An Assessment of Road Network Topology and Its Influence on Port Accessibility in Romania

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Abstract. Maritime ports represent the primary gateway between a country's land-based transport system and the global marketplace. Their capacity and configuration in relation to freight flow demands constitute a central topic of research within the field. However, vulnerabilities within the terrestrial transport network expose these ports to disruptive factors of both internal and external origin. In the case of Romanian maritime ports, the bridges crossing the Danube ensure their connection to the national road network, but they may also, in the event of external interference, lead to the isolation of these ports and a consequent reduction in the volume of goods passing through port terminals. The application of a macro-level network simulation model allows for the assessment of the impact generated by the unavailability of any of these critical road network components. The results obtained are useful for decision-makers in developing transport network strategies that ensure redundancy, with beneficial effects that can be economically quantified.

Keywords: Accessibility · Land transport network · Macroscopic simulation · Network Topology

1 Introduction

The relationship between maritime ports and the land transport network within their hinterland is a critically important aspect in the development strategy of any country. This is also influenced by the role of maritime ports within supply chain structures. Therefore, beyond the handling and throughput capacity of ports, their performance is also affected by the performance of the land transport networks that connect them to their hinterland. As freight volumes continue to grow and supply chains become more integrated, the efficiency of land network has become a key concern for researchers and practitioners also.

The structure and main infrastructure elements of road networks play a critical role in ensuring an acceptable level of accessibility and network connectivity. Engineering structures such as bridges, tunnels, and viaducts often become sets of critical links, especially where natural barriers limit the availability of alternative routes. In extreme

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cases, the failure of a single infrastructure component may lead to the partial isolation of key economic regions or transport hubs, as is the case with maritime ports.

The Romanian Road transport network provides a relevant example of this type of vulnerability. The Danube River, while representing an important transport corridor, also constitutes a major geographical barrier for road transport. Internal road crossings over the Danube are relatively few (only three at present) and are distributed along a stretch of more than 200 km, making them essential links between the maritime ports on the Black Sea coast and the rest of the national road network.

The occurrence of disruptions affecting the proper functioning of Danube bridges can alter freight routing patterns and increase travel distances and times for vehicles serving maritime ports. These increases are quantified by transport operators in monetary cost terms. In more severe scenarios, with significant impacts on the network, the reduced availability of these crossings leads to a limitation in the ability of ports to be efficiently connected to their hinterland. Despite these risks, the interaction between port performance and the vulnerability of road infrastructure has not been extensively explored, particularly at the macro-network level and in the context of Eastern European transport systems.

Existing research in the literature provides a range of results regarding port efficiency, hinterland connectivity, and transport network resilience. However, these topics are often addressed separately, without explicitly highlighting the interdependencies between them. Studies analyzing how disruptions to critical road infrastructure affect maritime ports are relatively limited, and while macro-level simulation approaches capable of capturing system-wide impacts do exist, they have not been specifically applied to the case of the Romanian road transport network. In response to these gaps, in this paper the authors investigate the vulnerability of Romanian maritime ports to disruptions affecting critical components of the road network. A macro-level transport network simulation model is used to assess the impact of the unavailability of road bridges across the Danube on freight flows directed toward maritime port terminals. The study aims, based on the conducted research, to provide a clear picture of the structural robustness of the existing road transport network in Romania.

The results of the research conducted by the authors contribute to the advancement of the transport field, particularly in relation to aspects such as the vulnerability and robustness of transport networks, highlighting the central role of critical infrastructure in maintaining port connectivity. From a practical perspective, the findings are useful for the planning of strategic transport infrastructure projects, as well as for informing public policy decisions aimed at increasing network robustness and reducing the potential impact of disruptive events on the performance of maritime ports.

Against this background, the study looks at disruptions in the transport network. The focus is on critical infrastructure elements. The analysis is carried out at a national scale. Special attention is given to maritime port accessibility. The research question is clear. How does the road network affect access to ports? Especially when disruptions occur. A national-level transport model is used. It helps track how traffic shifts to alternative routes. It also shows the extra costs for users. The contribution is mainly practical. It clarifies how vulnerability affects accessibility. It also supports better planning and resilience decisions.

The research is structured into six chapters. The first chapter outlines the context in which the study was conducted. Section 2, Literature Review, provides a critical analysis of the relevant bibliographic sources considered by the authors and identifies the existing research gap addressed by this study. The third chapter presents current methods for evaluating accessibility in territorial transport networks. Section 4, Modelling the Romanian Road Network, introduces the conceptual framework applied in modelling the national road network. In Sect. 5, a case study is developed using the PTV Visum platform, focusing on the influence of the operation of major Danube ports on the accessibility of Romanian maritime ports. Finally, Sect. 6, Conclusions, summarizes the main findings and outlines directions for future research.

