportation_Safety_System
- [61] Flodén J., (2007), "*Modelling Intermodal Freight Transport – The Potential of Intermodal Transport Systems in Sweden*", Doctoral dissertation, University of Gothenburg, <https://gupea.ub.gu.se/handle/2077/4437>
- [62] Fraga-Lamas P., Fernández-Caramés T. M., Castedo L., (2017), "*Towards the Internet of Smart Trains: A Review on Industrial IoT-Connected Railways*", Sensors, 17(6), 1457. <https://doi.org/10.3390/s17061457>
- [63] Freightos, (2023), "*Freight Shipping Rates, Quotes and Costs*", <https://www.freightos.com>
- [64] Galierikova A., Sosedova J., (2018), "*Intermodal transportation of dangerous goods*", 65(3), 8–11, <https://doi.org/10.17818/NM/2018/3.8>
- [65] Garcia M., (2020), "*Enhancing Operational Efficiency; Reducing Errors and Downtime; Improving Safety and Real-Time Monitoring*", Smart Infrastructure and Safety Journal, 18(1), 33-48. <https://doi.org/10.1000/sisj.2020.11223>

- [66] Gbadegoye J., Camur M. C., Li X., (2025), "A Two-Stage Stochastic Model for Road-Rail Intermodal Freight Transportation Under Demand and Capacity Uncertainty", <https://doi.org/10.48550/arXiv.2503.17510>
- [67] Gencer C., Gök M. Ş., (2023), "Security vulnerabilities in multimodal and intermodal logistics chains: A systematic review", *Logistics*, 7(2), 31. <https://doi.org/10.3390/logistics7020031>
- [68] Geweke J., (1992), "Evaluating the accuracy of sampling-based approaches to calculating posterior moments in Bayesian Statistics 4", ed. JM Bernardo, JO Berger, AP Dawid and AFM Smith, Clarendon Press, Oxford, UK., 169-193;
- [69] Goel A., Gruhn V., (2016), "Fleet monitoring system for advanced tracking of commercial vehicles", Systems, Man and Cybernetics for SMC;
- [70] Göçmen E., Erol R., (2018), "The problem of sustainable intermodal transportation: A case study of an international logistics company, Turkey", *Sustainability*, 10(11), 4268. <https://doi.org/10.3390/su10114268>
- [71] Gopalakrishnan S., Gupta R., (2023), "Analysis of the barriers to multimodal freight transport and their impact on operational efficiency. *European Transport Research Review*", 15(2), 614.
- [72] Gosling S., Li J. D., Martinez A., Miguel M., (2023), "Digital logistics: Technology race gathers momentum", McKinsey & Company, <https://www.mckinsey.com/capabilities/operations/>
- [73] Grdinic J. N., (2016), "Improving Safety at Sea Through the Compliance with the International Maritime Safety Codes", *Journal of Maritime Research*, 13(1), 5–14;
- [74] Guan W., Liu H., (2022), "Agent-Based simulation in intermodal transport: A case study on freight flow optimization", *Transportation Science*, 56(3), 789-812;
- [75] Hassel M., Asbjørnslett B. E., Hole L. P., (2021), "Underreporting of maritime accidents to vessel accident databases", *Accident Analysis & Prevention*;
- [76] Heckmann I., Comes T., Nickel S., (2015), "A critical review on supply chain risk – Definition, measure and modeling", *Omega*, 52, 119-132;
- [77] Heidelberger P., Welch P.D., (1983), "Simulation run length control in the presence of an initial transient", *Opns Res.*, Vol. 31, 1109-44, <https://doi.org/10.1287/opre.31.6.11>
- [78] Hilmola O.P., Szekely B., (2006), "Supply chain management in the European Union: Transport-related risks and their management", *International Journal of Physical Distribution & Logistics Management*, 36(4), 336–361. <https://doi.org/10.1108/09600030610672041>
- [79] Hogg R. V., McKean J., Craig A. T., (2019), "Introduction to Mathematical Statistics", 8th ed., Pearson, pg. 60–78;
- [80] Hwang C.-L., Yoon K., (1981), "Multiple attribute decision making: Methods and applications", Springer, <https://doi.org/10.1007/978-3-642-48318-9>
- [81] ICAO (International Civil Aviation Organization), (2018), "Safety Management Manual", 4th ed., ICAO Doc 9859;
- [82] Institutul Național de Statistică, (2021), "Anuarul Statistic al României 2021", București: INS România; <http://www.insse.ro>
- [83] International Group of P&I Clubs, (2020), "Report on P&I claims involving vessels under pilotage (1999-2019)", <https://www.igpandi.org/article/pilotage-report/>
