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Node Criticality Estimation in Intermodal Networks

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INTRODUCTION

Intermodal networks, which integrate rail, road, and sea modes, are essential for sustainable freight movement. However, their complexity introduces vulnerabilities, particularly at critical nodes like transhipment terminals, which can cascade through the supply chain and cause delays, increasing the overall transport costs.

Node disruptions (closure of a seaport or terminal) reduces network efficiency, making it crucial to identify the most impactful nodes. Stakeholders include carriers, logistics planners, infrastructure managers, and policymakers who need robust framework for planning the alternative transport strategies.

Proposed hybrid node criticality framework integrates centrality metrics with operational constraints (cost, emissions, capacities). The research questions are: Which nodes are the most critical and their impact on the whole network? The expected impact is to support modal shift in partially disrupted networks.

MATERIALS, METHODS & IMPLEMENTATION

Construction of an intermodal network of 45 nodes - ports, rail-road terminals, distribution centres (DC) using Python tools (NetworkX, GeoPandas) and synthetic European freight dataset (Speth et al., 2021). The optimisation model solves a transhipment problem, minimising total transport and emission costs with constraints for: supply, demand, and DC capacities; mode-specific costs (rail, road) and emission monetisation using €50/tCO_2. Solution: 8.1814e+07, gradually improving the total cost from 2.7413e+08 in 34 iterations. Simulated disruption of Zurich DC removal from a subnetwork of 15 neighbouring nodes and analysed rerouting impacts.

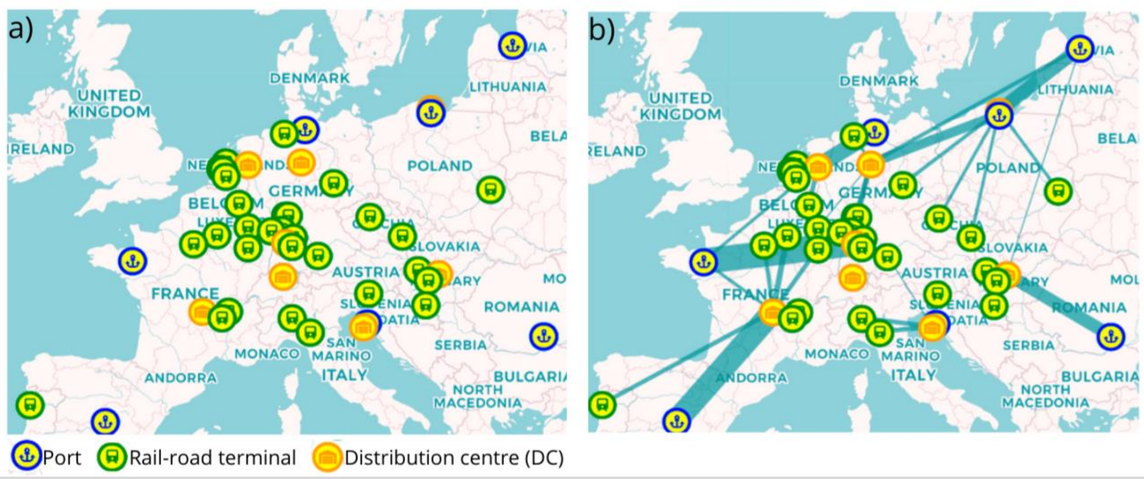

Fig 1.(a) Intermodal nodes in the network; (b) Capacitated distance-based solution in the intermodal network.

Objective function

$$\min \sum_i \sum_j \sum_{m \in M} (C_{ij}^m + E_{ij}^m) x_{ij}^m \quad (1)$$

Decision variables

x_{ij}^m = quantity of containers transported from node i to node j using mode m.

y_{ij}^m = binary variable, 1 if mode m is used for transport between i and j, 0 otherwise.

Parameters

C_{ij}^m = cost per unit transported (TEU) from i to j using mode m.

E_{ij}^m = emission cost per unit transported using mode m.

S_s = supply at port s.

D_d = demand at DC d.

C_c = capacity of rail-road terminal c.