2 Literature Review

The assessment of transport network exposure is based on the concepts of reliability and vulnerability of transport networks. Borrowed from the field of technical component reliability, these concepts allow the evaluation of the impact that disruptive events may have on the functioning of the transport network [1]. An important body of literature has focused on the vulnerability of transport networks and the consequences of disruptions affecting critical infrastructure elements. Berdica (2002) provided one of the earliest comprehensive discussions of road network vulnerability, emphasizing that failures of specific links may significantly affect network performance. Later studies proposed analytical approaches for identifying critical infrastructure components within transport systems [2]. For example, Jenelius, Petersen and Mattsson (2006) developed a framework for evaluating the exposure and importance of road network links [3], while Murray-Tuite and Mahmassani (2004) examined methods for identifying vulnerable links whose disruption may strongly affect network accessibility [4]. Similarly, Taylor and D'Este (2007) proposed diagnostic approaches for detecting critical locations within transport infrastructure systems [5]. It is also worth noting the analysis of the influence that the unavailability of certain critical links has on network reliability. In this case, the quantification of the results is based on travel time as the main parameter [6].

The interaction between maritime or inland ports and their hinterland has been extensively analyzed in transport geography and logistics research [7–11]. Ports function not only as nodes in global maritime networks but also as gateways connecting maritime flows with inland transport systems. This interaction is assessed starting from the port gate, by evaluating how the transport network is connected to the port's internal infrastructure [12]. The ports efficiency and long-term development therefore depend on the performance of the terrestrial infrastructure that supports freight movements beyond the port area. As highlighted by Rodrigue, Comtois and Slack (2020), modern ports operate as integrated elements of complex logistics systems where road, rail and inland waterways ensure the continuity of supply chains between maritime and inland regions [14].

A significant contribution to the understanding of port–hinterland dynamics was made by Notteboom and Rodrigue (2005), who introduced the concept of port regionalization. Their work explains how ports evolve from simple transshipment points into integrated logistics platforms connected to regional transport corridors and inland terminals [7]. In this framework, the quality and reliability of inland transport infrastructure

become essential factors shaping the size and accessibility of port hinterlands (Notteboom, 2008) [8]. A complementary perspective is offered by Balletto, Borruso and Campisi (2022), who underline that port–hinterland relations are increasingly shaped not only by waterfront functions, but also by inner harbor areas and peripheral logistics spaces, where intermodal and warehousing activities support the inland extension of port operations [15]. Other studies consider statistical parameters related both to the transport network and to the economic dimension in order to evaluate the efficiency of ports in relation to their served hinterland [10].

Although previous studies have examined both port–hinterland relations and the vulnerability of transport networks, relatively limited attention has been paid to the exposure of maritime ports to disruptions occurring in specific inland infrastructure elements. As situations may arise in which ports are connected to their hinterland through a limited number of transport links, they become particularly vulnerable when transport infrastructure becomes unavailable. This aspect is also relevant for Romanian maritime ports, whose road accessibility depends significantly on the bridges crossing the Danube River. The link between transport networks and ports has been widely studied. However, network vulnerability is less explored. This is especially true in relation to port accessibility. Many studies rely on economic indicators. Others focus on connectivity measures. Only a few consider disruption effects. This study builds on that gap. The research question is stated clearly. It focuses on the role of critical network elements. The contribution has two sides. First, it moves beyond static analysis. It introduces disruption scenarios. Second, it uses a modelling approach. This helps capture traffic redistribution. It also shows how accessibility is affected. In this way, the gap in the literature becomes clearer. The position of this research is also better defined.

3 Evaluating the Accessibility

The assessment of accessibility in transport networks represents one of the research directions in the field that has generated sustained interest among specialists. The first mathematical models aimed to quantify the potential of a node or an area to interact with other locations through the transport infrastructure, depending on travel cost and the spatial distribution of activities. An early definition described accessibility as the potential of opportunities that can be reached from a given location, mathematically formulated through a spatial interaction–type relationship [16]. The gravitational accessibility indicator can be expressed by the following relation:

$$A_i = \sum\nolimits_{j=1} O_j f(c_{ij}) \tag{1}$$

where A_i is accessibility of node or zone i, O_j is magnitude of opportunities in zone j (population, jobs, freight volume, etc.), c_{ij} is generalized travel cost between i and j and finally $f(c_{ij})$ is impedance function reflecting the negative effect of distance or travel time. A derived form of the accessibility assessment model is represented by the cumulative opportunity indicator. Accessibility is defined as the number of opportunities that can be reached within a given cost or time threshold:

$$A_i = \sum\nolimits_{j=1} O_j I(c_{ij} < C) \tag{2}$$

where $I()$ is an indicator function depending by the maximum acceptable cost or time threshold [17].

