Robustness assessment of multimodal freight transport networks

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A B S T R A C T

Multimodal freight transport allows switching among different modes of transport to utilize transport facilities more efficiently. This paper proposes an approach on network modeling and robustness assessment for multimodal freight transport networks, where the nodes represent junctions, terminals and crossings, and the links represent pathways. The network model captures the features of interconnection and interdependency. Freight can switch between different modalities at interconnected terminals, while disruption of a single interdependent node (e.g., bridge, tunnel, railway crossing) affects multiple modalities. Considering disruptions of infrastructure elements and capacity degradation of pathways as perturbations, the network robustness is evaluated as the increment of the total travel time caused by these perturbations. We apply our robustness assessment model to the Dutch freight transport, taking into account three modalities: inland waterway, road and railway. The node criticality, defined as the impact of a node removal on the total travel time, resembles a power-law distribution, independent of different traffic assignments. This scale-free property implies a relatively robust state of the network against single random disruptions. Further, we show that the most critical nodes can be roughly identified by their topological properties. Our research helps to schedule the maintenance by assigning priority to the critical infrastructure.

1. Introduction

The European hinterland freight transport sector has aimed at a shift towards multimodal transport such as railway, inland waterway and sea transport, in order to alleviate the saturation of road systems [1,2]. Intermodal transport and synchronodal transport are promoted as two promising solutions. Intermodal freight transport allows moving goods by using various modalities consecutively [3]. Synchronodal transport aims at real-time and flexible switching among different modes of transport according to the latest logistic information, so as to utilize all transport facilities more efficiently [4,5].

Transport networks are prone to suffer from various perturbations, for example infrastructure failures and temporary closures due to construction work. More severe perturbations, such as strikes or extreme weather (e.g. droughts, heavy snow, strong winds), could lead to the partial unavailability of transport networks. Network robustness is interpreted as a measure of the network’s response to perturbations or challenges imposed on the network [6,7], which considers both the network topology and the service for which the network is designed [8]. In transportation field, “Robustness” refers to the avoidance of direct and indirect economic losses of a transport network, which is defined as the degree to which the transportation network can function in the presence of various capacity disruptions on transport elements [9]. In the robustness analysis, evaluating the network performance reduction under network perturbations is a common approach. A more comprehensive review of related works refers to Section 2. Despite that many assessment approaches have been applied in different modes of transport, the framework of robustness assessment for multimodal networks has seldom been studied [10]. The issues including (i) how to abstract particular infrastructure (e.g. terminals and crossings) in multimodal transport? (ii) how to assess the network robustness under both structural disruptions and capacity degradation? (iii) what is the topological property of the traffic-based critical infrastructure element? are still open. This study aims at addressing the above questions.

Introducing concepts of Network Science to transportation research allows us to propose a framework of network modeling, robustness assessment and critical structure identification for multimodal freight transport. The study of robustness in Network Science started with the critical percolation threshold in random graphs [11,12]. In recent years, the research issues emerging in Network Science, e.g., interdependent network [13], cascading failure [14], spreading process, percolation model, are receiving attention since these models of a high interpretability can feature more comprehensive behaviors in real-world networks, e.g., power grids, water distribution networks, congestion propagation. An interdependent network in Network Science is a
Multi-layer network consisting of different types of networks that depend upon each other for their functioning [13]. The interdependency in networks has been applied to measure the robustness of communication networks, that control and are supported by power grids [15], notably by investigating the impact of cascading failure [14,16]. The representation of interdependent networks is an excellent proxy for the structure of multimodal networks, which is first applied in transportation systems. Taking into account several modalities (e.g. inland waterway, road and railway), the transport infrastructure is modeled as a multilayered network, where the nodes represent junctions, terminals and crossings, and the links represent pathways. This network features two properties: interconnection [17] and interdependency [16]. Specifically, transloading terminals are facilities where freight can be transferred from one mode of transport to another and are modeled as interconnections. The crossings, whose functioning influences multiple modes of transport (e.g. bridges), are interdependent nodes. Thus, the disruption of a crossing implies a simultaneous unavailability of related pathways in multiple layers of the network. Consequently, this macroscopic network model abstracts the intricate connectivity of multimodal transportation networks, and also characterizes various types of network perturbations.