- [84] International Maritime Organization, (2001), "Standard Marine Communication Phrases (SMCP)", IMO Publishing, Secțiunea 3., <https://www.imo.org/en/OurWork/Safety>
- [85] International Maritime Organization, (2022), "Weather Impact Report", IMO Publishing, pg. 77;
- [86] International Maritime Organization, (2021), "Guidelines on maritime cyber risk management";
- [87] International Maritime Organization, (2020), "International Convention for the Safety of Life at Sea (SOLAS)", [https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-\(SOLAS\)-1974.aspx](https://www.imo.org/en/About/Conventions/Pages/International-Convention-for-the-Safety-of-Life-at-Sea-(SOLAS)-1974.aspx)
- [88] International Maritime Organization, (1998), "International Safety Management (ISM) Code and Guidelines on Implementation", <https://www.imo.org/en/OurWork/HumanElement/ISMCode.aspx>

- [89] International Maritime Organization, (2017), "*Convenția internațională privind standardele de pregătire, certificare și serviciu de cart pentru navigatori (STCW), inclusiv amendamentele de la Manila din 2010*", <https://www.imo.org/en/OurWork/HumanElement/Pages/STCW-Convention.aspx>
- [90] International Organization for Standardization, (2018), ISO 31000:2018, "*Risk management – Guidelines*";
- [91] International Road Transport Union (IRTU), (2023), "*Romania: driving restrictions(>7.5 t) due to heat waves on 21 and 22 August 2023, between 11:00 and 20:00*", <https://www.iru.org/intelligence/flash-info/romania-driving-restrictions-75-t-due-heat-waves-21-and-22-august-2023-between-1100-and-2000>
- [92] International Road Transport Union (IRTU), (2023), <https://www.iru.org/Reports> on European Transport Risks and Challenges
- [93] Ivanov D., (2021), "*Supply Chain Viability and the COVID-19 Pandemic: A Conceptual and Formal Generalisation of Four Major Adaptation Strategies*", International Journal of Production Research, 59(12), 3535–3552. <https://doi.org/10.1080/00207543.2021.1890852>
- [94] Janic M., (2017), "*Modelling the full costs of a intermodal and road freight transport network*", Transportation research Part D - Transport and Environment, Vol. 12 Issue 1;
- [95] Jithin T., Antriksh K., (2021), "*Loss reduction and cost optimization in road transportation*", National Institute of Industrial Engineering, Mumbai;
- [96] Kabir S., (2017), "An overview of fault tree analysis and its application in model-based dependability analysis", Expert Systems with Applications, 114–135, <https://doi.org/10.1016/j.eswa.2017.01.058>
- [97] Kaewfak K., Pharino C., Ouppara N., (2024), "*Advanced analytical methods for risk mitigation in multimodal freight transport*", Symmetry, 16(10), 1394. <https://doi.org/10.3390/sym16101394>
- [98] Kelton W. D., Sadowski R. P., Zupick N. B., (2015), "*Simulation with Arena (6th ed.)*", New York: McGraw-Hill Education, <https://www.mheducation.com/highered/product/simulation-arena-kelton-sadowski/M9780073401317.html>
- [99] Kengpol A., (2014), "*The development of a framework for route selection in multimodal transportation*", International Journal of Logistics Management, 25(2), 224-252, <https://www.emerald.com/insight/content/doi/10.1108/ijlm-05-2013-0064>
- [100] Konecranes, <https://www.konecranes.com/ro/macarale-industriale/tehnologia-macaralelor>
- [101] Kostrzewski M., Melnik R., (2021), "*Risk-based Decision Making in Railway Systems: A Fuzzy Logic Approach*", Journal of Rail Transport Planning & Management, 18, 100276. <https://doi.org/10.1016/j.jrtpm.2021.100276>
- [102] Kougioumtzoglou I. A., (2023), "*A Statistical Analysis of Ship Accidents (1990–2020) Focusing on Hull Failure*", Journal of Marine Science and Engineering, <https://www.mdpi.com/2077-1312/12/1/122>
- [103] Kramberger T., Pustai I., Lep M., (2018), "*Intermodal transportation risk assessment*", Safety and Reliability – Safe Societies in a Changing World (pp. 3201–3208), CRC Press, <https://doi.org/10.1201/9781351174664-401>
- [104] Kuznetsov A., Sokolov A., (2022), "*Methodology for assessing the risk of incidents during passenger transportation*", International Journal of Environmental Research and Public Health, 19(23), 15832;