In modern transport modelling applications, accessibility is calculated using the generalized cost matrix obtained through shortest-path algorithms, integrated into network models implemented in specialized transport planning software. The application of macro-simulation models enables the estimation of traffic flows distributed across the transport infrastructure network. Within this framework, travel times can be determined as a function of the capacity of each individual network link, the allocated traffic volumes, and the topological and structural characteristics of the respective infrastructure elements. Building on this modelling framework, network accessibility can be evaluated using the outputs generated by macro-simulation models. These models produce origin–destination traffic flows and associated travel times across the transport network while accounting for factors such as congestion, link capacity and route choice behavior. As a result, the generalized travel cost between zones can be derived directly from the simulated network conditions.

Using these outputs, several accessibility indicators can be calculated. Gravity-based indicators rely on the generalized cost matrix obtained from the simulation, while cumulative opportunity measures identify the number of opportunities that can be reached within a given travel time threshold. Since travel times are determined based on traffic volumes obtained from the traffic assignment process, the results have a higher level of credibility, reflecting the actual operating conditions of the network. This aspect makes macro-simulation a useful tool for analyzing how changes or disruptions in transport infrastructure operation influence accessibility patterns across the network.

Building on the previous approach, accessibility can also be represented graphically through isochrone maps derived from macro-simulation outputs. An isochrone defines the area that can be reached from a given origin within a specific travel time threshold, using the travel times calculated on the simulated network. At the zonal level, isochrones are constructed from the generalized travel cost matrix obtained in the macro-simulation model. Isochrones represent spatial surfaces that group together locations within a network characterized by the same temporal distance from a reference point. In transport network analysis, specialized software tools enable the selection of one or several network elements (e.g., nodes, stations, or traffic zones), after which the travel time between these elements and all other relevant components of the network is computed, typically using shortest-path algorithms Based on the obtained travel time values, a set of isochrones can be graphically represented using these temporal attributes of the network, thereby providing a visual representation of the spatial distribution of accessibility of maritime ports in relation to the national territory. The territory for which the travel time from the considered origin is below a predefined threshold (e.g., 30, 60, or 90 min at the local level and 3, 6, and 9 h at the regional and national levels) is represented on the map as accessibility areas. Such graphical representations provide an intuitive way to visualize variations in accessibility across the transport network and to identify areas with limited connectivity or affected by changes in the operating conditions of transport infrastructure.

4 Modelling Romanian Road Network

From a topological perspective, the Romanian national road network is structured around a radial configuration centered on the Romanian capital, Bucharest. The national roads have the origin in the country's main city and extend toward the major regions, forming the primary transport corridors. These corridors are complemented by transversal connections that link adjacent areas, thereby contributing to the overall cohesion and connectivity of the network (Fig. 1).

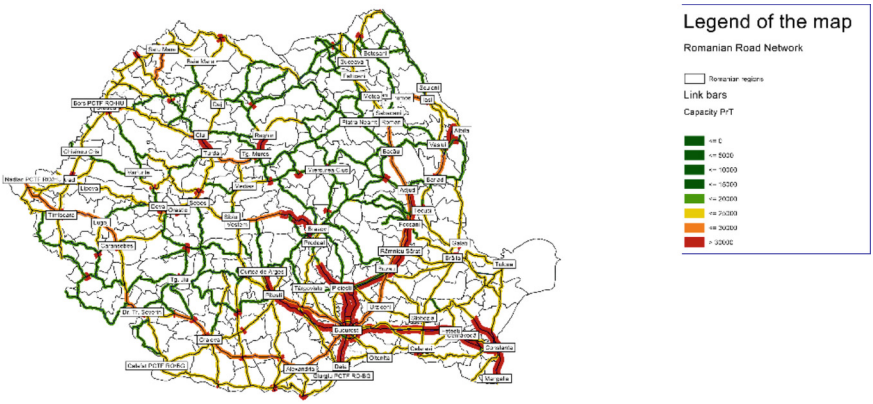


Fig. 1. Romanian road network (source: adapted and updated from [18]).