Based on the network model, we assess the robustness of multimodal transportation networks. We regard the total travel time of transporting all the freight as a performance indicator, which usually increases due to disruption of any infrastructure element [18]. Our framework assumes that the increment of total travel time due to a node removal reflects the criticality of this node. Then, the robustness of a network can be measured by considering the time increment arising from every node removal in a statistical way. The distribution of the nodal criticality in a large-scale network could provide insights on the evolution of transport behaviors. Further, we explore the correlation between the time increment due to a node removal and the topological properties of this node, which helps to identify the critical nodes faster.

We assess our approach by an extensive case study on the freight transport network in the Netherlands. The case study is not limited to the traffic assignment of all-or-nothing (AoN) [19], but also more practical traffic models, including modal split (MS) [20], user equilibrium (UE) [21] and system optimum (SO) [21]. We investigate the robustness performance and topological properties of the critical nodes under different traffic assignments. The assessment under single element disruptions identifies the critical nodes, whose disruption leads to a relatively high increment of the travel time. The critical nodes need to be given a higher priority for repairs and maintenance by the responsible organization. The robustness assessment under the capacity degradation of pathways can help to evaluate the impact of a large-scale disaster and work out contingency plans. A general recovery framework for any type of network is presented in [22], which allows to assess the performance of recovery measures in transport networks. One can refer to Project RMTN1 on Github for the open source of our assessment framework and the cartographic data of our Dutch transport network. The main contribution of this work can be summarized as:

- a. We introduce the concepts of interconnection and interdependency into modeling multimodal networks, which allow to evaluate the impact due to disruptions of the terminals and the crossings.
- b. The framework of transport network assessment systematically considers disruptions/degradation of infrastructure under different traffic behavior.
- c. The assessment framework develops the method of roughly identifying critical nodes by nodal topological properties.

This paper is organized as follows. A short overview on related work is presented in Section 2. We introduce the method for modeling a multimodal transport network in Section 3. Section 4 proposes a framework of robustness assessment and defines a robustness indicator. We apply the assessment method to the Dutch freight transport network in Section 5. Section 6 summarizes our findings and concludes this paper.

2. Related work

There is a large body of related work on robustness/resilience of transport networks [23,24], which can be categorized according to transportation modes, robustness metrics and perturbation types. The summary of some related research refers to Table 1.

2.1. Transportation modes

Due to different characteristics of various modes, previous research on robustness is categorized according to transportation modes including road network, freight transportation network, railway, waterway network, air network and multimodal transportation. This research focuses on multimodal/synchromodal transportation, which is in the agenda of the Dutch government and the Dutch Top Sector Logistics [25]. The main feature of multimodal/synchromodal transport includes a centralized management to monitor the traffic flow, to schedule the route of drivers and to allocate the cargo volume of vehicles, which helps to design a better traffic assignment and a more robust network [2]. As proposed by the Dutch Institute for Advanced Logistics (Dinalog), synchromodal transport entails that “A shipper agrees with a service operator on the delivery of products at specified costs, quality, and sustainability but gives the service operator the freedom to decide on how to deliver according to these specifications” [26]. The assumptions that (1) the freight from warehouses can be delivered from origin to destination via different modalities; (2) The quantity of freight from warehouses/regions can be divided into smaller units and carried by multiple vehicles/carriages/ships; allow the freight transport shares some similar traffic behaviors with urban traffic.

Comparing to single transportation modes, network modeling and robustness assessment of multimodal transport have not been studied extensively [2,24]. A network model of multimodal transportation processes was proposed to evaluate the network robustness allowing distinguished multimodal processes to continue in order to accomplish trips following an assumed set of multimodal chains [27]. A quantitative measure of resilience was employed to determine the best set of actions to improve security at critical components e.g., terminals and ports, in an intermodal network [28]. Chen et al. [29] built an integer programming model to obtain a quantitative measure of resilience of a port-hinterland container transportation from the perspective of shippers. Stamou et al. [30] presented a data-driven method for assessing the resilience of the European multimodal passenger transport network during extreme weather events. Darayi et al. [31] integrated a multi-commodity network flow formulation with an economic model to quantify the multi-industry impacts of a disruption in the network. The disruption management from passenger multimodal rerouting from airports due to the occurrence of perturbations on modes was considered in [32]. Although we have suffered the frequency occurrence and serious consequences of the crossings in transportation systems (e.g. 2019 Taiwan bridge collapses2 and 2018 Amsterdam Highway tunnel collapses3), an approach for modeling and assessing the impact of disruptions of these crossings are still lacking.