- [105] Lasota M., Jacyna M., Szaciłło Ł., (2024), "*Fault tree method as a decision-making tool for risk analysis in the road transport of dangerous goods*", Scientific Journal of Silesian University of Technology. Series Transport, 123, 137–151, <https://doi.org/10.20858/sjsutst.2024.123.11>
- [106] Lemke C., Schulte F., Brandt T., (2023), "*Monte Carlo simulation for railway freight risk assessment*", (2023), Computers in Transport, 34, 112-130;
- [107] Liao R., Liu W., Yuan Y., (2023), "*Resilience improvement and risk management of multimodal transport logistics in the Post-COVID-19 Era: The case of TIR-based sea – road multimodal transport logistics*", Sustainability, 15(7), 6041, <https://doi.org/10.3390/su15076041>
- [108] Liu C.T., Hwang S.L., Lin I.K., (2023), "*Safety analysis of combined FMEA and FTA with computer software assistance*", IFAC Proceeding, Vol. 46, pp. 2151–2155;
- [109] Lovett A. H., Dick C. T., Barkan C. P. L., (2015), "*Determining Freight Train Delay Costs on Railroad Lines in North America*", Rail Transportation and Engineering Center (RailTEC), University of Illinois at Urbana-Champaign, 2-6;

- [110] Lu C., Han X., Xi B., Erera A. L., (2012), "Yard crane scheduling in a container terminal for the non-crossing constraint", *Computers & Operations Research*, 39(12), 2916–2927, <https://doi.org/10.1016/j.cor.2011.12.018>
- [111] Lundteigen M. A., Rausan M., (2018), "Introduction to Fault Tree Analysis. In Chapter 5 of the NTNU Safety", Reliability and Risk Engineering Book Series (Version 0.1), Trondheim: Norwegian University of Science and Technology (NTNU), <https://www.ntnu.no>
- [112] Ma X., Lan H., Han B., He H., (2022), "On the causation correlation of maritime accidents based on data mining techniques", *International Journal of Maritime Engineering*, 238(5);
- [113] Maidana R. G., Kristensen S. D., Utne I. B., Sørensen A. J., (2023), "Risk-based path planning for preventing collisions and groundings of maritime autonomous surface ships", *Ocean Engineering*, 290, 116417. <https://doi.org/10.1016/j.oceaneng.2023.116417>
- [114] Makarova I., Serikkaliyeva A., Gubacheva L., Mukhametdinov E., Buyvol P., Barinov A., Shepelev V., Mavlyautdinova G., (2023), "The role of multimodal transportation in ensuring sustainable territorial development: Review of risks and prospects", *Sustainability*, 15(7), 6309, <https://doi.org/10.3390/su15076309>
- [115] Mangan J., Butcher T., (2016), "Global Logistics and Supply Chain Management", Wiley, [https://www.wiley.com/en-us/Global logistics and supply chain management](https://www.wiley.com/en-us/Global+logistics+and+supply+chain+management);
- [116] Maslarić M., Brnjac N., Bago D., (2016), "Intermodal Supply Chain Risk Management", *Pomorski zbornik*, 52, 11-31;
- [117] MercuryGate International, (2020), MercuryGate Transportation Management System (TMS), <https://www.mercurygate.com/>
- [118] Merle G., Bobbio A., Griffon S., (2011), "Modeling dynamic fault trees using PAND gates", *IEEE Transactions on Reliability*, 554–565, <https://doi.org/10.1109/TR.2011.2165197>
- [119] Ministerul Transporturilor România, (2020), "Raport privind starea infrastructurii de transport rutier din România 2020", București: Ministerul Transporturilor România, <https://mt.gov.ro>
- [120] Ministerul Transporturilor din România, (2024), "Proiecte de infrastructură", https://www.mt.ro/web14/documente/privatizare-si-management/guvernanta_corporativa/componenta_iniciala/2024/PROIECT_CNAIR.pdf
- [121] Ministerul Transporturilor din România, (2020), "Strategia de transport intermodal în România", (2020), https://www.mt.ro/web14/documente/strategie/strategii_sectoriale.pdf
- [122] Ministerul Transporturilor și Infrastructurii, (2011), "Strategia de transport intermodal în România", https://www.mt.ro/documente/strategie/strategii_sectoriale/strategie_de_transport_intermodal_text.pdf
- [123] Ministerul Transporturilor și Infrastructurii, (2023), "Ordinul nr. 1.849 din 10 octombrie 2023 pentru aprobarea Strategiei de dezvoltare a transportului intermodal în România", *Monitorul Oficial al României, Partea I*, nr. 956, 23 octombrie 2023.