The motorway network further supports these connections by offering higher-capacity links between inland regions and the network's external gateways. In this context, the role of the road network in linking inland areas to the maritime ports along the Black Sea coast becomes clearly visible. By relying on a mix of routes with different capacity levels, freight flows generated in the hinterland are able to reach port terminals, facilitating the integration of maritime transport nodes into the broader national transport system. To model the accessibility of maritime ports, the road network is represented within a macroscopic model implemented in the PTV Visum software environment. The road capacity and speed limits are incorporated in accordance with the parameters used in the national transport models or in previous research [19–21].

The algorithm used for the assessment of road network topology and its influence on port accessibility in Romania is presented in Fig. 2. Using the traffic flow equilibrium assignment method, an initial set of traffic distribution values across the transport network is obtained. The equilibrium assignment method is used in macrosimulation models to distribute vehicle flows across routes within a transport network [22]. This method is a tool within the PTV Visum software and is based on Wardrop's first principle: "Every road user selects their route in such a way that the impedance on all alternative routes is equal, and switching to a different route would increase their personal travel time (user optimum).". Impedance is a modeling parameter that represents a proxy for the travel cost perceived by users. These variations are incorporated by software tool PTV VISUM into the model calibration and control parameters using the default values (the N

maximum number of steps is set to 20 and the maximum relative gap is set to 0.001). In the specific case of this research, given the national-scale nature of the model, impedance was expressed as travel time. The value of impedance varies dynamically with traffic volumes through volume–delay relationships. For the input data are used data from the last General Transport Master Plan of Romania [18].

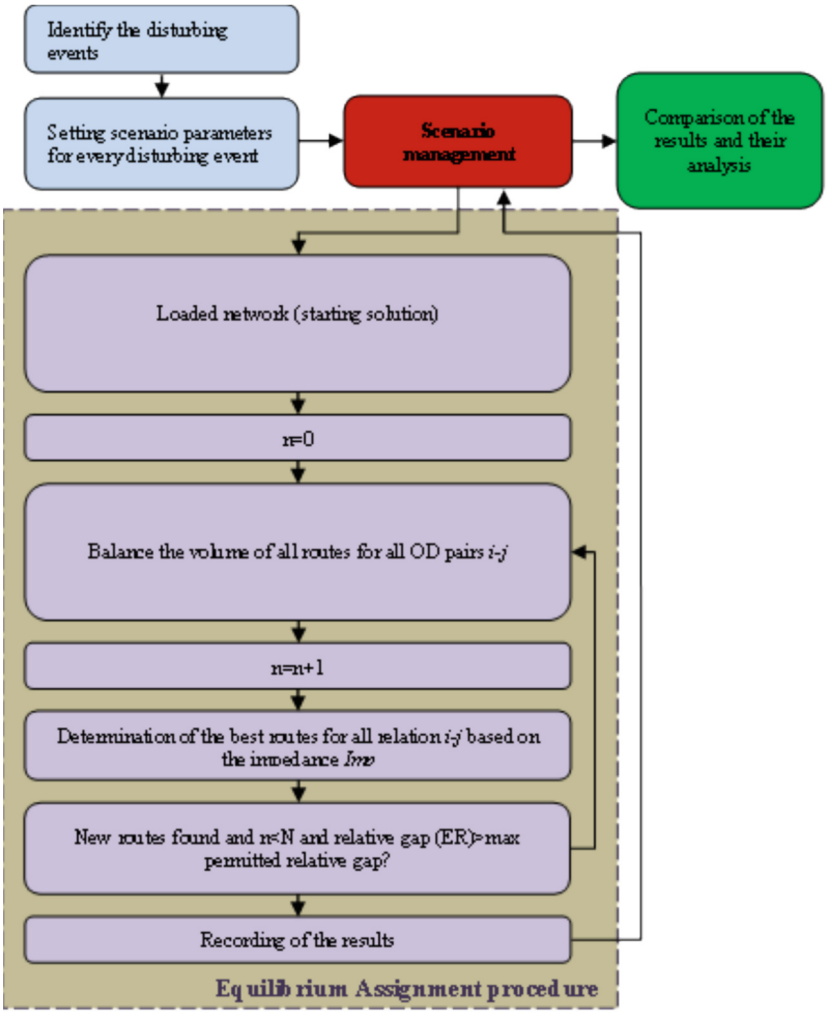


Fig. 2. The algorithm for evaluating the influence of disturbing events on port accessibility (source: adapted from [22]).