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1 https://github.com/krnavneet1/RMTN

2 cnn.com/2019/10/01/asia/taiwan-bridge-collapse-intl-hnk-scli

3 nltimes.nl/2018/01/03/ceiling-amsterdam-highway-tunnel-collapses
2.3. Perturbation types

The perturbation on transport networks can be categorized into two variants: connectivity-related and capacity-related. Connectivity-related perturbations [34,35,43] consider failures of infrastructure elements as removed nodes/links from a network. Capacity-related perturbations [9,36–38] consider failures of infrastructure elements as the capacity reduction of parts of the network, as opposed to an entire removal of parts of the network.

In this paper, we consider two types of real-world perturbations: disruptions of single infrastructure element and extreme weather events. We assume that the disruption of one node implies an entire unavailability of this infrastructure element and its blockage for safety, which belongs to the connectivity-related perturbations. The impact of extreme weather events usually leads to the partial unavailability of transport networks [30,39], which corresponds to the capacity reduction of this transport mode (e.g., low river level degrades riverway capacity, heavy snow degrades road capacity). Further, our proposed framework allows us to consider these two types of perturbations simultaneously, i.e., identifying critical nodes under extreme weather.

3. The synchromodal network model

In this section, we briefly introduce the network model for multimodal transport, which features multiple layers, interconnection and interdependency. We refer to our previous report [44] for supplementary information about the infrastructure considered and the network modeling.

3.1. Multi-layer network

The underlying topology of the multimodal freight transportation can be represented by an undirected network $G(\mathcal{N}, \mathcal{L})$ with the set $\mathcal{N}$ of $N$ nodes and the set $\mathcal{L}$ of $L$ links. The nodes in the network represent transloading terminals, crossings and junctions, which are...
3.2. Origins and destinations (OD centroid)

Centroids of regions are used to model the origins and destinations in each region, where the centroid of a polygonal area is located at the center of mass of that polygon. We split the country into several regions, where the centroid of each region represents the origin and destination of the freight transport demand in that region. For example, we apply the centroids of NUTS-3 regions\(^4\) (a statistical subdivision of Europe) as the OD centroid in our case study. Each centroid also represents the cargo demand of this region, which can abstract a storage facility of freight in actual transport networks. These centroids are represented by the nodes in the subnetwork \(G_{OD}\). We assume that the centroid is connected to all access points in the road subgraph of this region by small roads. The small roads are represented by the OD links in the subnetwork \(G_{OD}\). Fig. 1(a) illustrates the network model for centroids.

The amount of freight (in tons) that is transported between the origins and destinations is defined in the demand matrix \(D\), where the element \(D_{ij}\) defines the average amount of cargo transported from region \(i\) to region \(j\). Freight transported between the origin and the destination in the same region is not considered, and thus the diagonal elements of the demand matrix \(D\) are all equal to 0.

3.3. Interconnection

Intermodal transport allows switching among different modes of transport at transloading terminals. At a transloading terminal two or more modalities are interconnected. The containers can be trans-shipped in container terminals (sometimes called inland ports). We take three types of container terminals (i.e. rail terminals (connecting Rail and Road), waterway terminals (connecting Waterway and Road) and trimodal terminals (connecting all three modalities)) into account. Fig. 1(b) illustrates the network model for these terminals. Each transloading terminal is represented by a node in the subgraph \(G_T\). The terminal node is connected with links to nodes of the appropriate modes of transport. This modeling method captures the feature of disruptions of terminals, i.e. the freight cannot switch to a different mode of transport if the terminal node is removed.