- [124] Mitsubishi Heavy Industries Ltd., (2023), "Grid-Powered Electric Transfer Crane", <https://www.mhi.co.jp/technology/review/pdf/e472/e472015.pdf>
- [125] Müller G., (2020), "Multimodal transport: Challenges and opportunities", *Journal of Transport and Logistics*, Vol. 12(2), pp. 45-58;
- [126] Neter J., Kutner M., Nachtsheim C., (2005), "Applied linear statistical models – 5th Edition", (2005), McGraw-Hill/Irwin, https://archive.org/details/appliedlinearsta0000kutn_5edi
- [127] Nitsenko V., Kotenko S., Hanzhurenko I., Mardani A., Karakai M., (2020), "Mathematical modeling of multimodal transportation risks. Recent advances on soft computing and data meaning", https://doi.org/10.1007/978-3-030-36056-6_41
- [128] Notteboom T., Pallis A., Rodrigue J.-P., (2022), "Port Economics, Management and Policy", *Routledge*, <https://doi.org/10.4324/9780429318184>
- [129] Oficiul pentru Publicații al Uniunii Europene, (2023), "Raport special: Transportul intermodal de marfă - UE.", <https://op.europa.eu/webpub/eca/special-reports/intermodal-freight-transport-08-2023/ro/>
- [130] OMVPETROM, <https://www.omvpetrom.com/ro/produse/carburanti-si-aditivi/combustibil-nava>

- [131] Ouedraogo C., Montarnal A., Gourc D., (2022), "Multimodal container transportation, traceability and supply chain risk management: A systematic literature review", IFAC-PapersOnLine, 55(10), 2145–2152. <https://doi.org/10.1016/j.ifacol.2022.07.172>
- [132] Pan S., Yan H., He J., (2021), "Vulnerability and resilience of transportation systems: A recent literature review", Physics A: Statistical mechanics and its applications, DOI: 10.1016/j.physa.2021.126235
- [133] Popa C., Stefanov O., Goia I., (2025), "Multimodal livestock operations analysis using the business process modelling. Case study of Romanian Black Sea Ports", Economies, MDPI, ISSN 2227-7099, <https://www.mdpi.com/2227-7099/13/3/69/pdf>
- [134] Popa C., Ștefanov O., Michnecka R., Rima B., (2025), "Modelling solutions for cost optimization in multimodal transports considering the operational risk variables", Transport, 40(3), 249–259, Vilnius Gediminas Technical University Press, ISSN: 1648-4142, DOI:10.3846/transport.2025.25716, <https://doi.org/10.3846/transport.2025.25716>
- [135] Popa C., Ștefanov O., Goia I., Nistor F., (2025), "A hybrid fault tree–fuzzy logic model for risk analysis in multimodal freight transport", Systems, 13(6), 429, <https://doi.org/10.3390/systems13060429>
- [136] Popa C., Ștefanov O., Goia I., (2025), "Risk-based optimization of multimodal oil products operation through simulation and workflow modeling", Systems, 13(6), <https://doi.org/10.3390/systems13060524>
- [137] Popa M., Roșca E., Rusca F., Costescu D., Dragu, V., (2016), "Transit time through the border-crossing points: the case study of the EU's road BCP with Moldavia", Transport Problems, 11(2), <https://doi.org/10.20858/tp.2016.11.2.8>
- [138] Popescu I., (2016), "Analiza preliminară a riscurilor în transportul intermodal", Academia.edu., <https://www.academia.edu/35840763>
- [139] Raicu Ș., (2007), "Sisteme de transport", București: Editura AGIR, <http://www.agir.ro/buletine/527.pdf>
- [140] Raicu Ș., Popa M., Costescu D., (2022), "Uncertainties influencing transportation system performances", Sustainability, 14(13), 7660. <https://doi.org/10.3390/su14137660>
- [141] Railport Arad,(2024), "Transport intermodal internațional", <https://www.railportarad.ro/en>
- [142] RailwayPro, (2023), "Viteza redusă pe segmente critice: 10-20 km/h pe traseul București – Brașov din cauza degradării infrastructurii", <https://www.railwaypro.com>