Based on these results, events characterized either by a high probability of occurrence or by a potentially significant impact on network performance are identified. Subsequently, a series of plausible scenarios are developed to represent such disruptions.

For each scenario, the virtual representation of the transport network is modified accordingly, and the traffic assignment procedure is repeated in order to simulate the redistribution of traffic flows under the new network conditions. The resulting traffic patterns are then evaluated through the construction of isochrone maps, which allow for a comparative assessment of the changes in maritime port accessibility across the different simulated scenarios.

5 The Study Case. The Influence of Danube Briges Functionality

Romanian maritime ports are connected to their hinterland through the national road network. From a spatial perspective, these ports are located in the south-eastern part of Romania, within the historical region of Dobrogea. Connectivity between this region and the rest of the country is ensured primarily through crossings over the Danube River. Due to the challenging topography, historical development patterns, and the considerable width of the Danube in the sector adjacent to the maritime ports, only three road bridges have been developed (Fig. 3).

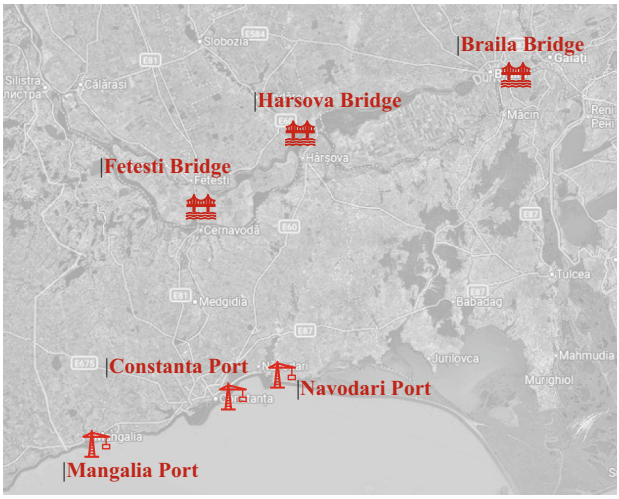


Fig. 3. Romania Maritime ports and Danube bridges

The operational performance of these bridges plays a critical role in determining the level of accessibility of Romanian maritime ports. Disruptive events—such as traffic accidents, maintenance works, or, in extreme cases, deliberate attacks—may lead to the partial or complete loss of functionality of one or more crossings. Although the resulting impact is inherently difficult to quantify, it can be systematically assessed through the development of scenario-based analyses reflecting different bridge availability conditions. The application of macroscopic traffic simulation models enables the evaluation of these scenarios, facilitating both quantitative and qualitative assessments of their effects on network performance and port accessibility.

The scenarios description are presented in Table 1. The analyzed three bridges are encoded as B1 for the Feteşti Bridge, B2 for the Hârşova Bridge, and B3 for the Brăila Bridge. The scenario numbering system employs a three-digit code reflecting the operational status of each bridge. A value of 1 indicates normal operation, while a value of 0 denotes the unavailability of the bridge due to a disruptive event.

Table 1. The macrosimulation scenarios

Scenario	Scenario description
S111	All three bridges are operational
S011	Bridge B1 is out of service, while the other two bridges remain operational
S101	Bridge B2 is out of service, while the other two bridges remain operational
S110	Bridge B2 is out of service, while the other two bridges remain operational
S100	Bridges B2 and B3 are out of service, while the remaining bridge is operational
S010	Bridges B1 and B3 are out of service, while the remaining bridge is operational
S001	Bridges B1 and B2 are out of service, while the remaining bridge is operational