3.4. Interdependency

The three modalities (waterway, road and rail) cross each other regularly (see Fig. 3 below). At each crossing, a civil engineering structure is needed (e.g. bridge, tunnel, railway crossing) to efficiently use both modalities. Thus, the disruption of a single civil engineering structure can affect multiple modalities, which causes the interdependency between the modalities. For example, the disruption of a bridge can affect both the road and the waterway simultaneously. Unlike for interconnection, transloading of freight is not possible at these crossings. Fig. 1(c) illustrates the network model of an interdependent node. We represent each crossing structure as two nodes in the subgraphs of the two modalities. The relation of interdependency between these two nodes implies a simultaneous removal due to a disruption, i.e. if either node is removed, the other node will be removed as well.
where the total travel time, \( t \), of Public Roads (BPR), is given by [19]:

\[
\alpha \text{ free flow travel time, where } t = \frac{d}{v} \text{ (in kilometers/hour) determines the travel time } \text{ for any amount of flow } x \text{ (in tons/hour) within } h \text{ hours, i.e., } t_f = \frac{d}{v_f}.
\]

For the same OD demands and the same traffic assignment, we recompute the performance indicator due to the perturbations. The framework provides the method for exploring the relation between the impact of the disrupted elements on the performance and several topological properties of these elements.

### 4.1. Link attributes

The performance of the transport system is related to the route condition of each modality, which translates to the link attributes in the network model. Each pathway segment represented by a link \( \ell \) in the network has two attributes: the free-flow average speed \( v_f \) (in kilometers/hour) and the capacity \( c_f \) (in tons/hour). The average speed \( v_f \) (in kilometers/hour) determines the travel time \( t_f \) (in hours) on link \( \ell \), i.e., \( t_f = \frac{d_f}{v_f} \), where \( d_f \) is the length of link \( \ell \) (in kilometers). Considering the travel time as the cost of freight transportation, the travel time \( t_f \) is regarded as the link weight in the network for computing the shortest path from the origin to the destination.

The average speed \( v_f \) is a constant for the traffic assignments without capacity constraint, i.e., the link travel time \( t_f \) is also constant for any amount of flow \( x_f \) (in tons/hour) assigned on the link \( \ell \). In contrast, the link capacity constraints are included in the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion. A popular form of these functions that reflects the travel time functions considering traffic congestion.

\[
t_f(x_f) = t_f^0 \left[ 1 + a \left( \frac{x_f}{c_f} \right)^\gamma \right]
\]

where \( c_f \) is the capacity of link \( \ell \) (in tons/hour), and \( t_f^0 = \frac{d_f}{v_f} \) is the free flow travel time, \( a \) and \( \gamma \) are the shape coefficients, for which the value of \( a = 0.15 \) and \( \gamma = 4 \) are generally applied [19]. The travel time \( t_f \) without considering congestion is consistent with an infinite link capacity \( c_f \to \infty \).

### 4.2. Network perturbation

Network perturbations refer [22,46] to two scenarios: the disruptions of transport elements and the degradation of capacity, which translate to the changes in the underlying topology and the link attributes, respectively. For the scenario of node disruptions, the unavailable nodes are regarded to be removed from the original underlying topology. In this paper, we mainly consider disruptions of individual nodes to investigate the impact of each node on the performance of the network. This analysis may help to identify the critical infrastructure elements and schedule improvement measures. The scenario of node disruptions also includes the case that multiple nodes can be removed simultaneously, which describes simultaneous accidents or cascading failures [16]. We define a random failure as the failure scenario where a given fraction of multiple elements are removed from the network uniformly at random [22].

The scenario of capacity degradation refers to the effect of capacity reduction of a single modality on the performance of the whole network. This scenario aims to describe the cases of large-scale natural and man-made disasters, e.g. driver strikes and low water levels in rivers due to droughts.

### 4.3. Performance indicator

We denote by \( z_f \) the total amount of freight (in tons) attempting to use link \( \ell \) as the flow rate \( x_f \) (in tons/hour) within \( h \) hours, i.e., \( z_f = x_f h \). Invoking that the delay time for each vehicle traveling on link \( \ell \) is \( t_f \) specified by (3), we apply the total travel time, also called the total delay time, \( C_G \) (in tons-hours) of transporting all the freights among all links to measure the performance of network \( G \), which is defined as

\[
C_G = \sum_{\ell \in G} x_f(t_f(x_f))
\]

The network performance indicator \( C_G \) usually increases to \( C_G + \Delta C_G \) due to node disruptions and degradation of link attributes. The robustness can be measured by the normalized increment of the total travel time due to the perturbation on the network, which defines the robustness indicator \( \eta_G \) as

\[
\eta_G = \frac{C_G - C_G}{C_G} = \frac{\Delta C_G}{C_G}
\]
where $G'$ is the network after perturbations.