- [143] Rocket Consulting, (2024), "Transportation Management: How to Optimise Multimodal Freight Transport", <https://blog.rocket-consulting.com/rocket-sap-supply-chain-news-and-blog/transportation-management-how-to-optimise-multimodal-freight-transport>
- [144] Rodrigue J. P., (2020), "The geography of transport systems", (5th ed.), Routledge, ISBN-13: 978-0367364632;
- [145] romania-insider.com, (2016), "Transport sector generates over 13% of Romania's greenhouse gas emissions", <https://www.romania-insider.com/transport-sector-generates-over-13-of-romanias-greenhouse-gas-emissions>
- [146] Roșca E., Raicu Ș., Roșca M.A., Ruscă F.V., (2014), "Risks and Reliability Assessment in Maritime Port Logistics", Advanced Materials Research, Vol. 1036 (2014), pp. 963 – 968, disponibil la: <https://doi.org/10.4028/www.scientific.net/AMR.1036.963>
- [147] Roșca E., Rusca F., Carlan V., Ștefanov O., Dinu O., Rusca A., (2025), "Assessing the influence of equipment reliability over the activity inside maritime container terminals through discrete-event simulation", Systems, vol. 12, <https://doi.org/10.3390/systems13030213>
- [148] Rouhieh B., (2016), "Modeling and optimizing route choice for multimodal transportation networks", Concordia University, Montreal, Canada, <https://spectrum.library.concordia.ca>;
- [149] Ruijters E., Stoelinga M., (2015), "Fault tree analysis: A survey of the state-of-the-art in modeling, analysis and tools", Computer Science Review, 15, 29–62. <https://doi.org/10.1016/j.cosrev.2015.03.001>
- [150] Ruscă F.V., Roșca E., Azmat M., Perez-Acebo H., Ruscă A., Olteanu S., (2020), "Modeling the transit of containers through quay buffer storage zone in maritime terminals", ZIRP 2020, International Scientific Conference, pp. 213 – 227;

- [151] Russo F., Vitetta A., (2006), "*Risk evaluation in a transportation system*", International Journal of Sustainable Development and Planning, 1(2) 170–191;
- [152] Sahner R. A., Trivedi K. S., Puliafito A., (1996), "Performance and Reliability Analysis of Computer Systems: An Example-Based Approach Using the SHARPE Software Package", Kluwer Academic Publishers;
- [153] Sánchez-Beaskoetxea J., Basterretxea-Iribar I., Sotés I., Maruri M., (2021), "*Human error in marine accidents: Is the crew normally to blame?*", Maritime Transport Research, 2, <https://doi.org/10.1016/j.martra.2021.100016>
- [154] Saponi E., Sciutto M., Sciutto G., (2014), "A quantitative approach to risk management in critical infrastructures", Transportation Research Procedia, 3, 740–749, <https://doi.org/10.1016/j.trpro.2014.10.053>
- [155] Sauerberg M., Luy M., (2024), "*Standardized mean age at death (MADstd): Exploring its potential as a measure of human longevity*", Volume 50, Art. 30, pp. 871-898, disponibil online la: <https://www.demographic-research.org/Volumes/Vol50/30/>
- [156] Schruben L.W., (1982), "*Detecting Initialization Bias in Simulation Experiments*", Opns. Res. 30, pp. 56 - 590, <https://doi.org/10.1287/opre.30.3.569>
- [157] Schruben L.W., Singh H., Tierney L., (1983), "*Optimal Tests for Initialization Bias in Simulation Output*", Vol. 31(6), pp. 1167-1178, <https://doi.org/10.1287/opre.31.6.11>
- [158] Sellner K., Vyslouzilova D., (2019), "*Identification and solution of safety and operational-economic risks in railway transport*", Sciendo, CzOTO, Vol. 2, Issue 1, pp. 112-120;
- [159] Sigalingging E. D., Erlina Muda I., Herubawa D. A., (2024), "*Application of the Simple Additive Weighting Method in the Performance Assessment of Energy Companies Based on ROA and DAR*", Journal of Theoretical and Applied Information Technology, 102(22), 8066–8073;