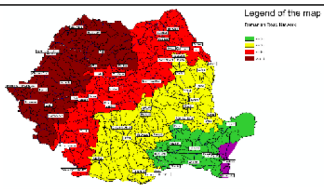
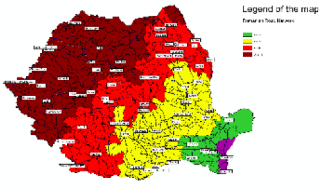
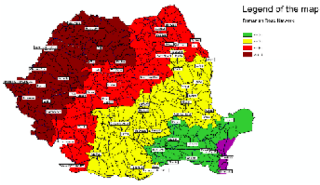
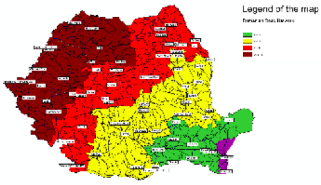
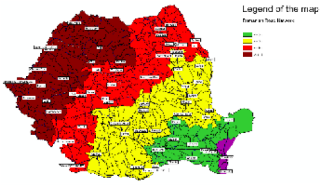
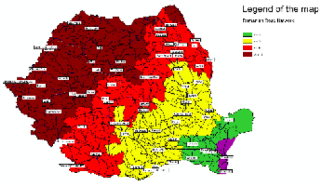
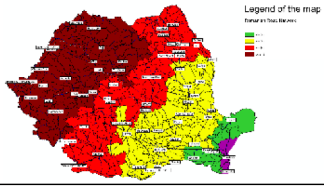
The results obtained with macrosimulation model are presented in Table 2. For every scenario is presented the accessibility map for time thresholds of 3, 6, and 9 h. Additionally, the percentage of territorial coverage is presented for the previously defined time thresholds.

The numerical results highlight that the unavailability of bridges B1, B2, or B3 leads to a direct degradation of maritime port accessibility, with the magnitude of the effect depending on the topological role of each bridge within the network. For example, the removal of bridge B1 results in a significant reduction in territorial coverage for the 3-hour threshold, indicating a rapid contraction of the ports' immediate hinterland. In the case where bridge B1 and B2 become simultaneously unavailable, the affected territory is increased, reflecting a major loss in port accessibility and the use of longer transport routes. Even in the case of disruptions affecting bridge B3, a negative impact is observed for the 6- and 9-hour analysis thresholds, confirming that each of these structures plays a critical role in maintaining efficient connectivity between the hinterland and maritime ports.

The analysis of the results highlights the critical importance of the Feteşti Bridge, coded as B1. In the event of a disruptive incident, the bridges included in the model—Hârşova Bridge and Brăila Bridge—play a redistribution role by absorbing part of the traffic originally assigned to B1, albeit with increased costs perceived by users.

Mitigation measures in this context include ensuring proper maintenance operations for all three bridges, encouraging users to also utilize network alternatives through neighboring Schengen countries (e.g., Bulgaria), and providing timely information regarding the operational status of these critical network elements.

Table 2. The results

Scenario	Macrosimulation output	Territorial coverage [km^2]			
		<3 h	<6 h	<9 h	>9 h
S111		31988	74296	67507	64679
S011		20169	58614	71921	87766
S101		31988	72102	69701	64679
S110		31988	72102	69701	64679
S100		31988	72102	69701	64679
S010		20169	58614	71921	87766
S001		17068	64311	75393	81698

6 Conclusions

The analysis of maritime port accessibility is of significant interest due to its economic implications. Maritime ports represent a key component of international supply chains. However, the performance of these transport nodes is not determined solely by the processes occurring within port areas. The connection between ports and their hinterland also plays a crucial role. The land transport network can either facilitate or hinder the connection between the port location and the areas from which freight flows originate or to which they are destined. In the case of road networks, it is essential to identify those critical infrastructure elements (such as bridges, tunnels, and viaducts) whose unavailability may lead to the isolation of network nodes or to the use of longer transport routes associated with higher costs. The use of macro-simulation models, combined with the representation of isochrones within the analyzed territory, constitutes a valuable analytical tool. This approach enables the assessment of the impact of disruptive events on the network, providing an integrated view of accessibility variations. It also facilitates the identification of critical points and vulnerable areas, offering a reliable basis for strategic decision-making.

In this study, the research focuses on the specific case of the Romanian road network that ensures the connection between maritime ports and their hinterland. Particular attention is given to the role of the Danube River, which effectively divides the network into two distinct regions connected by only three crossings considered critical. A set of scenarios was developed to evaluate the impact of the unavailability of each crossing individually, as well as in combined scenarios involving the simultaneous disruption of two links.

The obtained results allowed for the assessment of the relative importance of each crossing. The analysis highlights one particular link (the Feteşti Bridge) as having a major influence, while the impact of the unavailability of the other two bridges is less pronounced. This outcome is also supported by the topological structure of the network, which exhibits an egocentric configuration centered around the capital city of Romania.

The main limitations of the developed model are related to the nature of the data input. Traffic flow values were considered at an annual average level, while daily and seasonal variations were not included in the analysis. Future research aims to incorporate these temporal variations into both the modeling framework and the scenario analysis.

Overall, the proposed model represents a useful tool for the analysis of road transport networks and can support the justification of national development strategies by providing an increased level of credibility in the decision-making process.

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