For measuring the impact of a single node disruption on the performance of the network, we define the node criticality as the normalized increment of the total time caused by the node removal. The node criticality is similar to the network robustness index proposed by Scott et al. [40]. The node criticality of node $i$ is the same as the robustness indicator $\gamma_i$ under the single node disruption, which is

$$o_i = \frac{C_{G|\{i\}} - C_G}{C_G}$$

where $G\setminus\{i\}$ is the graph in which node $i$ is removed as well as all its incident links. The network robustness under isolated single disruptions can be measured by the average node criticality $E[o] = \frac{1}{N} \sum_{i=1}^{N} o_i$ among all nodes. In general, a smaller average node criticality $E[o]$ implies a more robust network.

4.4. Traffic assignment

Besides the common assignments (e.g., all-or-nothing and modal-split logit model), some practical traffic assignments (e.g., user equilibrium and system optimum), considering link capacity and congestion, have attracted lots of attention for inter-city logistics and urban freight transportation [39,47]. For example, the freight network equilibrium model (FNEM) [48] treats the route choice decisions of both shippers and carriers sequentially on a multimodal freight network, with nonlinear cost and delay functions which depend on commodity flow volumes as impedances to model congestion phenomena. To perform the traffic assignment, freight trucks are usually converted into their “passenger car equivalent” units based upon truck gross vehicle weight [49]. This assumption suggests that urban freight transport could share similar behaviors with urban transport planning. In this work, we investigate four kinds of traffic assignments: all-or-nothing (AoN), modal-split logit model (MS), user equilibrium (UE) and system optimum (SO).

4.4.1. All or nothing (AoN)

An all-or-nothing (AoN) assignment is commonly applied for traffic assignment in networks. The AoN assignment in this paper assigns all demand of each OD pair to the route with the lowest route time. The total flow assigned to link $\tau_s$ takes the value one if link $\ell$ is defined as

$$\sum_{s,d,k} \sum_{t=1}^{N} \sum_{k=1}^{K} D_{sd} \cdot P_{sd,k} \cdot \delta(P_{sd,k}, \ell)$$

where $\delta(P_{sd,k}, \ell)$ takes the value one if link $\ell$ is belong to the route $P_{sd,k}$ and zero otherwise.

4.4.2. Modal-split assignment (MS)

Modal-split assignment also assumes the infinite link capacity $c_s$. The demands between origins and destinations are distributed over the network by applying a probabilistic route choice model in modal-split assignment [20]. The freight between the origin and the destination is distributed over different routes in the route choice set by using a multinomial logit regression. Given the routes set $P_{sd}$ with the first $|P_{sd}| = K$ shortest paths from origin $s$ to destination $d$, the fraction of freight using the $k$th route $P_{sd,k}$ is defined as

$$P_{sd,k} = \frac{\exp(-\beta t_\ell)}{\sum_{k=1}^{K} \exp(-\beta t_\ell)}$$

where $t_\ell$ is the total time along the route $P_{sd,k}$ alone and $\beta$ is the parameter tuning the drivers’ preference for the route with a lower travel time. The total flow assigned to link $\ell$ follows

$$x_\ell = \sum_{s \in N} \sum_{d \in N} \sum_{k=1}^{K} D_{sd} \cdot P_{sd,k} \cdot \delta(P_{sd,k}, \ell)$$

4.4.3. User equilibrium (UE)

According to Wardrop’s first principle [52], drivers in a congested network prefer choosing their route selfishly, following a behavior that is captured by the Nash equilibrium of the underlying non-cooperative game. Assuming that the driver has perfect knowledge of the travel time on a network and able to choose the best route according to Wardrop’s first principle [53], the behavioral assumption will lead to a deterministic user equilibrium. Using a potential function $\phi_\ell(x_\ell) = \int_0^{x_\ell} t_\ell(x_\ell)dx$, this routing behavior minimizes the sum of the potential functions, which is formulated as a convex optimization problem:

$$\min_{x_\ell \in \mathbb{R}} \sum_{\ell \in L} x_\ell \cdot t_\ell(x_\ell)$$

subject to

$$\sum_{\ell \in L} f_\ell^d = \frac{D^d}{\lambda}$$

$$x_\ell \geq 0, f_\ell^d \geq 0.$$
documents, while the interdependent crossings are located manually according to Google map. Fig. 3 illustrates the transport network of the Netherlands.