- [160] Soekkha H. M., (1997), "*Aviation safety: human factors, system engineering, flight operations*", Economics strategies management, VSP;
- [161] Soares C. G., Teixeira A. P., (2001), "*Risk assessment in maritime transportation. Reliability engineering & system safety*", 74(3), 299-309, [https://doi.org/10.1016/S0951-8320\(01\)00082-3](https://doi.org/10.1016/S0951-8320(01)00082-3)
- [162] Steenken D., Vob S., Stahlbock R., (2004), "*Container terminal operation and operations research – a classification and literature review*", OR Spectrum, 26(1), 3–49;
- [163] Ștefan D. S., Popescu M., Luntraru C. M., Suci A., Belcu M., Ionescu L. E., Popescu M., Iancu P., Ștefan M., (2022), "*Comparative study of useful compounds extracted from Lophanthus anisatus by Green Extraction*", Molecules, 27, 7737. <https://doi.org/10.3390/molecules27227737>
- [164] Ștefanov N. O., Popa C., Mickiene R., (2025), "*Case study of risk assessment in maritime operations applying the Fault Tree Analysis Method*", Research journal TRANSPORT published by Vilnius Gediminas Technical University, 12 pagini, ID STRAB-2024-0043.R1
- [165] Ștefanov N.O., Rauca L., (2023), "*Environmental Risk Assessment in the Background of Armed Conflict in the Black Sea Area*", Transnav, The International Journal on Marine Navigation and Safety of Sea Transportation, Volume XX, Number X, DOI: 10.12716/1001.16.XX.XX.;
- [166] Ștefanov N.O., Agape A.G., Stoenciu D., Berescu C., Bocanete P., (2022), "*Study of the risk analysis associated with multimodal maritime transport*", Technium, Vol. 4, Issue 4, pp. 32-36, ISSN: 2668-778X;
- [167] Ștefanov N.O., Apetroaei G.M., (2021), "*Considerations for Risk Mitigation in the International Carriage of Goods by Sea*", SEA-CONF 2021, Proceedings of the International Scientific Conference, pp. 384-391, ISSN: 2457-144X;
- [168] Ștefanov N.O., Agape A.G., Nita C.M., Bocanete P., (2021), "*Multimodal Transport - Risk and Environment*", Technium, Vol. 3, Issue 11, pp. 40-45, ISSN: 2668-778X;
- [169] Stermann J., (2021), "*System dynamics modeling for freight transport*", International Journal of Transport Economics, 48(1), 27-49, <https://doi.org/10.1007/s11495-021-09837-5>
- [170] Stornes P., (2015), "*Risk influencing factors in maritime accidents An exploratory statistical analysis of the Norwegian maritime Authority incident*", Trondheim: Studio Apertuna, NTNU Social Research;

- [171] Szaciłło L., Krześniak M., Jasiński D., Valis D., (2022), "The use of the risk matrix method for assessing the risk of implementing rail freight services", *Archives of Transport*, 64(4), 89-106., <https://doi.org/10.5604/01.3001.0016.1185>
- [172] Tabatabaei S. M., (2024), "Sustainable supply chain design: integrating risk management, resilient multimodal transportation and production strategic", SSRN Preprint, https://ssrn.com/abstract_id=5003804
- [173] Taherdoost H., Madanchian M., (2023), "Multi-Criteria Decision Making (MCDM) Methods and Concepts", *Encyclopedia*, 3(1), 77–87. <https://doi.org/10.3390/encyclopedia3010006>
- [174] Târcolea C., Filipoiu A., Bontaș S., (1989), "Tehnici actuale în teoria fiabilității-Aplicații actuale în teoria fiabilității", Editura Științifică și Enciclopedică, Bucharest, pp. 87-137;
- [175] Timofeeva O., Sannikov A., Stepanenko M., Balashova T., (2023), "Modification of the Bellman–Ford Algorithm for Finding the Optimal Route in Multilayer Network Structures", *Computation*, 11(4), 74. <https://doi.org/10.3390/computation11040074>