M = set of transport modes (road or rail).

Supply constraints: Each port can only receive freight up to its available supply capacity.

Flow constraints: Rail-road terminals act as transhipment points, ensuring that incoming shipments are equal to outgoing shipments.

Demand satisfaction: Each DC must receive their required demand.

Intermodal terminal capacity limits: DCs cannot exceed their storage capacity.

Mode selection: A transport mode can only be used if it is selected for a given route.

Non-negativity and Binary constraints: Shipments must be non-negative, and transport mode selection is binary.

RESULTS

To analyse the importance of node performance after removal within an intermodal network, graph-based centrality metrics on a subnetwork of 15 nodes in Zurich corridor are applied. These indicators are implemented to quantify the influence of specific nodes on overall network functionality. Among all DC locations, Zurich demonstrates the highest percentage drop in total freight throughput resulting from node failure in a subnetwork (in Figure 2), indicating its vulnerability through Critical Node Index (CNI). It is calculated by comparing the total amount of freight successfully routed in the original network versus the disrupted subnetwork where that node is removed. The proposed method integrates subnetwork structure with the outputs of the intermodal transhipment problem. Table 1 presents a comparison of results. The higher CNI indicates that removing a critical node leads to a greater network disruption than in only topological methods. Similarly, the Average Path Length Increase (APLI) shows that intermodal congestion impacts routing causing delays. The Network Flow Reduction (NFR) demonstrates that this model captures key bottlenecks in intermodal networks caused by the removal of a critical node.

Table 1. Comparison of node criticality methods

Method	CNI (%)	APLI (%)	NFR (%)
Betweenness Centrality (BC)	45.2	18.7	35.4
Closeness Centrality (CC)	38.5	15.2	29.8
Network Flow Model	61.4	23.5	48.3
Proposed Method	**68.2**	**27.4**	**55.1**

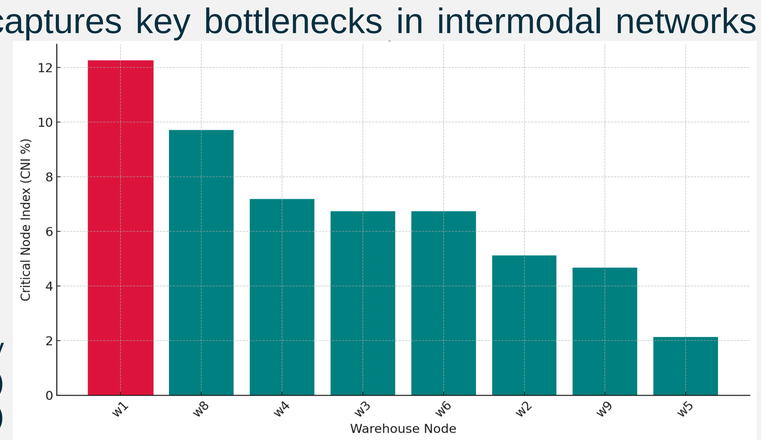

Fig 2. Warehouse node criticality measured by Critical Node Index (CNI) in the intermodal network. Zurich (w1)

CONCLUSION & IMPLEMENTATION PATH

The study of node criticality in intermodal networks represents a key research area with direct implications for resilient and efficient freight transport. While traditional centrality-based approaches provide valuable topological insight, they often overlook operational constraints such as congestion, terminal capacity, and rerouting delays. This research introduces a hybrid framework that combines centrality indicators with a congestion-aware intermodal transhipment model. By simulating node removals and evaluating their effect on cost, duration, and flow redistribution, the model delivers a more realistic assessment of node vulnerability. The proposed method outperforms classical metrics in capturing the systemic impact of critical node disruptions, as shown in the comparative results for Zürich. The findings support the prioritisation of highly connected intermodal nodes in strategic planning. This methodology provides decision-makers with a more robust toolset for identifying infrastructure bottlenecks and developing contingency routing strategies. Future work will explore real-time network updates, broader node interaction effects, and the integration of stochastic demand profiles to further refine dynamic criticality assessments in intermodal network.

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