The Netherlands is divided into 40 regions (NUTS-3 used by Eurostat) based on BasGoed, each of which is represented by a centroid node. Fig. 4 illustrates the amount of containers transported from and towards all regions in the Netherlands, which determines the OD demand matrix $D$. We assume that all the freights enter the traffic system in the peak period within one hour, i.e., $h = 1$. The Dutch freight transport network consists of 1457 nodes, 44 terminals, 40 centroids, 1897 main-pathway links, 101 terminal links and 692 OD links.

### 5.1.2. Link attributes configuration

We assume that the travel time of road, railway and waterway has a similar behavior. More specifically, the travel time is nearly a constant under low-flow conditions, while the travel time increases sharply for the high flow approximating the path capacity under congested conditions. For simplicity without loss of generality, we apply the BPR function (3) to feature the above characteristic where the parameters can tune the behavior of different modalities. Different modalities yield different configurations of link attributes in each layer of the network in Fig. 3(a), which define the parameters (i.e., the parameter $a$, $\gamma$, the average speed $v_r$, the capacity $c_r$) in the BPR function (3) for each link. Table 2 presents the link attributes used. The small roads between OD/terminals have a lower average speed than the main roads. Compared with the Road and the Water, the travel time for the Rail depends more on the capacity of the railway, as the maximum number of trains on a railway is predetermined. Therefore, we set a large $\gamma$ for the Rail. This means the travel time $t_r$ per unit of freight increases little with the freight amount below the capacity, but increases a lot for the amount above the capacity. The information about the average speed and the capacity of each modality is provided in the reports.

### 5.2. Robustness assessment under random failures

We next investigate the robustness performance of the network under random failures. Under the scenario of random failure, we remove a fraction of nodes uniformly at random from the network, then compute the increment of the total travel time $4C_G$ due to the removals. The ratio of the increment travel time and the original travel time referring to (5), i.e., $\eta_G = \frac{4C_G}{C_G}$, is used to measure the robustness of a transport network. Fig. 5 shows the average indicator $E[\eta_G]$ among all realizations of random node removals under the AoN assignment. The interconnection of multiple modalities can decrease the average normalized increment of the total travel time $E[\eta_G]$, thus improves the robustness for transport services against random failures. Meanwhile, the interdependency effect of the crossing nodes between different modalities could degrade the robustness indicator $E[\eta_G]$ slightly, which is due to the fact that the failure of an interdependent node impacts two modalities simultaneously. Thus, we observe from Fig. 5 that the interconnection improves the robustness and the interdependency degrades the robustness under random failures.

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![Fig. 4. Demand matrix $D$ for the amount of containers (in tons per business day) transported in the Netherlands (domestic transport only). Source: The data is from BasGoed.](image-url)

![Fig. 5. The average robustness indicator $E[\eta_G]$ under random failures as a function of the fraction of removed nodes. We compare four cases: (1) the Road, (2) the Road interconnected with the Rail, (3) three interconnected modalities without the interdependent nodes, (4) the whole network. Each data point is based on 100 realizations.](image-url)
5.3. Robustness assessment via node criticality

Next, we investigate the distribution of the node criticality $\omega$ for all nodes and the interdependent nodes. Fig. 6 shows the probability density function (PDF) $f_\omega(w)$ of the node criticality $\omega$ as random variables on log–log scale. We fit the distribution of the node criticality $\omega_i$ by a power-law PDF that $f_\omega(w) \sim w^{-k}$. We observe from Fig. 6 that the node criticality resembles a power-law distribution, where different traffic assignment models, i.e., the AoN, the MS2 (i.e. the modal split assignment with $K=2$ routes), the UE and the SO, have little influence on this scale-free property of robustness. The power-law distribution of the node criticality $\omega_i$ implies that the removal of most nodes yields a small increment of the total travel time $\Delta C_G$, while the removal of some critical nodes can increase the travel time $C_G$ significantly. Interestingly, the real-world transport network already tends to be robust against individual failures, which may be caused by the topological evolution [59] and traffic optimization during the development of the network.