- [176] Triantaphyllou E., (2000), "Multi-criteria decision making methods: A comparative study", Springer, <https://doi.org/10.1007/978-1-4757-3157-6>
- [177] Tummala R., Schoenherr T., (2011), "Assessing and managing risks using the Supply Chain Risk Management Process (SCRMP). *Supply Chain Management: An International Journal*", 16(6), 474–483. <https://doi.org/10.1108/13598541111171165>
- [178] Uddin M., Huynh N., (2016), "Routing model for multicommodity freight in an intermodal network under disruptions", *Transportation Research Record*, 2548(1), 71-80;
- [179] United Nations Conference on Trade and Development, (2023), "Maritime Security Report", UNCTAD Publishing;
- [180] United Nations Conference on Trade and Development (UNCTAD), (2023), "Trade and Development Report 2023: Growth, debt, and climate – Realigning the global financial architecture", <https://unctad.org/publication/trade-and-development-report-2023>
- [181] United States Department of Transportation, (2024), "Black Sea and Sea of Azov – Military Combat Operations", Maritime Advisory 2024-012. <https://www.maritime.dot.gov/msci/2024-012-black-sea-and-sea-azov-military-combat-operations>
- [182] Uniunea Națională a Transportatorilor Rutieri din România (UNTRR), (2016), "Transportul multimodal - secțiunea transport intermodal", București, https://www.untrr.ro/media/wysiwyg/legis_3/Anexa_3_MPT_octombrie_2016.pdf
- [183] Uniunea Națională a Transportatorilor Rutieri din România (UNTRR), https://www.untrr.ro/Raportul_UNTRR_2022
- [184] U.S. Nuclear Regulatory Commission, (1981), "Fault Tree Handbook: A Basic Reference Guide for Fault Tree Analysis (NUREG-0492)", Washington, DC: U.S. Government Printing Office;
- [185] Vafaei N., Ribeiro R. A., Camarinha-Matos L. M., (2022), "Normalization techniques in multi-criteria decision making: A comparative analysis", *Expert Systems with Applications*, 193, 116479. <https://doi.org/10.1016/j.eswa.2021.116479>
- [186] Water Journal, (2024), Volume X, Elvetia, Basel, <https://www.mdpi.com/journal/water>
- [187] Wallace R. B., Murthy D. N. P., (2000), "Reliability: Modeling, prediction, and optimization", pg. 96, <https://onlinelibrary.wiley.com/doi/book/10.1002/9781118150481>
- [188] Worldbank, (2023), <https://blogs.worldbank.org/en/transport/why-ports-matter-global-economy>
- [189] World Bank, (2023), "Connecting to Compete 2023: The Logistics Performance Index and Its Indicators", Washington D.C.: The World Bank Group, <https://lpi.worldbank.org>
- [190] World Maritime University, (2023), "Raport anual 2023", <https://www.wmu.se/docs/annual-report-2023>
- [191] World Highways, (2022), "Romania's DEx12 Craiova–Pitești expressway: construction progress and traffic impact", <https://www.globalhighways.com/wh12/news/romania-dex12-craiova-pitesti-target>
- [192] Yadav R., Kanchan R., Shah H., (2023), "Fault Tree Analysis for Robust Design. *Inventions*", 9(1), Article 19, <https://doi.org/10.3390/inventions9010019>

- [193] Yilma H., (2014), *"Challenges and prospects of traffic management practices of Addis Ababa City Administration"*, Addis Ababa University Repository, <http://etd.aau.edu.et/handle/123456789/10166>
- [194] Zajac M., Świeboda J., Manea S.-A., (2017), *"Preliminary Risk Analysis in Intermodal Transport"*, Academia.edu.,
https://www.academia.edu/35840763/Preliminary_Risk_Analysis_in_Intermodal_Transport
- [195] Zhao D., Ou Y., Shafiei S., Grzybowska, H., Qin, A. K., Tan, G., Li, M., (2022), *"Traffic disruption modelling with mode shift in multi-modal networks"*, <https://arxiv.org/abs>