A larger slope $k$ in the PDF $f_\omega(w) \sim w^{-k}$ implies a better robustness indicated by the node criticality $\omega$ of network. Comparing the traffic assignment AoN and the MS2, both with an infinity capacity, the AoN surprisingly presents a better performance against single failures with a larger slope $k$ than the MS2. The AoN employs fewer nodes than the MS2, so that some removed nodes have little influence on the increment of the total travel time $\Delta C_G$. Comparing the UE and the SO, the robustness indicated by the distribution of the node criticality $\omega$ under the SO outperforms the UE for disruptions among both all nodes and the interdependent nodes. This implies that a centralized and information-sharing schedule could lead to both a lower total travel time $C_G$ and a better robustness $E[\omega]$. In addition, Fig. 6 shows that the interdependent nodes usually have a higher node criticality among all nodes. Thus the maintenance of the interdependent nodes should be of a higher priority.

5.4. Robustness assessment under capacity degradation

We further investigate the robustness of networks under capacity degradation. First, we define the modal load $\chi_m$ as the total flow $\sum_{\ell \in M} x_{\ell}$ on all the links in this modality divided by the number of links $L_m$ of this modality, i.e. $\chi_m = \frac{\sum_{\ell \in M} x_{\ell}}{L_m}$, which reflects the usage of each modality. Fig. 7 shows the modal load $\chi_m$ and the total travel time $C_G$ versus the degradation of the capacity of each modality. The degradation of the capacity of a modality decreases the modal load of this modality, while the load shifts to the other two modalities. For the Rail and the Waterway, the total time $C_G$ presents a linear function of the fraction of the original capacity, while the degradation of the Road capacity increases the total travel time $C_G$ sharply. The high sensitivity of the total travel time $C_G$ with the capacity degradation of the Road may be due to the fact that the Road is the dominating modality, and the other two fail to balance the loads if the availability of the Road decreases too much. Fig. 7 also shows that the SO presents a lower travel time $C_G$, which indicates that the difference in the usage of
Bar plots show the modal load versus the fraction of the original capacity of a determined modality (the Road, the Rail or the Waterway) and a given traffic assignment (the UE or the SO). The purple lines show the total travel time $C_T$ as a function of the fraction of the original capacity.

Fig. 8. The average node criticality $E[\omega]$ as a function of the fraction of the original capacity for each modality, which measures the robustness against single disruption under degradation of capacity. The average node criticality $E[\omega]$ increases with degradation of the capacity of the Road and the Railway and more sensitive to degradation of the Road capacity. By contrast, the average node criticality $E[\omega]$ presents different behaviors for the degradation of the Rail capacity, which more or less presents a Braess’s paradox [60], i.e., the robustness degrades for a higher capacity of the Rail.

5.5. Topological properties of critical nodes

We investigate the relation between the nodal topological properties and the node criticality in order to identify the most vulnerable and critical nodes faster [61]. A larger absolute correlation coefficient implies a better nodal metric to identify the critical node. The metric of the unweighted degree is the number of links incident to a node, and the other metrics (i.e., degree, closeness [62], node betweenness [62] and the diagonal element of the pseudo-inverse matrix [63]) of the weighted Laplacian matrix $Q^\dagger$ are computed in the weighted network with the link weight $a_\ell = t_{\ell\ell} = \frac{d_{\ell\ell}}{\nu_{\ell\ell}}$. The element $Q^\dagger_{ii}$ is calculated by the Laplacian matrix $\tilde{Q}$ of the weighted adjacency matrix $\tilde{A}$ with entry $\tilde{a}_\ell = \frac{1}{a_\ell}$ for each link $\ell$. Fig. 9 shows that the betweenness has the highest rank correlation with the node criticality, but the correlation degrades under the MS2, the UE and the SO assignments. Considering that the UE and the SO are more practical in real-world, this degradation implies that the identification of the critical nodes could be difficult if the effect of capacity is taken into account under the UE and the SO.

We define the flow network as the network with the link weight $a_\ell = x_\ell$ and denote the corresponding metrics by *. The flow network reflects the usage of each link under a specific traffic assignment. The unweighted degree* in the flow network is the number of non-empty links ($x_\ell \neq 0$) incident to a node. The other metrics are computed in the weighted flow network. The degree* in the flow network is

Waterway, i.e., the SO has a higher modal load of the Waterway than the UE. This result hints a possible optimization for transportation by making full use of the Waterway.

We consider the single node disruption under capacity degradation of each modality. Fig. 8 shows the average node criticality $E[\omega]$ as a function of the fraction of the original capacity for each modality, which measures the robustness against single disruption under degradation of capacity. The average node criticality $E[\omega]$ increases with degradation of the capacity of the Road and the Railway and more sensitive to degradation of the Road capacity. By contrast, the average node criticality $E[\omega]$ presents different behaviors for the degradation of the Rail capacity, which more or less presents a Braess’s paradox [60], i.e., the robustness degrades for a higher capacity of the Rail.

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Fig. 9. The Spearman’s rank correlation coefficients between the node criticality and the topological metrics in the structural network (with \(a_l = t_0\)) and the flow network (with \(a_l = x_\ell\)) under different traffic assignments. The coefficients for (a) all nodes and (b) the interdependent nodes are shown in the subgraphs, respectively. We neglect the element \(Q^*_{ij}\) in the flow network since the weighted adjacency matrix \(\tilde{A}\) is not applicable for the network with zero-weighted links \(a_\ell = x_\ell = 0\).

actually the total amount of freight passing this node, which becomes the best indicator of the critical nodes. However, the rank correlation also degrades in the MS2, the UE and the SO, which implies that the critical nodes do not entirely depend on the local traffic flow.

We also investigate the topological properties of critical interdependent nodes. Since the closeness* is calculated as the reciprocal of the sum of the length of the shortest paths between the node and all other nodes in the flow network [62], the important nodes nearby the links with a high link weight \(a_\ell = x_\ell\) usually have a smaller closeness*, which leads to the negative correlations between the node criticality and the closeness*. Fig. 9 shows that the interdependent nodes present similar behavior of the topological properties with all nodes, but have a higher correlation with the closeness*. The strong correlation allows us to identify the most critical interdependent nodes by using the degree* and the closeness* in combination.

6. Conclusion

Multimodal transport opens a new door for mitigating congestion in road transport and for reducing transportation costs. This paper addresses the approaches to both the network modeling and the robustness assessment of multimodal transport networks. The consideration of the interdependent property of multimodal networks fills the gap for modeling the disruptions of the crossings. Although the interdependency degrades the robustness of the network slightly, the interconnection of multiple modalities benefits the total travel time and outweighs the negative effect of interdependency on the robustness performance. The robustness is assessed by both element disruptions and capacity degradation. The case study of the Dutch transport network provides several new insights. First, the power-law-like distribution of the node criticality implies a good robustness of the real-world network. The dynamics of self-evolution and overall planning leading to this robust state could be an open question beyond this paper [64]. Second, we observe that the capacity degradation of the Road could exert a disastrous growth of the total travel time, while shifting more loads to the inland waterways can decrease the total travel time. Lastly, the node criticality is strongly correlated to the amount of freight passing this node. The most critical interdependent node can be identified by the degree and the closeness of nodes in the flow networks. This study can support network planners in tactical and operational decisions for improving the performance of multimodal transport networks.

The proposed framework can be employed to a general transport system, but some details merit further improvements. A better experimental formula for the travel time in terms of the freight flow on links in railway and inland waterways, instead of the BPR function as (3), can characterize more features of different modalities. In addition, we employed the total travel time as travel cost for this case study, while different definitions of costs, e.g., \(CO_2\) emissions [10], could exhibit different results.

CRediT authorship contribution statement

Zhidong He: Methodology, Writing - original draft, Writing - review & editing.
Kumar Navneet: Software, Data curation, Validation.
Wirdmer van Dam: Resources, Data curation, Software, Visualization.
Piet Van Mieghem: Conceptualization, Supervision.

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